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Industrial Technologies Program
Industrial Materials for the Future

Final Technical Report

Development of a New Class of Fe-3Cr-W(V) Ferritic Steels for Industrial Process Applications

March 2005

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Disclaimer

Contents

Appendices

List of Figures

List of Tables

Abbreviations and Acronyms

ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CCT	continuous cooling transformation
DBTT	ductile brittle transition temperature
EQS	Ellwood Quality Steel
ESR	electroslag remelting
Grade A	a new Fe-3Cr-W(Mo) steel developed in this project (also known as Grade 315 in this report)
Grade B	a new higher-strength Fe-3Cr-W(Mo) steel with 0.1 Ta developed in this project (also known as Grade 315T in this report)
Grade 22	2.25Cr-1Mo steel
GTA	gas-tungsten arc
LMP	Larson-Miller parameter
N	normalized
N/T	normalized and tempered
ORNL	Oak Ridge National Laboratory
PWHT	postweld heat treatment
SA	submerged arc
SMA	shielded metal arc
T23	highest strength Fe-2.5Cr-W alloy from Japan
TTT	time-temperature transformation
VAR	vacuum-arc remelting
VIM	vacuum-induction melted

1. Executive Summary

The project described in this report dealt with improving the materials performance and fabrication for hydrotreating reactor vessels, heat recovery systems, and other components for the petroleum and chemical industries. The petroleum and chemical industries use reactor vessels that can approach ship weights of approximately 300 tons with vessel wall thicknesses of 3–8 in. These vessels are typically fabricated from Fe-Cr-Mo steels with chromium ranging from 1.25 to 12% and molybdenum from 1 to 2%. Steels in this composition range have great advantages of high thermal conductivity, low thermal expansion, low cost, and good properties obtainable by heat treatment. With all of the advantages of Fe-Cr-Mo steels, several issues are faced in design and fabrication of vessels and related components. These issues include the following:

1. The low strengths of current alloys require thicker sections.
2. Increased thickness causes heat-treatment issues related to nonuniformity across the thickness and thus a failure to achieve optimum properties.
3. Fracture toughness (ductile-to-brittle transition) is a critical safety issue for these vessels, especially in thick sections because of the nonuniformity of the microstructure.
4. The postweld heat treatment (PWHT) needed after welding makes fabrication more time-consuming with increased cost.
5. PWHT needed after welding also limits any modifications of the large vessels in service.

The goal of this project was to reduce the weight of large-pressure-vessel components (ranging from 100 to 300 tons) by approximately 25%, reduce fabrication cost, and improve in-service modification feasibility through development of Fe-3Cr-W(V) steels with a combination of nearly a 50% higher strength, a lower ductile-brittle transition temperature (DBTT), a higher upper-shelf energy, ease of heat treating, and a strong potential for not requiring PWHT.

1.1 New Class of Fe-3Cr-W(V) Steels

The goals of the project were carried out through research and development efforts conducted by a team consisting of chemical and petrochemical industries (ExxonMobil Chemical Company, BP Amoco, and DuPont), materials producers (ISG Plate, Ellwood Materials Technologies Company, Plymouth Tube Company, and Ellwood National Forge), a component fabricator and welding process developer (Nooter Fabrication Services, Inc.), a weld wire producer and process developer (Stoody Company), a heat recovery unit construction company (Nooter-Eriksen), and a national laboratory (Oak Ridge National Laboratory [ORNL]). Industry participated by (1) identifying reactor vessels and other components that can take advantage of the new steel, (2) testing components, (3) assisting in producing production-size heats of the new steel, (4) assisting in component fabrication and process development, and (5) developing the welding process. Welding wire suppliers produced small batches for trials by Nooter Fabrication Services and ORNL. Industry representatives also provided guidance and direction to the project through active participation in identifying and monitoring project deliverables and technical progress reports.

The project developed two new steel compositions using Fe-3Cr-W(V) as the base. The new compositions were designated as Grades A and B (sometimes referred to as 315 and 315T). Grades A and B have the same nominal composition except that Grade B contains 0.10 wt % tantalum. Both grades were commercially scaled up to 50-ton heats. Round and slab ingots from these heats were processed into forgings, hot-rolled plate, bar, and tubing. Processing of ingots from large heats was carried out using currently available commercial practice. Both grades were chosen for use in the normalized and tempered condition: 2012/1345°F (1100/730°C).

Forging and plate from three commercial heats of each grade were subjected to tensile, Charpy-impact, and creep testing. Tensile tests were conducted from room temperature to 1300°F (704°C), impact tests from −60°F to +150°F (−51 to +65°C), and creep tests from 900 to 1300°F (482 to 704°C). All of the data were generated in accordance with ASME Pressure Vessel and Boiler Code requirements.

Welding studies were carried out on 1-in.-thick plate from both Grades A and B. Welding process studies included studies with gas-tungsten arc (GTA), submerged arc (SA), and shielded-metal arc (SMA). Lincoln 880 was found to be the best flux for producing the desired weld chemistry with low oxygen content in SA welds. Filler wire compositions that did not require PWHT were identified for GTA welds. Project team members decided that PWHT had to be used for SA and SMA welds, given their high oxygen content in the weld deposit. A PWHT of 1292°F (700°C) was found to result in acceptable Charpy-impact properties.

Table 1.1 shows a comparison of the Grade A steel composition with the commonly used 2.25Cr-1Mo steel and a recent high-strength version from Japan known as T23. The new steels can be welded by all common welding processes (GTA, SA, and SMA). For the GTA process, welds can be used in the as-welded condition. For SA and SMA, a PWHT of 1295°F (700°C) is recommended.

Table 1.1. Comparison of the new Grade A steel composition with two commercial steels

	Comparison of Grade A Fe-3Cr-W(V) steel with	
Property	2.25Cr-1Mo steel	T23 steel
Yield strength at room temperature	60% higher	25% higher
Yield strength at high temperatures	110% higher at 900°F (482°C)	45% higher at 1110°F (600°C)
Tensile strength at room temperature	50% higher	33% higher
Tensile strength at high temperatures	50% higher at 900°F (482°C)	33% higher at 1110°F (600°C)
Charpy-impact upper shelf energy	*a*	*a*
Ductile-to-brittle transition temperature	*b*	*b*
Creep-rupture strength	—	35% higher for 10^5h at 932ºF (500ºC) Same for 10^5h at 1100ºF (590ºC)

[a]Values of upper shelf energy in the range of 50 to 100 ft-lb. No comparable data available.
[b]Ductile-to-brittle transition temperature of −20 to −40ºF. No comparable data available.

Grade B steel, investigated less detail than Grade A, showed the following attributes:

- Tensile property improvements were similar to those described for Grade A.
- Impact properties were similar to the impact properties of Grade A.
- Grade B showed 10–20% higher creep rupture strength than Grade A for conditions causing rupture in 10^5 h at temperatures ≤ 1100°F (593°C). However, for higher test temperatures, Grade B had a slightly lower creep rupture strength than Grade A.

- Limited welding trials with Grade B showed no unusual problems. We anticipate that the weld wire for this grade of steel will require a higher tantalum content in order to obtain the target value.

1.2 Technology Transfer

As noted in the previous section, the project team consisted of steel producers; producer of products such as forgings, plate, and tubing; a welding wire producer; component and pressure vessel fabricators; and users. The team partners actively participated in all aspects of this project and, thus, acquired significant knowledge of the newly developed steels in this project.

The technology transfer beyond the team partners was accomplished through (1) presentations at annual DOE portfolio project review meetings, (2) three presentations at national and international technical review meetings, and (3) publication of two technical papers in conference proceedings. Further technology transfer was also accomplished through presentations by industrial partners at certain committee meetings such as the American Society for Testing and Materials (ASTM) and presentations of data on the new steels to their customers.

1.3 Commercialization

Significant progress towards commercialization of the new steels developed in this project has been made through the following steps:

1. ASTM approval of specifications was obtained for both Grades A and B.
2. Progress was made on obtaining American Society of Mechanical Engineers (ASME) Pressure Vessel and Boiler Code approved design-allowable stresses for Grade A by submitting its comprehensive mechanical properties data package to the code committees.
3. Dr. Maan Jawad was retained as a consultant to the project for participation in the ASME Code Committee review meetings to answer any questions that might arise during deliberations.
4. Further commercialization will occur through visits by Dr. Maan Jawad to various companies. The purpose of these visits will be to familiarize their system design engineers with the advantages of using the new steels.

1.4 Recommendations

This project has accomplished nearly all of the planned goals. However, the following additional activities are recommended to further advance the potential of this project:

1. Provide additional long-term creep testing of the Grade A steel. These data are essential for obtaining ASME code approval and gaining confidence from users in the long-term stability of the new steels.
2. Perform creep tests on the Grade B steel. These tests were discontinued because of lack of funds.
3. Test components from the new steel under commercial production conditions. Successful installation and operation under production conditions develops user confidence in trying new steels. One example of this installation could include tubing in heat recovery boilers.
4. Develop more extensive data on the mechanical properties of weldment. Although we made progress on the welding process and filler wire development during this project, there is a need to develop a significant amount of mechanical property data of weldment. This effort is needed initially for welds in 2- to 4-in.-thick plates of Grade A steel, and subsequently for welds in Grade B steel.

5. Demonstrate the welding process for actual components such as tube-to-tube or tube-to-tube sheet. Again, this is required initially for Grade A, followed by Grade B.

2. Introduction

This project dealt with the development of a new class of Fe-3Cr-W(V) steels for use in the construction of chemical processing equipment such as hydrocrackers, hydrotreaters, and heat recovery systems. The key attributes targeted for the new steel were the following: (1) 50% higher tensile strength at temperatures up to 1022–1112°F (550–600°C) than is available in current materials, (2) the potential for eliminating postweld heat treatment (PWHT) for certain welding processes, (3) reduction in equipment weight by 25%, and (4) impact properties of approximately 100 ft-lb of upper shelf energy and a ductile-to-brittle transition temperature (DBTT) of −10°F.

Quite a number of the components in chemical processing equipment are currently fabricated from Fe-2.25Cr-1Mo steel, commonly known as Grade 22 steel. Section thicknesses of up to 10 in. are required for some of the equipment fabricated from this steel, with equipment weights reaching as much as 100–300 tons. Most of this equipment is built to ASME code specifications. Thus, if PWHT is required, no equipment modifications are possible once the equipment is installed and operating. The 50% higher tensile strength of the newly developed steel will reduce section sizes by nearly half, thereby reducing the equipment weight to 50–150 tons. Furthermore, since some welds are made by the gas tungsten arc (GTA) process, they require no PWHT; once the equipment is erected, it can be modified by using the GTA welding process.

The project team and interactions between the team members during the project are shown in Fig. 2.1.

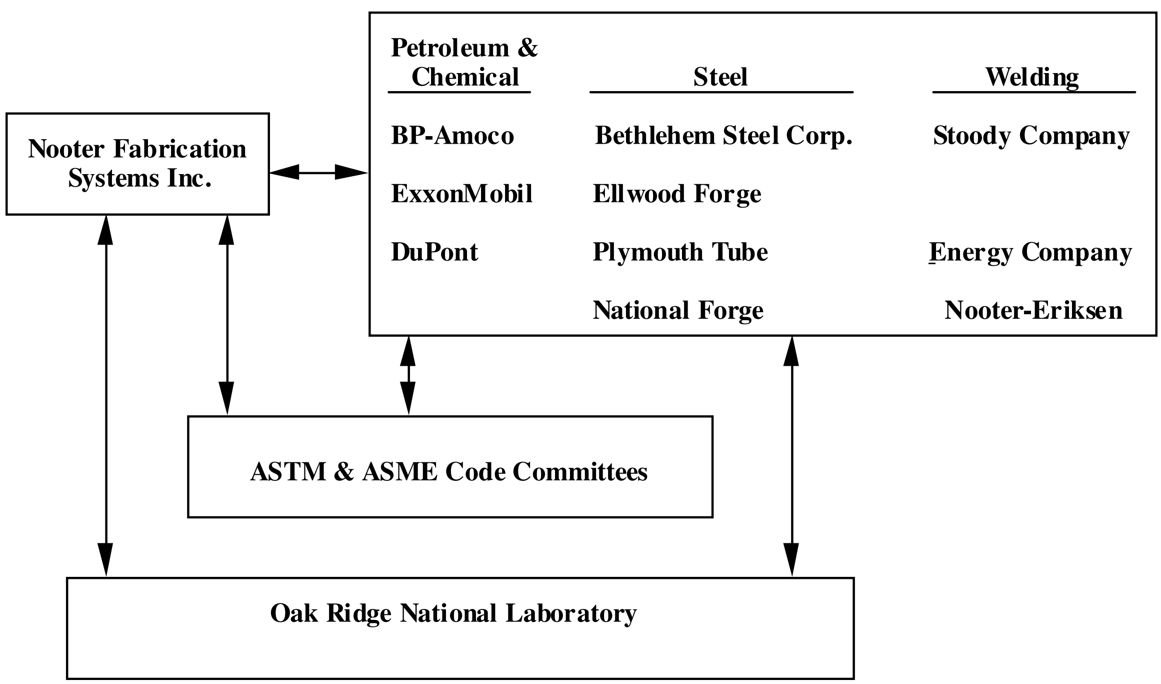


Fig. 2.1. Organization plan for project coordination and management.

2.1 Potential Applications, Target Industries, and Energy Savings

As noted at the beginning of Section 2, the newly developed steel was targeted for chemical process reactors such as hydrocrackers, hydrotreaters, and industrial heat recovery systems. For the chemical process reactors, this alloy is needed as forgings and plate, and for tubing in heat recovery systems.

The target industries for this project include chemical and petrochemical companies, energy companies, steel producers and steel product manufacturers, component fabricators, and welding consumable producers. Each of these industries were had one more representatives as part of this project.

The development of an advanced steel that meets project goals will result in energy savings from a combination of several factors: (1) reduction in energy use in steel production because 25–50% less steel will be needed for fabricating components, (2) significant reduction in energy needed to weld 25–50% thinner steel sections, and (3) reduction in energy by eliminating PWHT for certain weld practices such as GTA.

Energy savings are also anticipated through the following:

- Improvement in chemical process efficiencies by operating at higher temperatures through the use of the new alloy; chemical processes such as hydrotreating could increase by 1.5%
- For heat recovery units, the thinner tubes made possible by the new alloy will result in higher heat transfer and, thus, higher heat recovery; this improvement is estimated at 1%

It is estimated that by 2020, full-scale implementation of the advanced alloy developed in this project will result in an energy savings of 21 trillion Btu/year.

2.2 Commercialization Status and Plans

A plan that identified steps needed for commercialization of the new steels was developed. The steps identified were the following: (1) getting specifications for the new steels approved by ASTM, (b) getting ASME Pressure Vessel and Boiler Code approved allowable-design stresses for the new steels, (3) familiarizing system designers with the properties of the new steels so that these steels can be specified as the material of choice, and (4) providing test material and welding filler so that fabricators can become familiar with the use of the new steels.

Progress towards commercialization is as follows:

1. Both Grade A and Grade B were approved for inclusion in American Standards for Testing Materials (ASTM) specifications. The new alloys are listed in Specification A1041-04.

2. Design-allowable stresses for the alloy must be set by ASME Boiler and Pressure Vessel Code committees. Setting of the design allowables requires the submission of a detailed mechanical property data package for review and analysis by the code committees. The data package for the advanced alloy developed in this study was submitted in August 2004 (see Appendix A).

   It typically takes 12 to 24 months for ASME code bodies to review all of the information submitted and perform an analysis to set design-allowable stresses. To expedite this approval process, we have subcontracted Dr. Maan Jawad of Global Engineering (previously with Nooter Corporation) to actively pursue the process by participating in ASME Code Committee meetings on a regular basis and respond to any questions that may be asked.

3. In addition to approvals by ASTM and ASME Code committees, a parallel activity is needed to educate equipment designers about the benefits of the new alloy. This activity was partially accomplished by presenting papers at technical conferences and by the sharing of information on this alloy by the industrial partners of this project within their companies (for the users) and with their customers (for the alloy producers). Although both of these activities are making users aware of the new alloy, we are relying on our consultant, Dr. Maan Jawad, to further this cause by making visits to individual companies and making presentations about this alloy. Because of his design background gained at Nooter Corporation and his familiarity with both chemical and heat recovery systems, we anticipate that his involvement will further reduce the time for commercial use of the new alloy.

4. For the new alloy to be the material of choice, it has to be commercially available at a competitive price in various product forms (forgings, plate, tubing, and piping). Furthermore, the welding consumables such as filler wire, flux, and electrodes need to be available commercially. The team members of this project are capable of meeting both of these requirements as they arise.

   The component fabricators have been contacting ORNL to receive the plate samples from the newly developed alloy so that they can develop their own procedures for bending, forming, and welding. The plate samples are currently being offered at no cost to U.S.-based companies for their use. Based on these trials, these companies will be ready to build equipment when the need arises.

In summary, all elements essential for commercialization of the new alloy are in place, and further technology transfer is necessary.

3. Background

3.1 Domestic Technology Status Including Emerging Technologies

Ferritic 1-3Cr-Mo steels have a variety of uses at temperatures of 842–1022°F (450–550°C) and below, due to their combination of better oxidation/corrosion resistance and their elevated temperature strength relative to carbon steels with less chromium [1]. These applications include piping, heat exchangers, superheater tubing and pressure vessels in oil refineries, chemical processing plants, and fossil-fired electrical power generating plants. The most common steel in this class is the 2.25Cr-1Mo steel, designated Grade 22 (ASME code), which was first used in the United States in the 1940s [refs. 2,3]. The improved heat resistance combined with the low thermal expansion and excellent thermal conductivity of such ferritic steels and alloys drive their use in many applications. These steels have good weldability, can be fabricated by various wrought methods, and can be used in the bainitic or tempered-martensitic conditions. They have good impact toughness and a ductile-brittle transition temperature (DBTT) below room temperature. There are a number of domestic producers.

The Cr-Mo-V steels were developed in the late 1940s and early 1950s for improved creep strength above 480°C in steam turbine bolting and rotor applications [2]. They are also used for steam turbine casing applications. 1Cr-1Mo-0.25V is a typical composition, with many different minor variants. Bainitic structures (upper bainite) produce the best combination of creep resistance, ductility, and toughness. Several research efforts in the mid-1980s (including work at ORNL) produced vanadium-modified bainitic steels related to Grade 22 but with improved creep strength, including 2.25Cr-1Mo-VTiB and 3Cr-1MoV, for coal-gasification and other advanced coal conversion technologies [2,4–6]. However, the development efforts were essentially Japanese (see next section), and these steels are not produced in the United States.

In the United States, new 2.25Cr-2WV and 3Cr-3WV bainitic steels were developed between 1985 and 1990 as part of an effort of the U.S. Fusion Reactor Materials Program to develop new steels with faster radioactivity decay for fusion reactor applications that began to be produced in the mid-1980s [refs. 7–9]. These new steels, which are the subject of this report, were radically different from standard Grade 22, both in terms of their as-processed microstructures and their mechanical properties. These new steels are much stronger than Grade 22 at 1022–1112°F (550–600°C) and have good toughness properties (see Sect. 1.1) after normal tempering [7]. They were also found to have good toughness in the untempered condition (DBTT of –35°C and upper-shelf impact energy of 100 ft-lb), a property not found in the Grade 22 steel. Normally tempered Grade 22 contains both coarse and finer dispersions of chromium-rich $M_{23}C_6$, whereas the 3Cr-3WV steels contain some coarse iron-rich M_3C, chromium-rich $M_{23}C_6$, and uniform dispersions of very fine vanadium- and tungsten-rich MC (which has not been observed previously) [9]. Martensitic 9-12Cr steels cannot be used at all without optimum tempering, and their use necessitates preweld and postweld heat treatment for welding such steels in most engineering applications. The behavior of the 3Cr-3WV steels in the untempered condition strongly suggests that these new steels may be useful after welding without the preweld and postweld heat treatments. These new steels also have not yet been fully optimized with regard to the minor or micro additions of titanium, tantalum, boron, and nitrogen being used in such advanced bainitic steels by the Japanese today.

While there have been significant efforts worldwide to continuously improve 9-12Cr-Mo martensitic steels with the addition of tungsten, cobalt, vanadium, niobium, carbon, boron, and nitrogen following the significant improvements achieved in modified 9Cr-1Mo in the late 1970s and early 1980s [refs. 10,11], there have only been Japanese efforts since the mid-1990s to similarly improve Grade 22 [refs. 3,12]. The most advanced of these is the new 2.25Cr-1.6W-V-Nb (T23) steel, developed jointly by Mitsubishi Heavy Industries, Ltd., and Sumitomo Metal Industries, Ltd., and the 2.5Cr-1Mo-V-Ti (T24) steel developed by Japan Steel Works in 1994 [refs. 3,12–14]. These new steels have almost twice the creep strength of Grade 22 at 1112°F (600°C), and have good weldability (it is claimed they can be welded without preweld and postweld heat treatments). The steels were approved in Section 1 of the ASME Boiler and Pressure Vessel Code Committee for construction use as T23 and T24 in 1995. Testing of T23 and T24 continues in large-diameter and thicker wall piping and pressure vessel applications, with examination of components after service, and the effects of different component fabrication methods. More advanced properties testing include aging and creep-fatigue interactions.

3.2 State of the Art

After the start of the project reported here, ASME organized a conference held in July 2004 and entitled “Experience with Creep-Strength Enhanced Ferritic Steels and New Emerging Computational Methods” [15]. Most of the work reported in this conference on materials of similar composition to the steels in this project was from Japan—with the exception of one paper from the United States on this DOE project.

This project dealt with improving the materials performance and fabrication for the hydrotreating of reactor vessels, heat recovery systems, and other components for the petroleum and chemical industries. The petroleum and chemical industries use reactor vessels that can approach ship weights of approximately 300 tons, with vessel wall thicknesses of 3–8 in. These vessels are typically fabricated from Fe-Cr-Mo steels, with the chromium content ranging from 1.25 to 12% and that of molybdenum from 1 to 2%. Steels in this composition range have great advantages of high thermal conductivity, low thermal expansion, low cost, and good properties obtainable by heat treatment. With all of the advantages of Fe-Cr-Mo steels, several issues are faced in design and fabrication of vessels and related components. These issues are the following:

- Because of their low strength properties, current alloys require thicker sections.
- Increased thickness causes heat-treatment issues related to nonuniformity across the thickness; thus, thicker steels do not have optimum properties.
- Fracture toughness (ductile-to-brittle transition) is a critical safety issue for these vessels, and it is affected in thick sections due to the nonuniformity of the microstructure.
- The PWHT needed after welding makes fabrication more time-consuming with increased cost.
- The needed PWHT also limits any modifications of the large vessels in service.

The goal of this project was to reduce the weight of large pressure vessel components (ranging from 100 to 300 tons) by approximately 25% and reduce fabrication cost and improve in-service modification feasibility through development of Fe_3Cr-W(V) steels with combination of nearly a 50% higher strength, a lower DBTT and a higher upper-shelf energy, ease of heat treating, and a strong potential for not requiring PWHT.

The research and development work was conducted by a team consisting of chemical and petrochemical companies (Exxon Mobil Chemical Company, BP Amoco, and DuPont), materials producers (ISG Plate, Ellwood Materials Technologies Company, Plymouth Tube Company, and Ellwood National Forge), a component fabricator and welding process developer (Nooter

Fabrication Services, Inc.), a weld wire producer and process developer (Stoody Company), a heat recovery unit construction company (Nooter-Eriksen), and a national laboratory (ORNL).

Industry participated by (1) identifying reactor vessels and other components that can take advantage of the new steel, (2) testing components, (3) assisting in producing production-size heats of the new steel, (4) assisting in component fabrication and process development, and (5) developing the welding process. Welding wire suppliers produced small batches for trials by Nooter Fabrication Services and ORNL. Industry representatives also provided guidance and direction to the project through active participation in identifying and monitoring project deliverables and technical progress reports. The work breakdown structure for the project is shown in Table 3.1.

Table 3.1. Work breakdown structure for this project

ID	Task	Year 1	Year 2	Year 3
1	**Alloying Effects and Composition Optimization**			
	1.1 ThermoCalc™ and kinetic modeling to understand effects of tungsten versus molybdenum			
	1.2 Development of TTT curves for heat treatment			
	1.3 Verification of compositions and heat treatment			
2	**Materials/Process Modeling**			
	2.1 Methods for melting pilot (300 to 500 lb) and large (10 to 50 ton) heats			
	2.2 Modeling and processing of heats into rolled plate, forged sections, and casting			
	2.3 Mechanical properties of pilot and large heats			
3	**Welding Process Development and Weldment Properties**			
	3.1 Process and filler metal development			
	3.2 Weld and weldment properties			
4	**Microstructural Thermal Stability and Characterization**			
	4.1 Thermal aging of pilot and large heats to various temperatures and times			
	4.2 Properties of aged materials			
	4.3 Microstructural characterization			
5	**Manufacturing and Testing of Prototype Components**			
	5.1 Fabrication of welded and cast components			
	5.2 Installation of components in chemical plant			
	5.3 Cost benefit analysis			

ID	Task	Year 1	Year 2	Year 3
6	**Preparation of Data Packages for ASTM and ASME code Approvals**			
	6.1 Complete data package for ASTM Specification			
	6.2 Complete data package for ASME code approval			
7	**Meetings and Reports**			
	7.1 Hold at least two technical meetings per year			
	7.2 Complete final report			

4. Results and Discussion

The main objective of this project was to develop a new class of Fe-3Cr-W(V) ferritic steels for chemical process applications based on a patented ORNL steel. The project goal was to reduce the weight of large pressure vessels and associated components by approximately 25% and eliminate the need for PWHT. These improvements can yield an estimated energy savings of 21 trillion Btu/year and cost savings of approximately $237 million for chemical vessels and related components used in the United States.

4.1 Project Approach

The objectives of the project were achieved through the successful completion of the following steps, which included application of several concepts.

1. **Understanding the role of replacing molybdenum with tungsten in currently used Fe-2.25Cr-1Mo alloys**
   Work reported in the literature as well as the preliminary background work on ORNL alloy compositions has shown that Fe-Cr-W alloys with partial or complete replacement of molybdenum with tungsten have superior strength properties at room temperature and retain those properties at high temperatures. We carried out a systematic prediction of phase formation during heat treatment of Fe-Cr-W alloys and compared those predictions with similar predictions for Fe-Cr-Mo and Fe-Cr-Mo(W) alloys. Phase and stability predictions were conducted by using ThermoCalc™ and kinetic modeling. The predicted results were verified with experimental data, and once verified, these data were used to optimize alloy compositions to desired levels of strength and thermal stability. In addition to developing nominal compositions, ThermoCalc™ was also used to set limits on residual elements such as manganese, silicon, and phosphorus. Predicted results for residual elements were verified by producing and testing experimental-size heats.

2. **Development of time-temperature-transformation (TTT) curves for conducting heat treatment for selected properties**
   Ferritic steels derive their strength, toughness, and thermal stability from the microstructure that develops during heat treatment. A TTT diagram was developed for each of the identified compositions through the use of Gleeble equipment available at ORNL. The TTT diagrams provide information on critical phase transformation temperatures and the cooling steps (continuous vs step cooling) required for generating a desired microstructure. This information is needed for selecting cooling parameters for a range of component section thicknesses.

3. **Melting and processing of Fe-Cr-W alloy compositions**
   In this step, experimental-size heats of the alloy compositions identified in Step 1 above were melted and processed into plate product. Both hot forging and rolling processes were carried out. The results of experimental heats become the input for selecting the composition and processing of large production-size heats and component fabrication.

4. **Mechanical properties characterization**
   The most important aspect of this project was to develop an alloy or alloys that will reduce component weights by approximately 25%. In order to achieve such weight

reductions, the new alloy or alloys had to have nearly 50% higher strength than that of currently used Fe-Cr-Mo alloys. This step required determining the mechanical properties such as tensile, toughness, and creep for both the experimental- and commercial-size heats.

5. **Welding process development and weldment properties**
For the Fe-Cr-W steels to be useful for fabrication of large components, development of a process for their welding is essential. The work in this area consisted of (a) validation of the applicability of currently used processes for Fe-Cr-Mo steels, (b) identification of weld wire compositions, and (c) determination of the need for any PWHT. For the sake of comparison with base metal and currently used Fe-Cr-Mo steels, we measured the mechanical properties of the weldments such as hardness, tensile, creep, and toughness.

6. **Microstructural thermal stability**
As noted above, ferritic steels derive their properties from the microstructural features that result from phase transformations during heat treatment and precipitation. The thermal stability of these structural features determines the life of the component in service. In this step, both base and weldments were subjected to thermal exposures at ranges of temperatures and times. The changes from thermal exposures were measured by mechanical property tests such as tensile, creep, toughness, and hardness. Thermal stability results carried out in the laboratory were modeled using kinetic model and verified. The results of this analysis were used to predict the end-of-life of components in service.

7. **Manufacturing and testing of prototype components**
This step will encompass fabricating prototype components with the selected Fe-Cr-W alloy composition and evaluating the alloy's performance by installing these components in a chemical plant environment and in other potential applications in basic oxygen furnace (BOF) hoods and recovery boilers. Testing of the prototype components will provide additional data about corrosion performance of the alloy under actual operating conditions.

8. **Preparation of data packages for ASTM and ASME code approvals**
Chemical pressure vessels are designed and constructed to ASME code design stress values. For Fe-Cr-W alloys to find applications in pressure vessels and other components for the chemical industry, data on alloy composition and properties, along with information on the welding process and component testing results, were assembled into a data package for approvals from the appropriate ASTM and ASME code bodies.

Significant results were obtained during this project for each of the proposed concepts. The most relevant and important results are described below. Details are presented in the appendices to this report.

4.2 Alloy Phase Stability Analysis

One focus during this project was to develop an alloy that would be superior to the currently available commercial or near-commercial alloys in the composition range of Fe-3 to 9Cr-Mo(W) and containing refractory carbide formers such as niobium and vanadium. These alloys included a well-known base alloy Fe-2.25Cr-1Mo, designated as Grade 22; two recent high-strength versions of the alloy from Japan, designated as T23 and T24; and a high-strength Fe-9Cr-1Mo grade developed nearly 22 years ago at ORNL, designated as T91. Detailed chemical compositions of these alloys are presented in Table 4.1. In addition to the commercial alloys, R. L. Klueh at ORNL had developed patented alloys [16] of nominal Fe-3Cr-3W composition.

Detailed chemical analysis of two Fe-3Cr-3W compositions that were scaled up to 400-lb heats is shown in Table 4.2. Although the proposed project was based on Fe-3Cr-3W alloys, early in the project the industrial team recommended that those alloys be replaced with new compositions so that new U.S. and international patents could be obtained. The new alloys developed during this project replaced part of the tungsten in Klueh's alloys [16] with molybdenum. Nominal compositions of the new alloys are also included in Table 4.2. Both U.S. and international patents were filed for the new compositions.

A detailed phase analysis was carried out using ThermoCalc™ modeling for the alloy compositions listed in Tables 4.1 and 4.2. The results presented in Fig. 4.1 show that after a 700°C temper, the base Fe-2.25Cr-1Mo alloy contains only the $M_{23}C_6$ phase. By comparison, alloy T23 contains V(C,N), M_6C, $M_{23}C_6$, and M_2B. Alloy T24 contains the same phase as T23 with the exception of the absence of the M_6C phase. The ORNL alloys (Klueh's base patents) containing the Fe-3Cr-3W base (identified as "ORNL" in the figure) and that containing 0.1 wt % tantalum (ORNL-VT) showed only V(C,N) M_6C, and M_7C_3 phases. The $M_{23}C_6$ phase was absent in both ORNL alloys. It was recognized that the absence of $M_{23}C_6$ in the Fe-3Cr-3W alloys was the one important reason for their unique mechanical properties of high-temperature strength and toughness.

Table 4.1. Chemical analysis of commercial or near-commercial alloys used or proposed for the petrochemical industry

Element	Alloy (wt %)			
	T22[a]	T23[a,b]	T24[a,c]	T91[a,d]
C	0.15 max	0.04–0.10	0.05–0.10	0.08–0.12
Si	0.25–1.00	0.50 max	0.15–0.45	0.20–0.50
Mn	0.30–0.60	0.10–0.60	0.30–0.70	0.30–0.60
P	0.030 max	0.030 max	0.020 max	0.020 max
S	0.030 max	0.010 max	0.010 max	0.010 max
Cr	1.9–2.6	1.9–2.6	2.2–2.6	8.0–9.5
Mo	0.87–1.13	0.05–0.30	0.90–1.10	0.85–1.05
N	*e*	0.030 max	0.12 max	0.030–0.070
W	*e*	1.45–1.75	*e*	*e*
V	*e*	0.20–0.30	0.20–0.30	0.18–0.25
Nb	*e*	0.02–0.08	*e*	0.06–0.10
Ta	*e*	*e*	*e*	*e*
B	*e*	0.0005–0.0060	0.0015–0.0070	*e*
Ti	*e*	*e*	0.05–0.10	*e*
Ni	*e*	*e*	*e*	0.40 max
Al	*e*	0.030 max	0.020 max	0.040 max
Fe	*f*	*f*	*f*	*f*

[a]ASTM A213. [b]Code Case 2199. [c]Code Case draft. [d]Code approved.
[e]Not specified. [f]Balance.

Figure 4.2 shows the comparative phase analysis for the baseline Fe-3Cr-3W alloy (ORNL) and the newly developed composition based on Fe-3Cr-W(Mo), A79741. The compositions of both of these alloys are given in Table 4.2. Results in Fig. 4.2 are for tempering temperatures of 700 and 730°C and show that the partial replacement of tungsten with tungsten plus molybdenum changes the phase stability. The Fe-3Cr-3W alloys contained V(C,N), M_6C, and M_7C_3; and the new alloys contain V(C,N), M_6C, and $M_{23}C_6$.

Table 4.2. Chemical composition of Fe-3Cr-3W (heats 10293 and 10294) and Fe-3Cr-3W(Mo) (heat 79741) alloys

	Heat (wt %)		
Element	10293	10294	A79741
C	0.10	0.1	0.099
Mn	0.39	0.41	0.34
P	0.01	0.011	0.009
S	0.004	0.005	0.003
Si	0.16	0.16	0.21
Ni	0.01	<0.01	0.15
Cr	3.04	3.02	2.97
Mo	0.01	0.01	0.73
V	0.21	0.21	0.22
Cb	0.003	0.004	0.002
Ti	0.001	0.001	0.003
Co	0.005	0.006	0.014
Cu	0.01	0.01	0.11
Al	0.003	0.003	0.008
B	0.001	0.001	<0.001
W	3.05	3.07	1.68
As	0.001	0.001	0.005
Sn	0.003	0.004	0.008
Zr	<0.001	<0.001	<0.001
N	0.004	0.003	0.009
O	0.005	0.004	0.004
Ta	<0.01	0.09	—

A summary of the predicted phases present in various alloys is given in Table 4.3. As this table shows, the lowest-strength alloy contains a simple $M_{23}C_6$ phase. All of the higher-strength alloys contain three or four phases. The ORNL Fe-3Cr-3W and Fe3Cr-3W alloys with 0.1 wt % tantalum (ORNL-VT) are unique in that they do not contain any $M_{23}C_6$. However, when part of the tungsten was replaced in the new alloy (A79741) with tungsten plus molybdenum, the $M_{23}C_6$ phase stabilized instead of the M_7C_3 phase. The effects of this change in phase stability will be discussed in later sections of this report.

Transmission electron micrographs of 2.25Cr-1Mo and 2.25Cr-2WV are compared in Fig. 4.3. These micrographs show the presence of $M_{23}C_6$ in 2.25Cr-1Mo (T22) as predicted and its absence in the molybdenum-free 2.25Cr-2WV alloy, which matches the predicted phases. The 2.25Cr-2WV alloy also showed the presence of fine MC carbides, which is consistent with the prediction of V(C, N), and the presence of M_3C +M_7C_3, which is qualitatively consistent with the prediction of M_6C + M_7C_3.

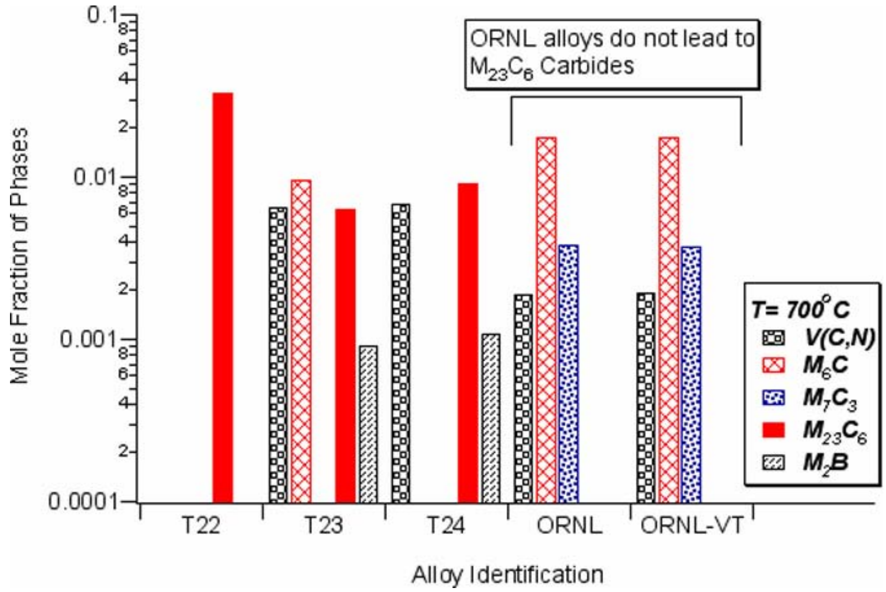


Fig. 4.1. Comparison of stable phases predicted in various commercial and near-commercial alloys and ORNL alloys (Fe-3Cr-3W based). All calculations are for a tempering temperature of 700°C.

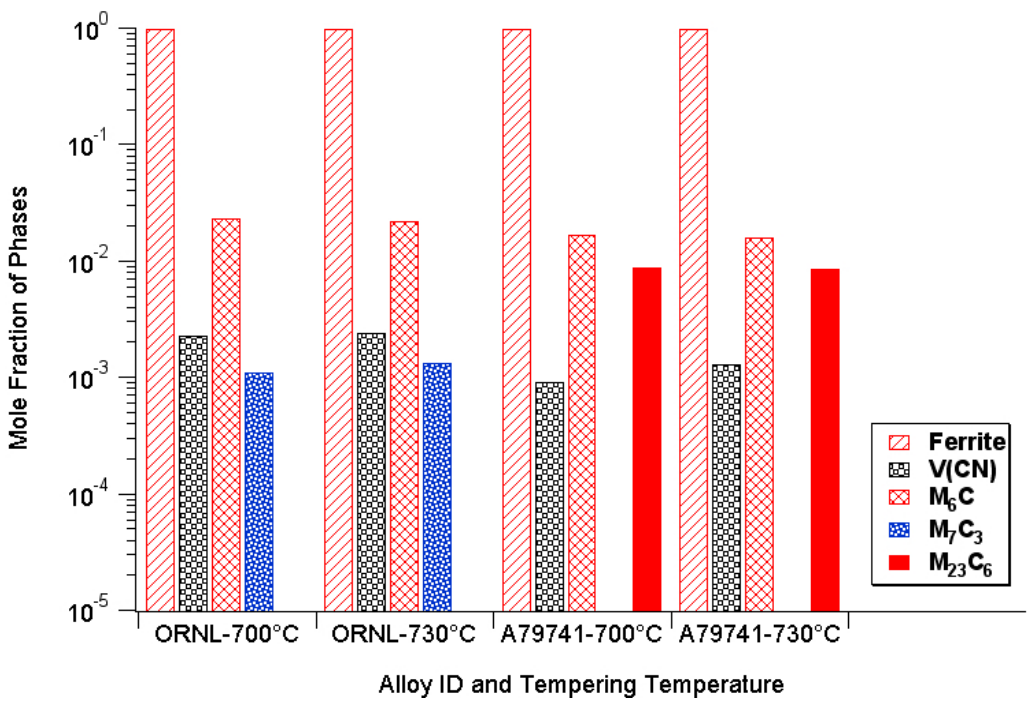
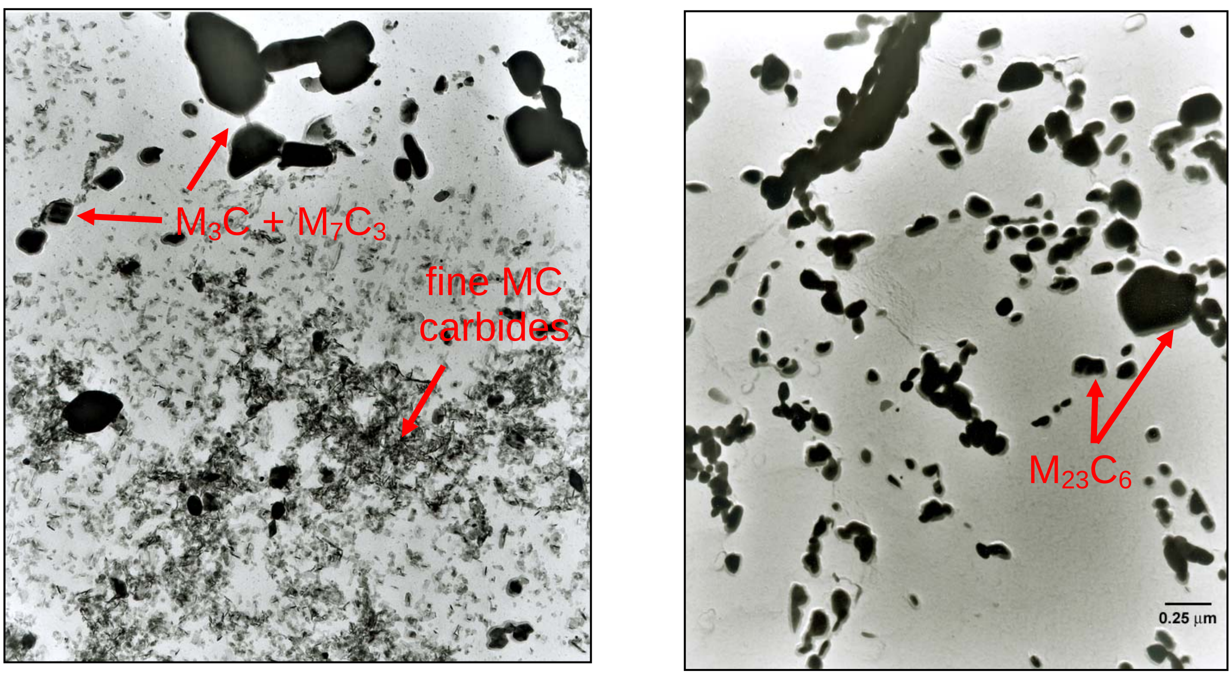


Fig. 4.2. Comparison of stable phases predicted in ORNL alloys containing ORNL Fe-3Cr-3W vs heat 79741 Fe-3Cr-W(Mo). Calculations were for tempering temperatures of 700 and 730°C.

Table 4.3. Presence of predicted phases in various alloys after tempering temperatures of 700 or 730°C

Phase	Alloys					
	T22[a]	T23[a]	T24[a]	ORNL[a,b,c]	ORNL-VT[a,d]	A79741[a,b,e]
V(C,N)	No	Yes	Yes	Yes	Yes	Yes
M_6C	No	Yes	No	Yes	Yes	Yes
M_7C_3	No	No	No	Yes	Yes	No
$M_{23}C_6$	Yes	Yes	Yes	No	No	Yes
M_2B	No	Yes	Yes	No	No	No

[a]Analysis carried out for tempering temperature of 700°C.
[b]Analysis also carried out for tempering temperature of 730°C.
[c]ORNL heat 10293.
[d]ORNL-VT heat 10294.
[e]Newly developed alloy from this project. It is also referred to as Grade A and alloy 315 in the report text and figures.



AEM/XEDS analysis of carbides on extraction replicas

Fig. 4.3. Comparison of phase observed in 2.25Cr-1Mo and 2.25Cr-2WV alloys after normalizing and tempering treatment.

4.3 Alloy Development and Commercial Heat Melting and Processing

The alloys were developed based on heats weighing 500 g (1 lb) that were initially melted using nonconsumable-arc melting and casting into water-cooled copper molds. Alloys with acceptable microstructure, impact, and strength properties were vacuum-induction melted (VIM) in 7.5-kg (15-lb) heats. The next incremental steps were 150- and 500-kg (300- and 1000-lb) heats, which were both done at commercial vendors. Based on data for these heats, both Grades A and B [(Fe-3Cr-3(W+Mo)] alloys were melted in 50-ton heats at Ellwood Quality Steel (EQS), New Castle, Pennsylvania. The heats were melted by an electric-arc furnace, vacuum degassed, and cast into three round ingots and two slab ingots for each heat. The two round ingots from each grade were remelted by electroslag remelting (ESR) and vacuum-arc remelting (VAR) processes and recast in round ingots.

The round ingots from the electric furnace, ESR, and VAR heats were hot-forged to 305-mm (12-in.) rounds and 152-mm (6-in.) round-corner square billets at Ellwood City Forge, Ellwood City, Pennsylvania. The slab ingots were hot-rolled to 1.5- by 3-in.-thick plate product at ISG, Coatsville, Pennsylvania. Part of the 152-mm (6-in.) round-corner forgings were hot-rolled to 95-mm (3.75-in.) round bars for processing into seamless tubing at Plymouth Tube Company, Winamac, Indiana. Two different sizes of tubes were produced by the piercing process. No problems were encountered in the processing of slab and round ingots into hot-rolled plate, forgings, or bars and tubing from either Grades A or B.

The melting of 50-ton heats, their pouring into various molds, and processed product forms such as forged billets, rolled plates, and seamless tubing are shown in Fig. 4.4.

4.4 Alloy Compositions

The chemical composition of 50-ton heats of electric-furnace-melted heats of Grades A and B are shown in Table 4.4. Target compositions ("Aim") are included for comparison.

The chemical composition of the electric-furnace-melted heats changed when they were remelted by VAR and ESR processes. The chemical analyses of Grades A and B steel after the electric-furnace, VAR, and ESR processes are shown in Tables 4.5 and 4.6. These tables show that all elements of the electric-furnace-melted 50-ton heats met the target compositions. The following are the significant changes observed in the chemistry of Grades A and B after the remelting processes:

1. Electroslag remelting reduces the content of silicon in both Grades A and B. It also lowers the tantalum content for Grade B.
2. VAR reduces the content of manganese in both grades. It also reduces the oxygen content for both alloys.

Both grades still meet the specified chemistry range for these alloys.

4.5 Heat Treatment

The alloys developed in this project derive their strength through the generation of a bainitic microstructure. Attaining the desired bainitic structure requires knowing the temperature at which the ferrite is converted into austenite and identifying the cooling rates that produce this structure. The continuous cooling transformation (CCT) diagram that yields such information were developed for both Grades A and B, as shown in Figs. 4.5 and 4.6. These figures indicate that there is only a very minor difference in the transformation behavior of the two grades. Figure 4.7 shows the CCT curve for Grade B, which is also valid for the Grade A steel. A cooling curve showing a cooling rate of 20°C/min is shown on this graph. Based on this figure, it is estimated that a cooling rate of 20°C/min is required to avoid ferrite formation in these steels.

Fig. 4.4. Electric furnace melting of 50-ton commercial heats and their casting into ingots and processing into hot-forged ingots, hot-rolled plate, and tubing.

Table 4.4. Vendor and check analysis of two 50-ton heats of Fe-3Cr-W alloy (wt %)

Element	Grade A, heat L7974				Grade B, heat L8644			
	27-in. round			12-in. slab	27-in. round			12-in. slab
	Aim[a]	Vendor	Check	Vendor	Aim[b]	Vendor	Check	Vendor
Carbon	0.10	0.11	0.099	0.11	0.10	0.11	0.11	0.11
Manganese	0.35	0.36	0.34	0.36	0.35	0.36	0.35	0.36
Phosphorus	0.01[c]	0.007	0.009	0.007	0.01[c]	0.008	0.009	0.008
Sulfur	0.01[c]	0.002	0.003	0.002	0.01[c]	0.002	0.002	0.002
Silicon	0.2	0.21	0.21	0.21	0.2	0.2	0.2	0.2
Nickel	0.02[c]	0.15	0.15	0.15	0.02[c]	0.12	0.12	0.12
Chromium	3.00	2.99	2.97	2.99	3.00	3.01	3.02	3.01
Molybdenum	0.75	0.76	0.73	0.76	0.75	0.74	0.73	0.74
Vanadium	0.25	0.249	0.22	0.249	0.25	0.236	0.21	0.236
Columbium			0.002				0.002	
Titanium	—		0.003				0.004	
Cobalt	—		0.014				0.016	
Copper		0.11	0.11	0.11	—	0.17	0.17	0.17
Aluminum		0.013	0.008	0.013	—	0.011	0.006	0.011

Table 4.4 (continued)

Element	Grade A, heat L7974				Grade B, heat L8644			
	27-in. round			12-in. slab	27-in. round			12-in. slab
	Aim[a]	Vendor	Check	Vendor	Aim[b]	Vendor	Check	Vendor
Boron	0.01[c]	0.0002	<0.001	0.0002	0.01[c]	0.0001	<0.001	0.0001
Tungsten	1.5	1.55	1.68	1.55	1.5	1.48	1.62	1.48
Arsenic			0.005				0.006	
Tin			0.008				0.009	
Zirconium	—		<0.001				<0.001	
Nitrogen			0.009				0.011	
Oxygen			0.004				0.001	
Hydrogen		1.6[d]		2.2[d]	—	1.3[d]	—	2.3[d]
Tantalum	—				0.10	0.107	0.1	0.107

[a] See Table 4.5 for ranges. [b] See Table 4.6 for ranges.
[c] Maximum. [d] Parts per million.

Table 4.5. Chemical analysis of the electric-furnace-melted 50-ton heat 79741 of Grade A after electroslag remelting heat 79742 and vacuum-arc remelting heat 79743 (wt %)

Element	Range	Heat		
		79741 (electric furnace)	79742 (electroslag remelted)	79743 (vacuum-arc remelted)
C	0.08–0.12	0.099	0.11	0.11
Mn	0.25–0.45	0.34	0.33	0.25
P	0.01 Max	0.009	0.008	0.008
S	0.01 Max	0.003	0.001	0.001
Si	0.15–0.4	0.21	0.15	0.21
Ni	0.25 Max	0.15	0.15	0.15
Cr	2.8–3.2	2.97	2.95	2.97
Mo	0.65–0.85	0.73	0.74	0.74
V	0.2–0.3	0.22	0.22	0.22
Cb	—	0.002	0.001	0.002
Ti	—	0.003	0.003	0.003
Co	—	0.014	0.013	0.013
Cu	—	0.11	0.11	0.1
Al	—	0.008	0.005	0.008
B	0.001 Max	<0.001	<0.001	<0.001
W	1.35–1.65	1.68	1.67	1.68
As	—	0.005	0.007	0.007
Sn	—	0.008	0.008	0.008
Zr	—	<0.001	<0.001	<0.001
N	—	0.009	0.013	0.004
O	—	0.004	0.001	<0.001
Ta	—	——	<0.001	<0.01

Table 4.6. Chemical analysis of the electric-furnace-melted 50-ton heat 86441 of Grade B after electroslag remelting heat 86442 and vacuum-arc remelting heat 86443 (wt %)

		Heat		
Element	Range	86441 (electric furnace)	86442 (electroslag remelted)	86443 (vacuum-arc remelted)
C	0.08–0.12	0.11	0.11	0.11
Mn	0.25–0.45	0.35	0.33	0.22
P	0.01 Max	0.009	0.009	0.009
S	0.01 Max	0.002	0.001	0.001
Si	0.15–0.4	0.2	0.15	0.2
Ni	0.25 Max	0.12	0.12	0.12
Cr	2.8–3.2	3.02	3.03	3.03
Mo	0.65–0.85	0.73	0.72	0.72
V	0.2–0.3	0.21	0.21	0.21
Cb	—	0.002	0.002	0.002
Ti	—	0.004	0.003	0.003
Co	—	0.016	0.016	0.016
Cu	—	0.17	0.17	0.15
Al	—	0.006	0.009	0.006
B	0.001 Max	<0.01	<0.001	<0.01
W	1.35–1.65	1.62	1.61	1.61
As	—	0.006	0.008	0.007
Sn	—	0.009	0.01	0.01
Zr	—	<0.001	<0.001	<0.001
N	—	0.011	0.012	0.004
O	—	0.001	0.001	<0.001
Ta	0.07–0.13	0.1	0.08	0.1

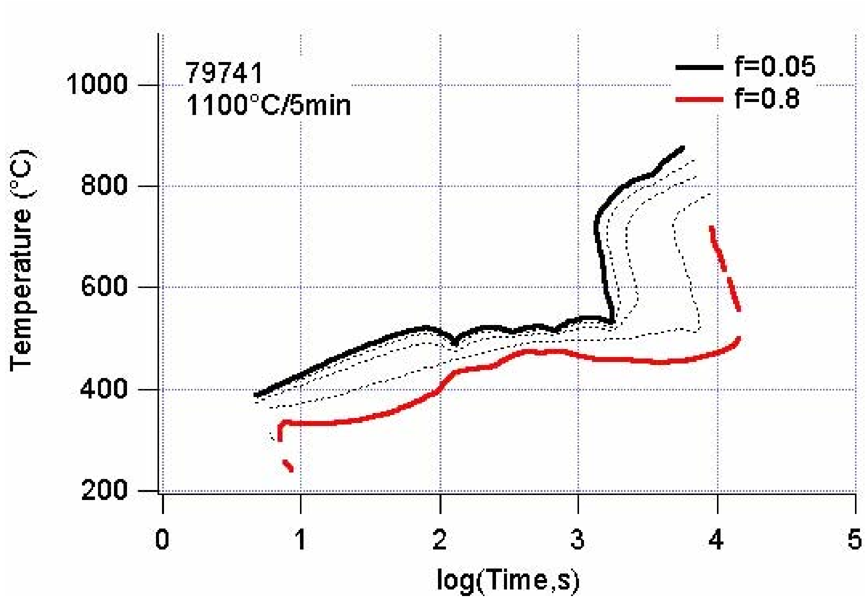


Fig. 4.5. Continuous cooling transformation diagram for Grade A (heat 79741).

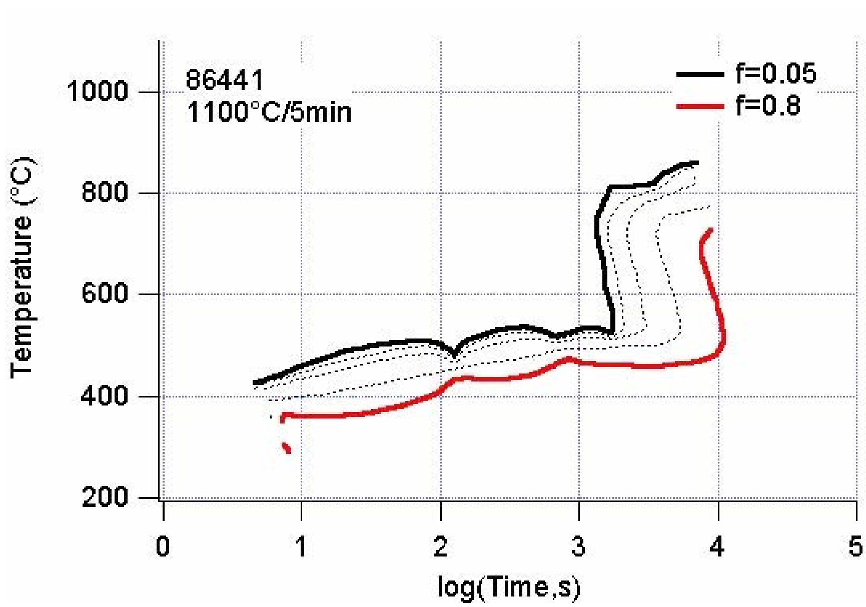


Fig. 4.6. Continuous cooling transformation diagram for Grade B (heat 86441).

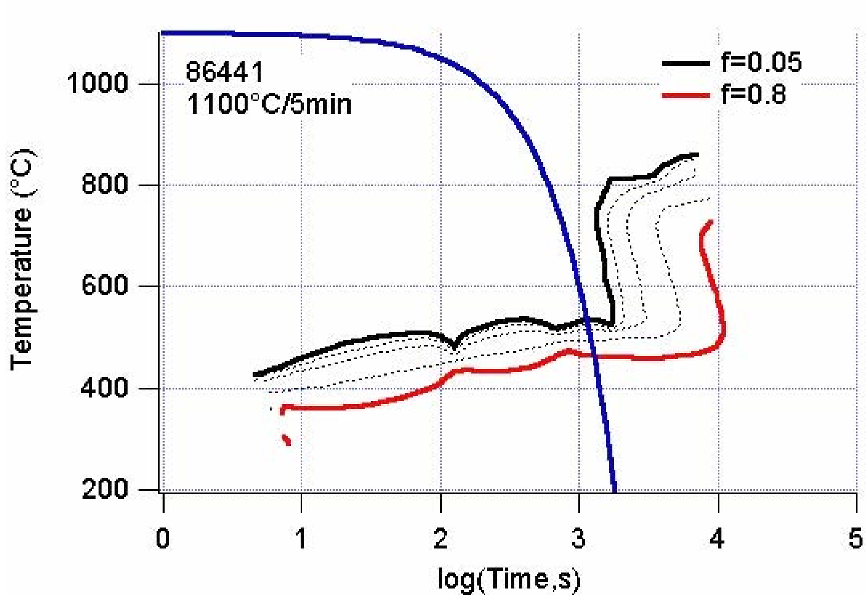


Fig. 4.7. Curve for cooling rate of 20°C/min shown on the cooling transformation temperature plot of Grade B (heat 86441).

The upper-use temperature of ferritic steels is limited by critical transformation temperatures known as A_1 and A_3. A_1 is the lowest temperature at which ferrite transforms to austenite, and A_3 is the highest temperature above which the ferrite-to-austenite transformation is complete. The A_1 and A_3 temperatures for Grades A and B are given in Table 4.7.

Table 4.7. Critical transformation temperatures (°C) for Grades A and B

Critical temperature	Grade A (Heat 79741)	Grade B (Heat 86441)
A_1	865	858
A_3	967	970

The effect of tempering on the tensile properties of plates of both Grades A and B (alloys 315 and 315T) was studied in a comprehensive manner by Ken Orie of ISG Plate (see Appendix C for his detailed presentation). He investigated the tensile properties of both the 1.5- and 3-in.-thick plates after tempering with temperatures in the range of 1225 to 1380°F (663 to 749°C). Test data were developed on sections of the plates heat-treated in the laboratory heat-treating furnace and on the plates heat-treated in mill heat-treating furnace. The resulting yield strength data at room temperature for both Grades A and B are plotted in Fig. 4.8. In this figure, the plates designated as A8141 refer to electric-furnace-melted heat 79741 of Grade A without tantalum; and the plates marked A8142(Ta) refer to electric-furnace-melted heat 86441 of Grade B, containing 0.1 wt % tantalum. Similar plots for ultimate tensile strength and total elongation are shown in Figs. 4.9 and 4.10. Data in Figs. 4.8, 4.9, and 4.10 show that the strength values for the 3-in.-thick plate are generally lower than those for 1.5-in.-thick plate. The mill-annealed plates showed somewhat lower ductility than plates tempered in the laboratory furnace at ISG Plate.

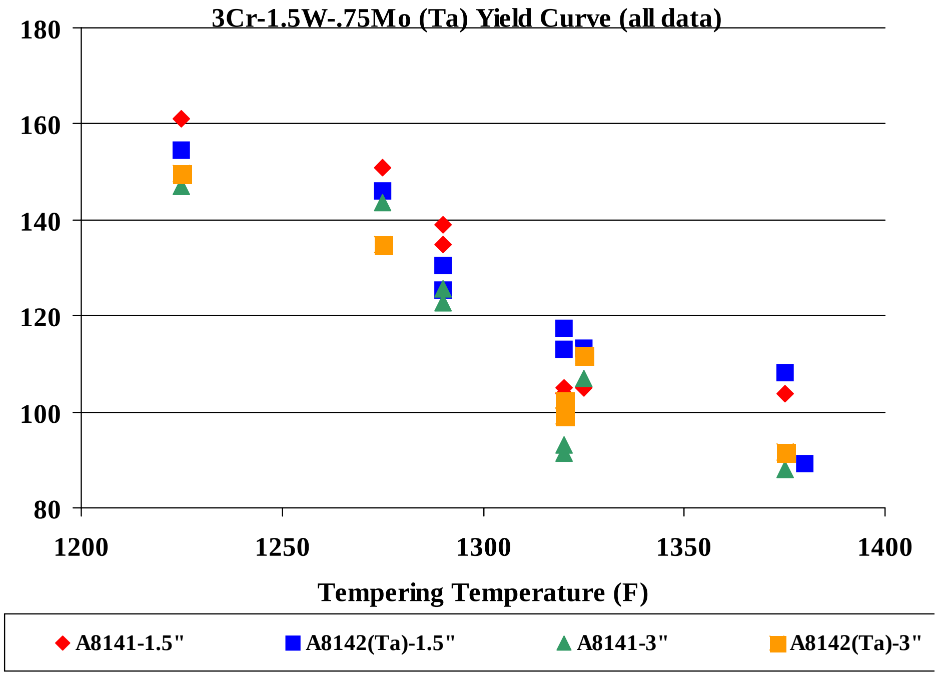


Fig. 4.8. Plot of yield strength at room temperature as a function of tempering temperature for 1.5- and 3-in.-thick plates of Grades A and B steel [A8141 and A8142(Ta)]. (Data from Ken Orie, ISG Plate, Coatesville, Penn.)

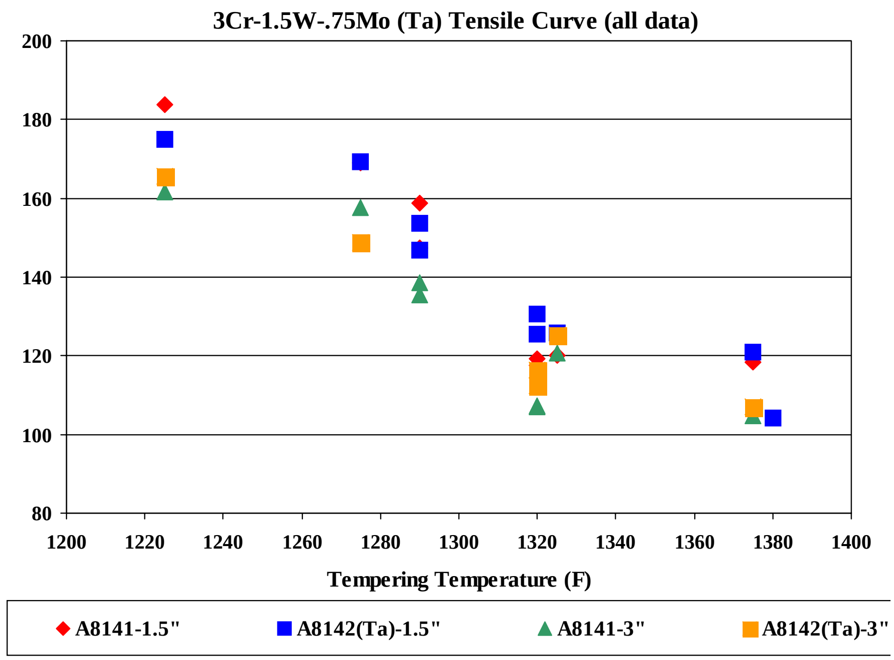


Fig. 4.9. Plot of ultimate tensile strength at room temperature as a function of tempering temperature for 1.5- and 3-in.-thick plates of Grades A and B steel [A8141 and A8142(Ta)]. (Data from Ken Orie, ISG Plate)

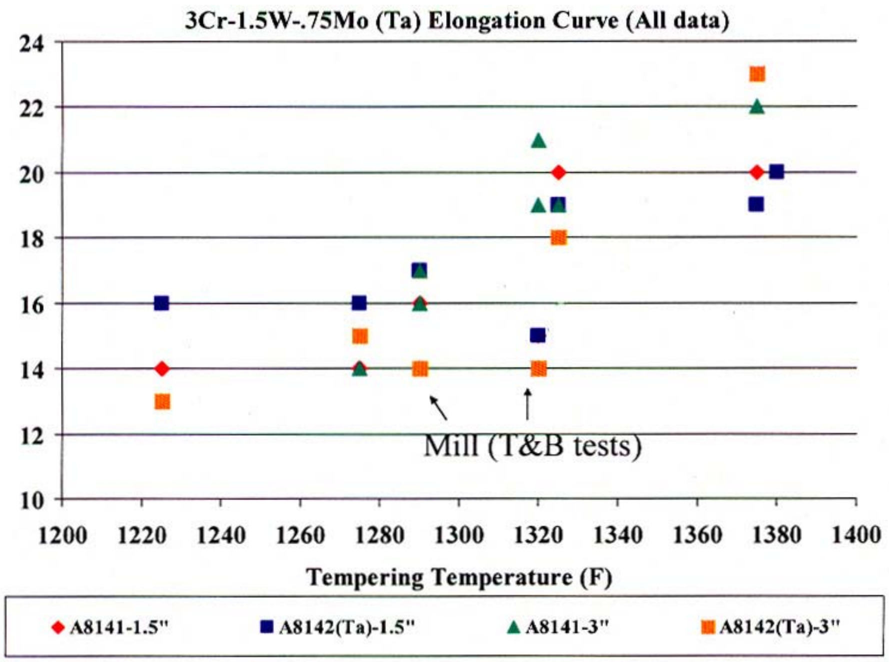


Fig. 4.10. Plot of total elongation at room temperature as a function of tempering temperature for 1.5- and 3-in.-thick plates of Grades A and B steel [A8141 and A8142(Ta)]. (Data from Ken Orie, ISG Plate)

The effect of tempering temperature on the tensile properties of 1.5- and 3-in.-thick plates of Grade A (heat 79741) (data generated by Ken Orie at ISG Plate) are compared with the data generated on 6- by 6-in. forgings at ORNL in Figs. 4.11 through 4.13. These figures show that data on forgings are in good agreement with the data on plate product and, thus, form a good basis for selecting tempering temperature for desired tensile properties.

The effect of tempering temperature on the Charpy-impact properties of 1.5- and 3-in.-thick plates of Grades A and B was also extensively investigated by Ken Orie of ISG Plate. These data are summarized in Table 4.8. The Charpy-impact energy at 32°F for 1.5-in.-thick plates of Grades A and B is plotted as a function of the Larson-Miller parameter (LMP) in Fig. 4.14. The LMP for tempering is described as follows:

$$LMP = (T + 460)(20 + \log t) \ , \qquad (1)$$

where

- T = tempering temperature in °F
- t = tempering time in hours
- 460 = factor used to convert °F to °R
- 20 = Larson-Miller constant

The plot in Fig. 4.14 shows that the Charpy-impact energy at 32°F increases with increasing LMP, which reflects an increase in temperature, time, or both. Ultimate tensile levels of 120 and 140 ksi are also shown in this figure. Based on Fig. 4.14, plates of Grades A and B, tempered for 120-ksi tensile strength, will result in Charpy-impact values at 32°F of ~40–110 ft-lb. The LMP corresponding to a 120-ksi ultimate tensile strength and acceptable Charpy values gives a target tempering temperature of ~1345°F. Thus, a temperature of 1345°F (730°C) was chosen as the tempering temperature for both Grades A and B for all of the remaining studies in this project.

In a separate study, we investigated the effect of replacing 3 wt % tungsten with 1.5 W + 0.75 Mo on Charpy-impact properties of Grade A (tantalum-free alloy). Data from this study are shown in Fig. 4.15. The detailed compositions of alloys containing tunsten and tungsten plus molybdenum are also included in this figure. Note that for 1.5 W + 0.75 Mo alloys (heats 18608 and 18609), the carbon contents were 0.075 and 0.14 wt %. All of the data were generated for 5/8-in.-thick plates, normalized at 2012°F (1100°C) and tempered at 700°C. It can be seen that the Charpy-impact data for 3 W (heat 10293) and 1.5 W + 0.75 Mo (heat 18609) are very similar. Furthermore, the lower carbon value of 0.075 results in expected improvement in Charpy-impact properties.

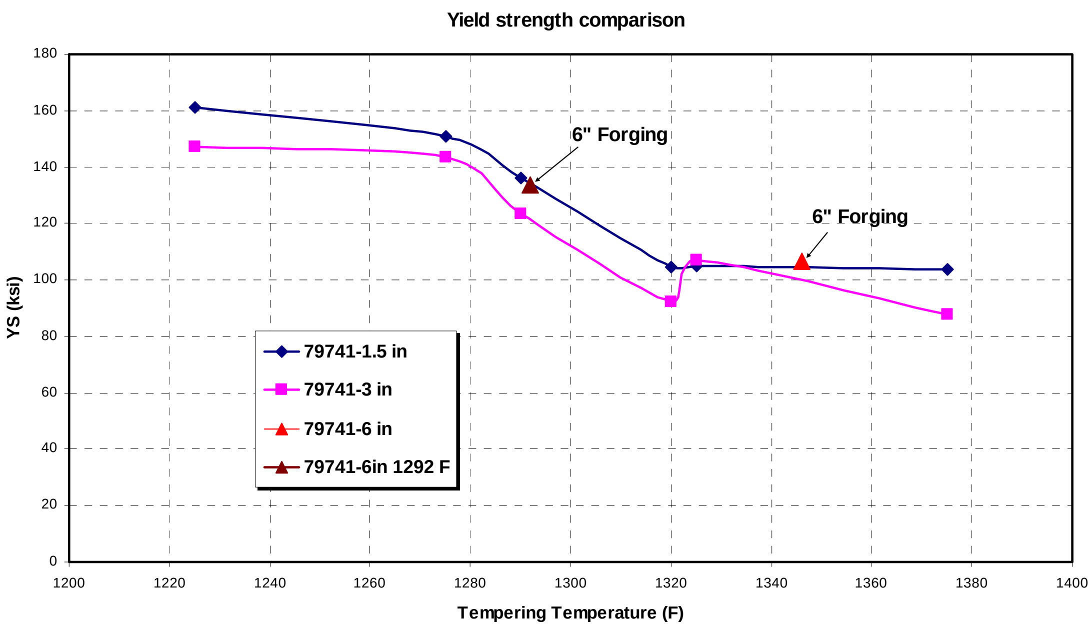


Fig. 4.11. Comparison of tempering response for yield strength at room temperature of 1.5- and 3-in.-thick plates tested at ISG Plate with 6- by 6-in. forging tested at ORNL for Grade A (heat 79741).

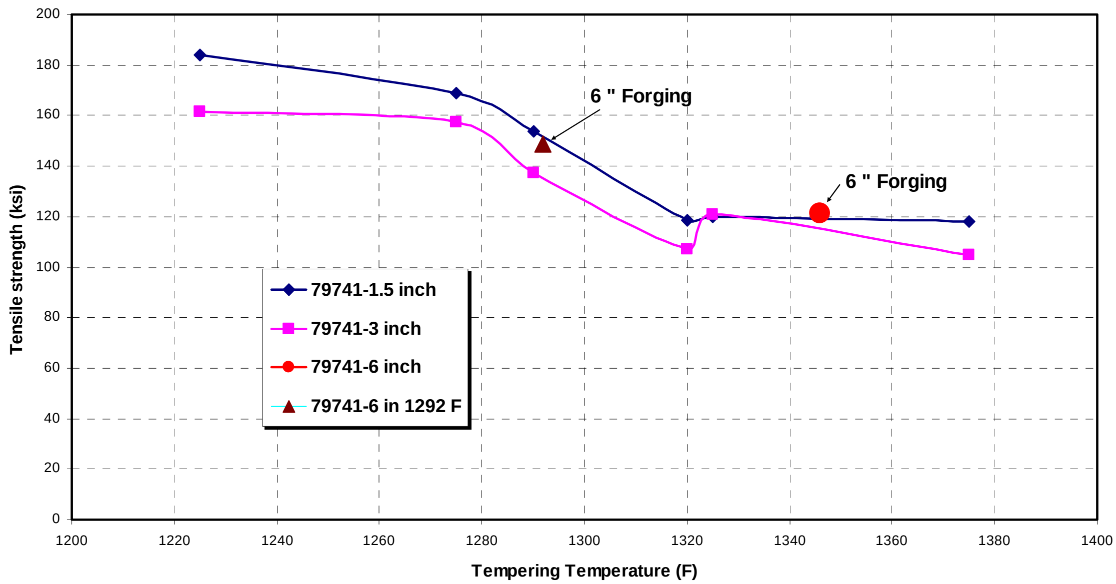


Fig. 4.12. Comparison of tempering response for ultimate tensile strength at room temperature of 1.5- and 3-in.-thick plates tested at ISG Plate with 6- by 6-in. forgings tested at ORNL for Grade A (heat 79741).

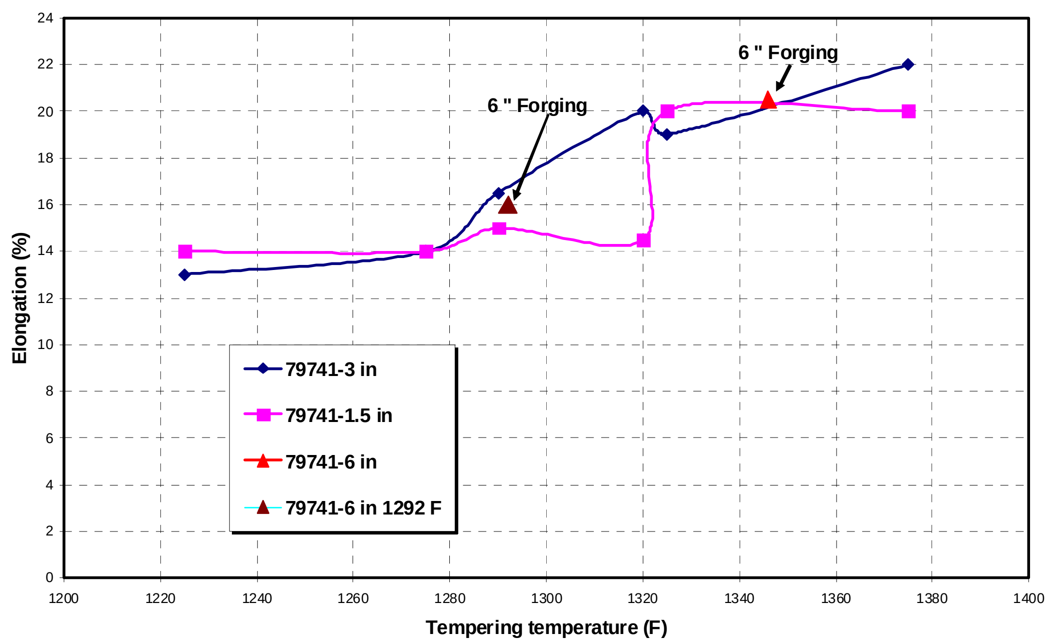


Fig. 4.13. Comparison of tempering response for total elongation at room temperature of 1.5- and 3-in.-thick plates tested at ISG Plate with 6- by 6-in. forgings tested at ORNL for Grade A (heat 79741).

Table 4.8. Charpy-impact properties of 1.5- and 3-in.-thick plates of Grade A (79741) and Grade B (86441) as affected by various tempering temperatures (data from Ken Orie at ISG Plate)

Impact Results for 3Cr-1.5W-.75Mo (Ta)														
			Energy (Ft-lbs)			Energy (Ft-lbs)			Energy (Ft-lbs)			Energy (Ft-lbs)		
Melt	Ga	Temper (F)	+68 F (L)			+32 F (Long / Trans)			0 F (L)			-40 F (L)		
A8141-1	1.5"	1225	8	8	9	5/4	6/4	12/8	5	11	11	3	5	7
(L7974)		1275	5	6	14	8/8	10/10	11/12	6	10	12	3	5	5
		1290(M)B				8/11	11/14	12/14						
		1290(M)T				20/7	24/12	24/13						
		1320(M)B				105/102	107/105	108/105						
		1320(M)T				112/111	117/111	117/116						
		1325	93	96	104	94/59	95/69	100/71	62	82	88	17	33	34
		1375	84	89	92	40/24	47/26	69/34	44	49	61	26	30	32
A8142-1	1.5"	1225	5	6	17	8/3	9/9	11/11	2	3	13	5	6	7
(Ta)		1275	6	7	24	6/6	14/8	18/14	4	5	8	1	3	5
(L8644)		*1290(M)B*				7/8	19/12	25/17						
		1290(M)T				10/6	11/6	23/15						
		1320(M)B				38/33	39/34	38/39						
		1320(M)T				66/43	65/43	60/45						
		1325	69	86	94	83/57	93/62	96/86	64	74	88	4	5	13
		1375	4	7	11	63/na	67/na	70/na	7	10	38	3	4	5
		1380 (M)B				193/123	193/131	195/131						
		1380 (M)T				149/127	167/152	184/157						
A8141-2	3"	1225	4	7	9	6/5	8/6	17/9	3	4	4	2	2	3
(L7974)		1275	7	8	13	4/5	6/7	8/9	3	5	5	4	4	5
		1290(M)B				6/8	18/10	25/20						
		1290(M)T				10/6	11/10	13/13						
		1320(M)B				128/121	126/122	129/125						
		1320(M)T				110/100	113/107	121/104						
		1325	81	86	88	63/19	69/23	75/25	26	29	42	6	6	8
		1375	97	99	114	109/na	115/na	118/na	43	48	59	20	28	36
A8142-2	3"	1225	9	21	57	5/13	16/16	19/29	3	6	6	4	5	6
(Ta)		1275	4	11	12	6/7	6/9	7/9	4	6	8	5	5	7
(L8644)		*1290(M)B*				na	na	na						
		1290(M)T				na	na	na						
		1320(M)B				69/63	65/64	61/66						
		1320(M)T				96/85	98/88	103/84						
		1325	69	76	93	75/35	82/35	96/40	27	33	39	8	11	18
		1375	105	120	151	111/71	118/98	121/102	73	67	137	76	86	86

4.6 Mechanical Properties

The commercial heats of both Grades A and B were subjected to mechanical properties tests in support of developing the database for approvals by ASTM and ASME code. Although both grades were tested for tensile and impact properties, creep testing of Grade B was limited because of lack of funding to develop the needed data on both grades. The long-term creep testing is continuing on Grade A in order to meet the test time of 10,000 h required by ASME code. The detailed mechanical properties data tables for Grade A are presented in the ASME data package in Appendix A. The data plots and observations are presented here.

4.6.1 Tensile Properties

The yield, ultimate tensile, total elongation, and reduction of area for three commercial heats of each for Grades A and B are plotted in Figs. 4.16–4.23. All tests were on specimens taken from 6- by 6-in. forgings and were normalized and tempered for 1 h at 2012 and 1346°F (1100 and 730°C), respectively. General observations from these figures are as follows:

1. There is some variation in properties between the three heats of each alloy.
2. A good combination of strength and ductility are noted for both grades across the entire test temperature range. Only one data point at 600°F (316°C) for one of the heats showed unusually low ductility.

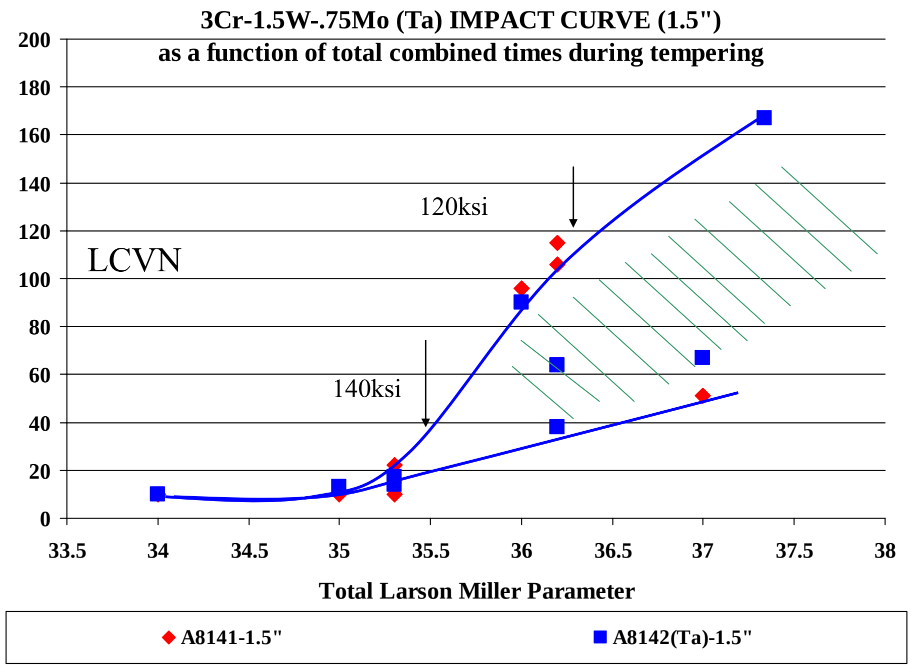
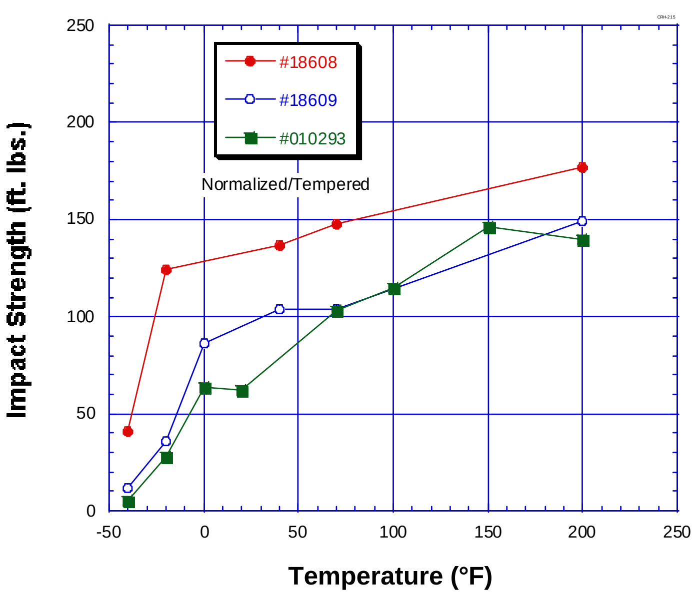


Fig. 4.14. Charpy-impact data at 32°F for 1.5-in.-thick plates of Grades A and B as a function of the Larson-Miller parameter.



Chemical Composition			
	#18608	#18609	#010293
Carbon	0.075	0.14	0.10
Manganese	0.24	0.480	0.39
Phosphorus	0.006	0.007	0.01
Sulfur	0.01	0.005	0.004
Silicon	0.21	0.21	0.16
Nickel	<0.01	<0.01	0.01
Chromium	3.01	3.02	3.04
Molybdenum	0.75	0.76	0.01
Vanadium	0.24	0.24	0.21
Columbium	0.001	0.002	0.003
Titanium	0.003	0.003	0.001
Cobalt	0.007	0.006	0.005
Copper	<0.01	<0.01	0.01
Alumnium	0.004	0.004	0.003
Boron	0.001	<0.001	0.001
Tungsten	1.54	1.52	3.05
Arsenic	0.002	0.001	0.001
Tin	0.003	0.002	0.003
Zirconium	<0.001	0.001	0.001
Nitrogen	<0.001	<0.001	0.004
Oxygen	0.001	0.004	0.005
Tantalum	<0.01	<0.01	

Fig. 4.15. Comparison of Charpy-impact data for Fe-3Cr-3W alloy (heat 010293) with alloys containing 1.5 W + 0.75 Mo (heats 18608 and 18609) as opposed to 3 W. All plates were tested after normalizing at 1100°C and tempering at 700°C.

3. Grade B showed lower tensile properties than Grade A across the entire test temperature. There is no obvious explanation for this behavior because as seen later, Grade B with 0.1 wt % tantalum did show higher creep strength.

The tensile properties of commercially melted, electric furnace heats of Grades A and B (heats 79741 and 86441) are compared with the properties of commercial and near-commercial alloys (T22, T23, and T24) in Figs. 4.24–4.26. These figures show the following:

1. Yield strength values for both Grades A and B are over 20 ksi higher across the entire test temperature range than for the highest-strength alloy, T23. This is especially significant at 1200°F, where yield strength values for Grades A and B are nearly 75% higher than those for T23. Both grades have nearly twice the yield strength of the commercial grade of 2.25Cr-1Mo steel (T22) for the entire use temperature of T22.
2. Ultimate tensile strength values for Grades A and B are also more than 20 ksi higher than for T23 across the entire test temperature range. As compared to 2.25Cr-1Mo steel, Grades A and B are nearly 1.5 times stronger for the entire use temperature range of 2.25Cr-1Mo steel (T23).
3. Total elongation values for Grades A and B are little lower than for T22 and T24. However, these values are generally acceptable for most of the component forming and equipment fabrication needs.

Data in Figs. 4.23 through 4.26 clearly show that the new grades meet the tensile strength objectives set for them in this project.

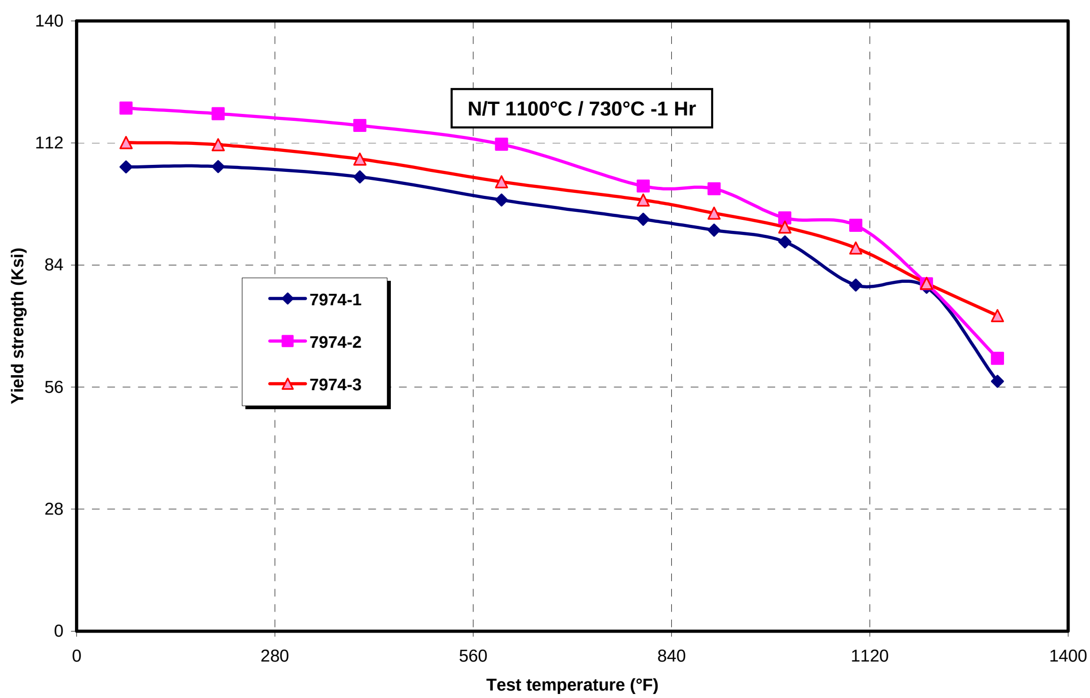


Fig. 4.16. Yield strength as a function of test temperature for three commercial heats of Grade A.

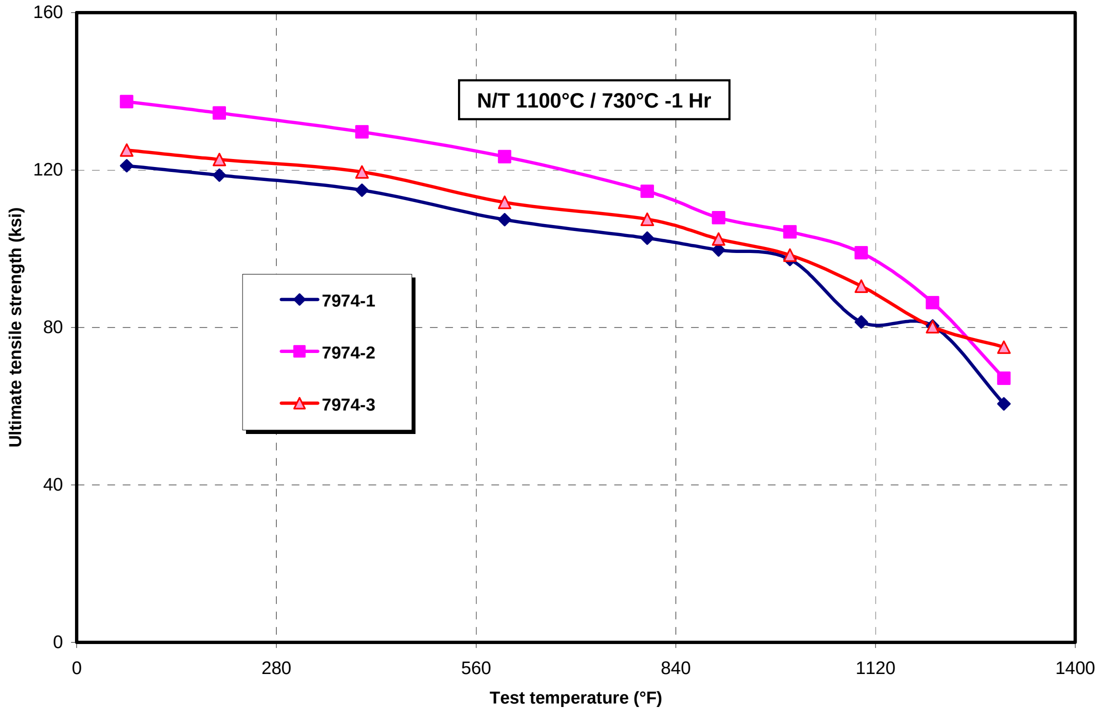


Fig. 4.17. Ultimate tensile strength as a function of test temperature for three commercial heats of Grade A.

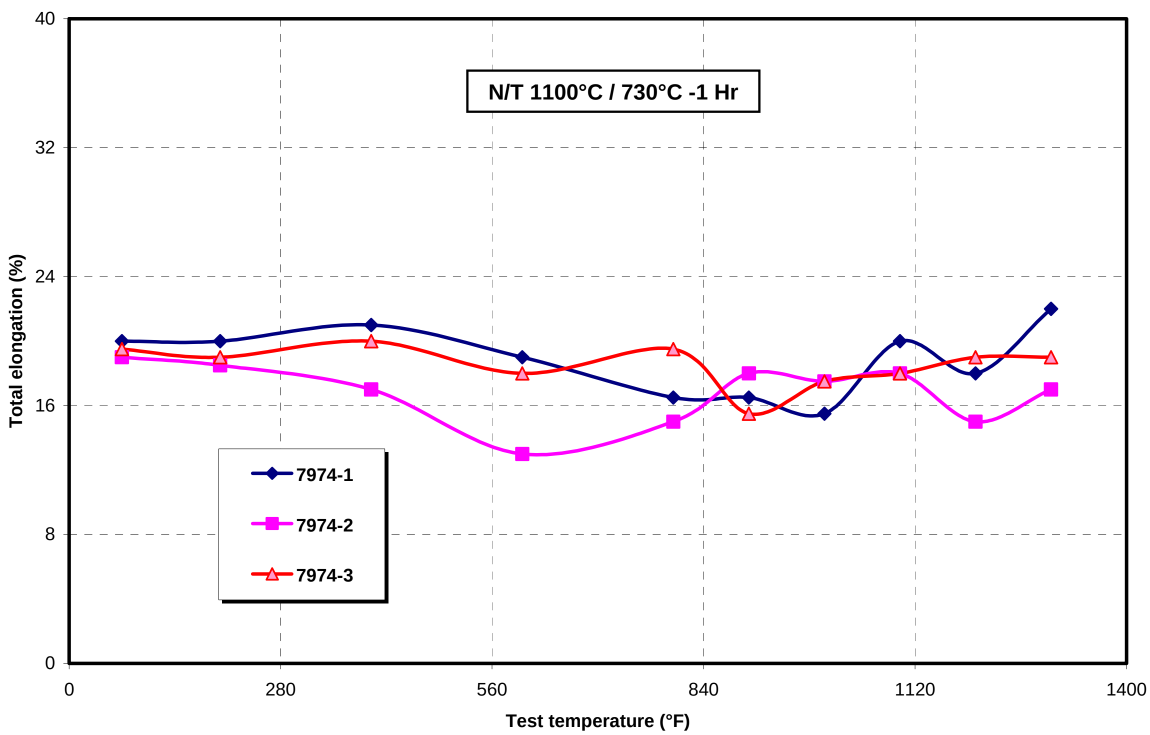


Fig. 4.18. Total elongation as a function of test temperature for three commercial heats of Grade A.

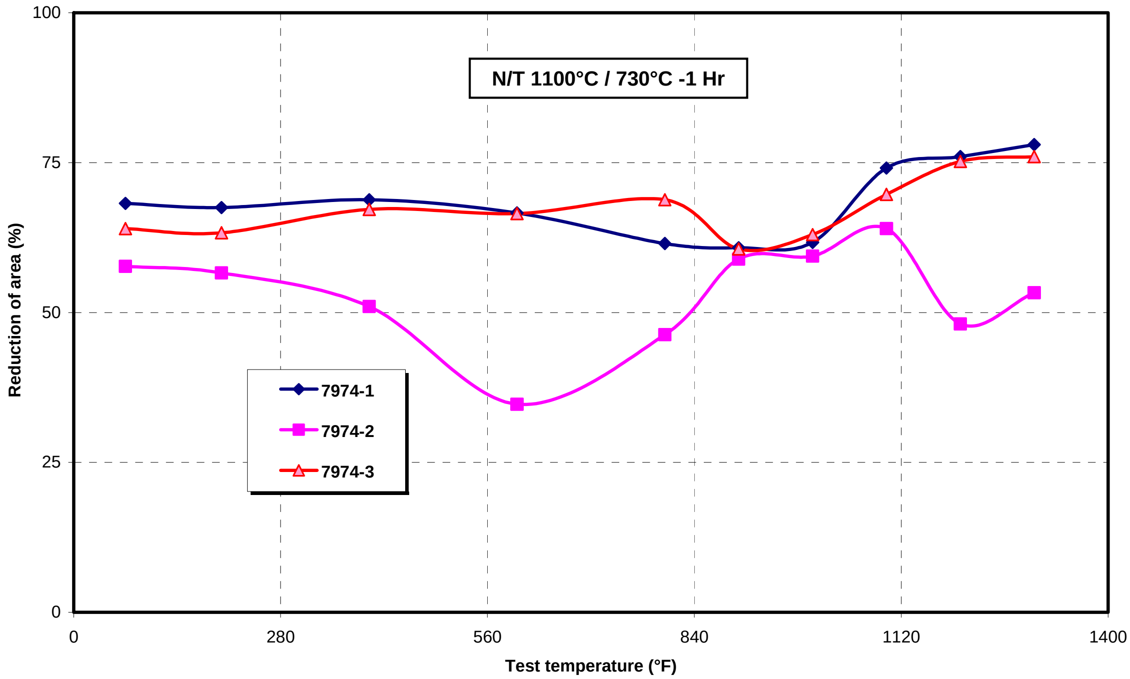


Fig. 4.19. Reduction of area as a function of test temperature for three commercial heats of Grade A.

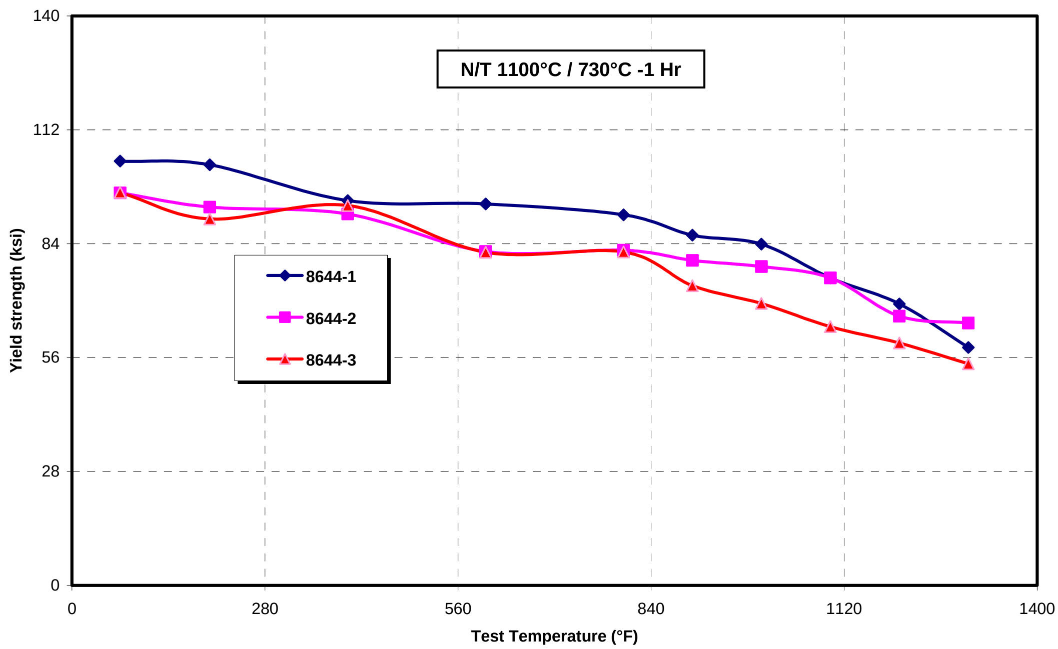


Fig. 4.20. Yield strength as a function of test temperature for three commercial heats of Grade B.

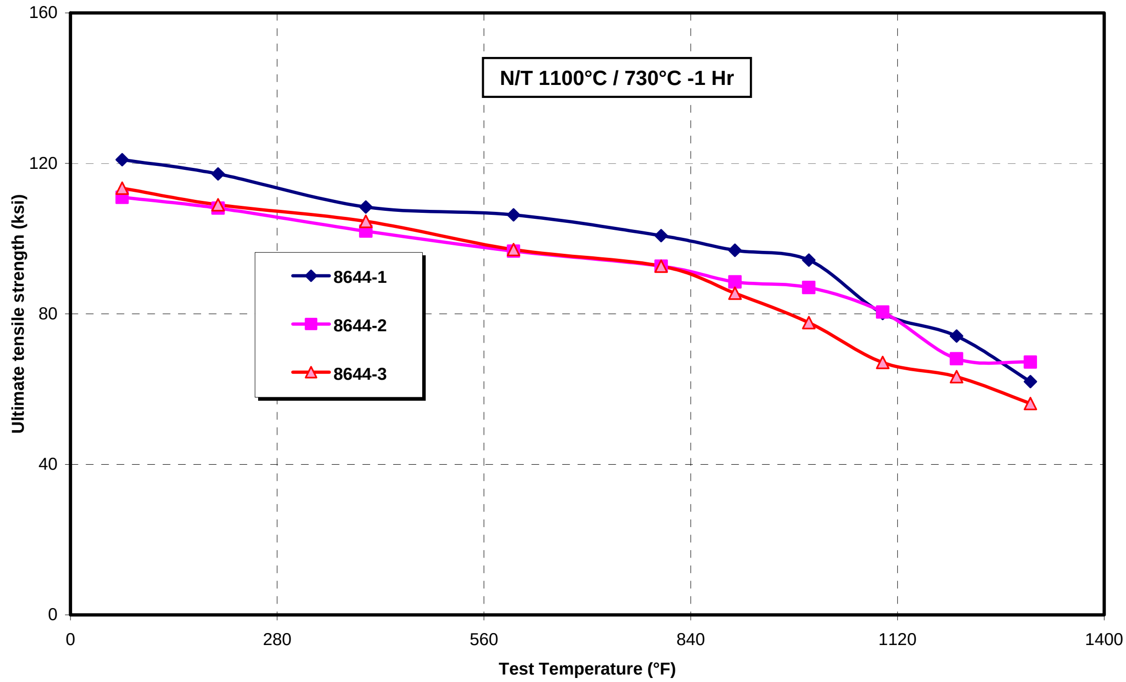


Fig. 4.21. Ultimate tensile strength as a function of test temperature for three commercial heats of Grade B.

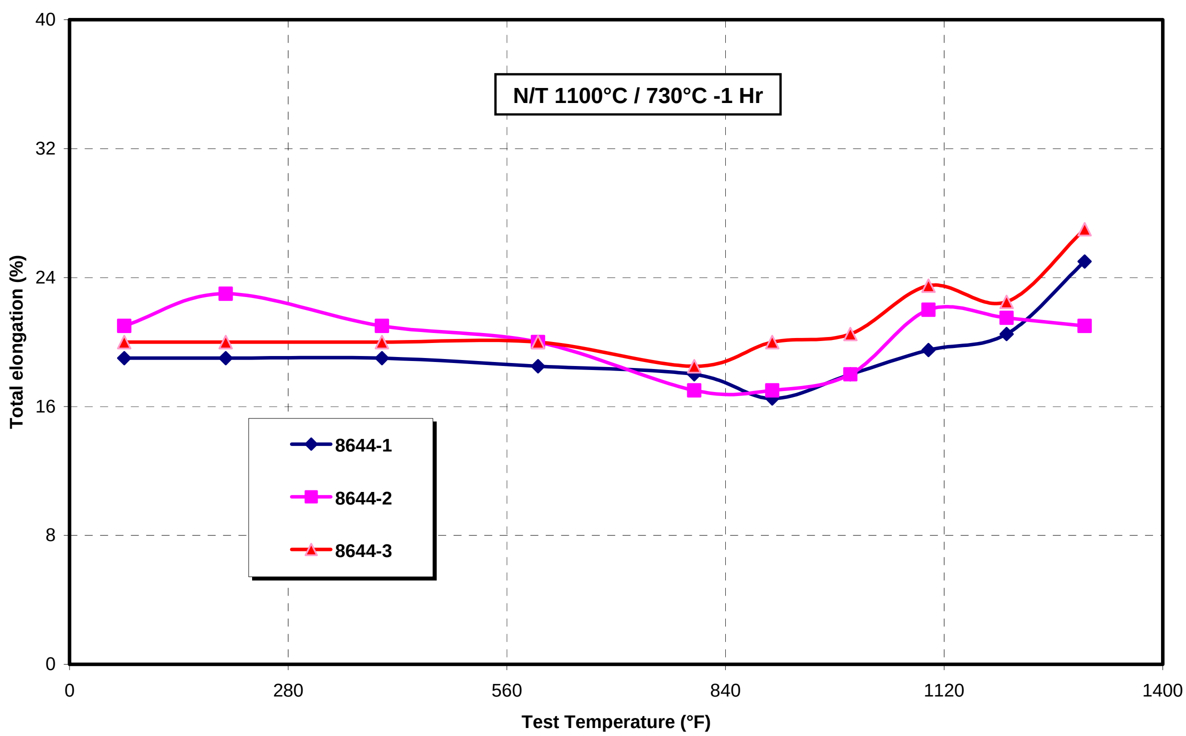


Fig. 4.22. Total elongation as a function of test temperature for three commercial heats of Grade B.

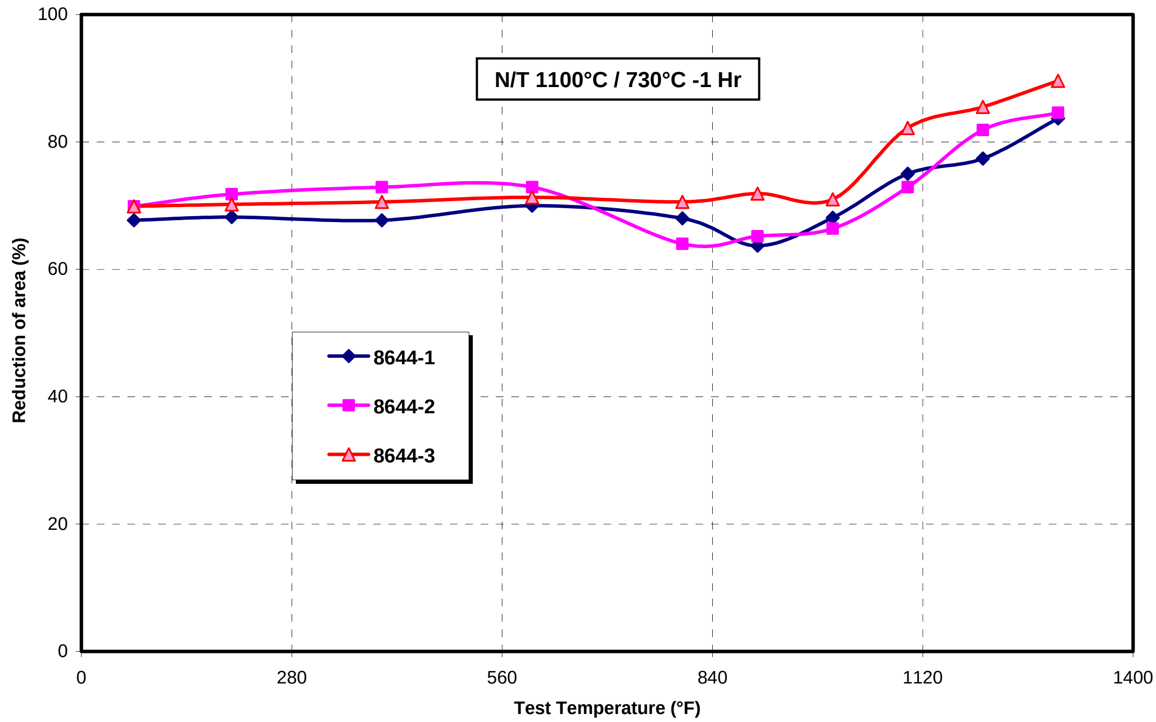


Fig. 4.23. Reduction of area as a function of test temperature for three commercial heats of Grade B.

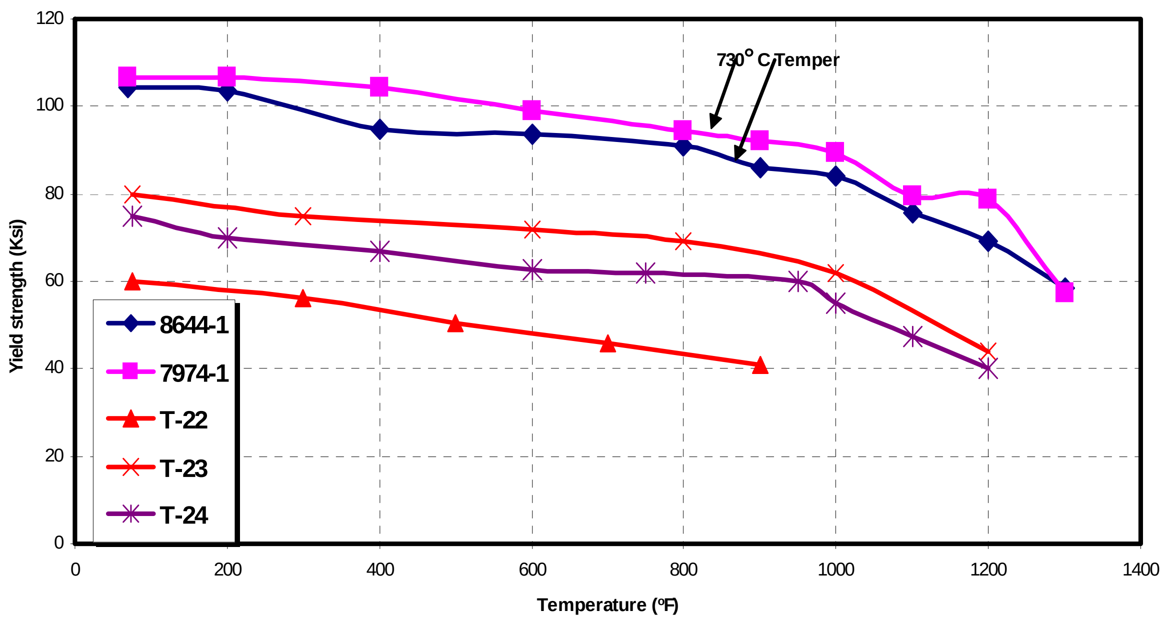


Fig. 4.24. Comparison of yield strength of Grades A and B as compared to commercial and near-commercial grades of steel in a similar chemical analysis range.

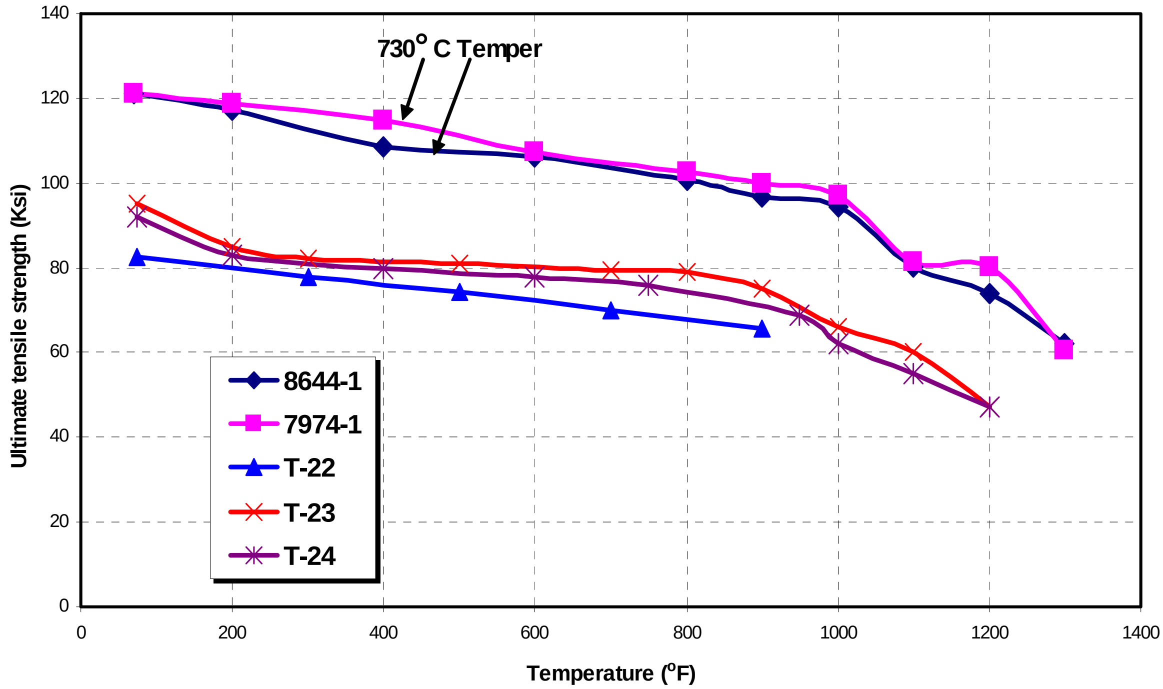


Fig. 4.25. Comparison of ultimate tensile strength of Grades A and B as compared to commercial and near-commercial grades of steel in a similar chemical analysis range.

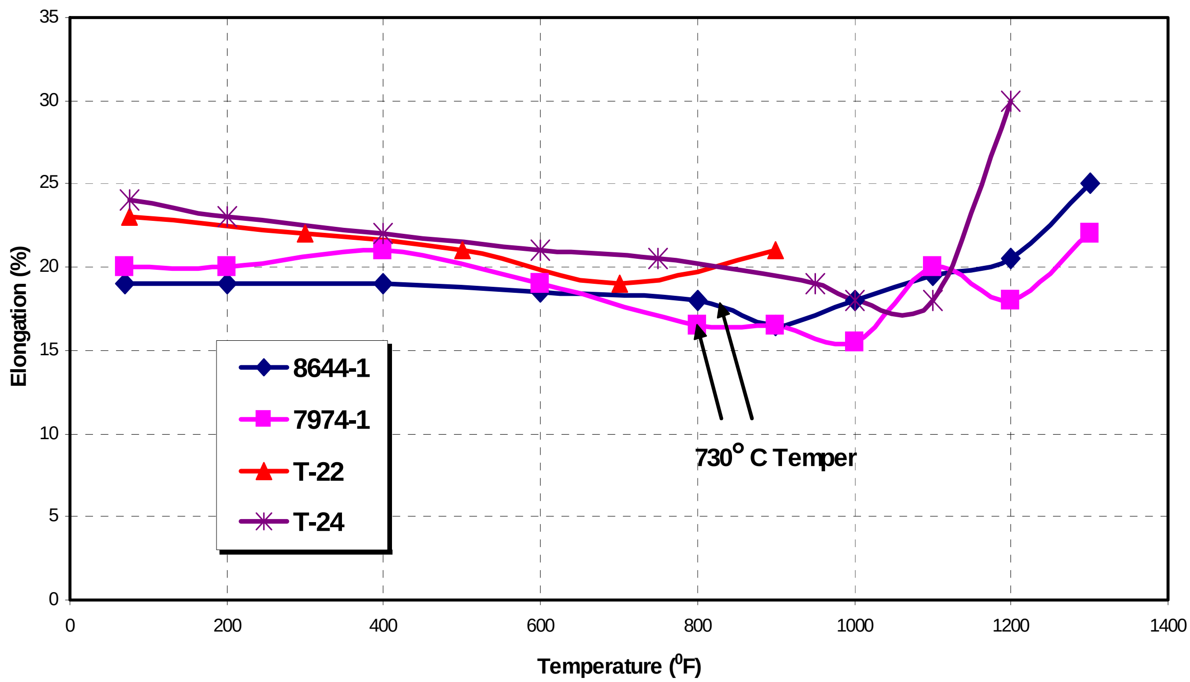


Fig. 4.26. Comparison of total elongation of Grades A and B as compared to commercial and near-commercial grades of steel in a similar chemical analysis range.

4.6.2 Charpy-Impact Properties

The Charpy-impact properties of electric-furnace-melted commercial heats of Grades A and B are plotted in Fig. 4.27. These data are for samples taken from the 6- by 6-in. forgings. These plots show the following:

1. The impact properties in the longitudinal orientation are superior to those in the transverse orientation.
2. The impact properties for tantalum containing Grade B (heat 86441) are slightly poorer than those for tantalum-free Grade A (heat 79741).
3. The impact properties for forgings of both Grades A and B are quite impressive, with 15 ft-lb DBTT of −20 to −40°F. The corresponding DBTT for 15-mil lateral expansion is also −20 to −40°F.

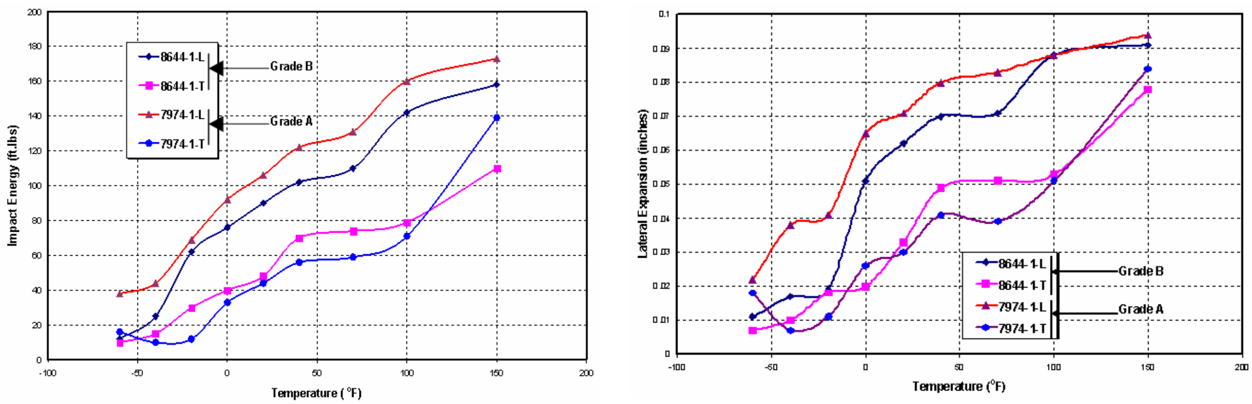


Fig. 4.27. Charpy-impact energy and lateral expansion data for 6- by 6-in. forgings of Grades A and B (heats 79741 and 86441). Both grades were tested in the normalized and tempered conditions (1100 and 730°C).

Charpy-impact energy data for the 1-in.-thick hot-rolled plate of Grade A (heat 79741) is plotted in Fig. 4.28. The plate data for Grade A are compared with the data on the 6- by 6-in. forgings of Grades A and B in Fig. 4.29. These data show some improvement in the Charpy-impact properties of the plate as opposed to the forgings.

Data in Figs. 4.27 through 4.29 also show that the Grades A and B steels developed in this project have upper-shelf Charpy-impact values of ~100 ft and DBTT of −20 to −40°F. Both of these values have met or exceeded the project objectives of 100 ft-lb of upper-shelf energy and a DBTT of −10°F.

4.6.3 Creep Properties

Creep tests were conducted on commercial heats of both Grades A and B. As stated earlier, creep testing on Grade A is continuing, but no tests on Grade B are currently in progress because of lack of funds. Tables of creep data on both grades, updated on December 16, 2004, are presented in Appendix D. The isothermal plots of creep-rupture data at 900, 950, 1000, 1100, 1150, and 1200°F (482, 510, 538, 593, 621, and 640°C) are shown in Figs. 4.30 through 4.35. All of the data shown in these figures were developed for a tempering temperature of 1346°F (730°C). A limited set of data was also generated for both Grades A and B after tempering at a temperature of 1292°F (700°C). These data are plotted in Figs. 4.36 and 4.37 for Grades A and B.

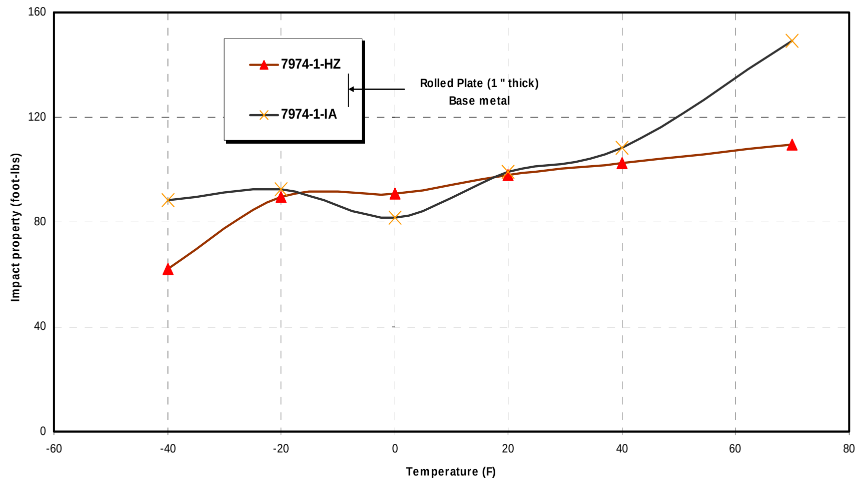


Fig. 4.28. Charpy-impact energy data for 1-in.-thick plate of Grade A (heat 79741). Two different plates designated as 79741-HZ and 79741-IA were tested. All data are for plates in the normalized and tempered conditions (1100 and 730°C).

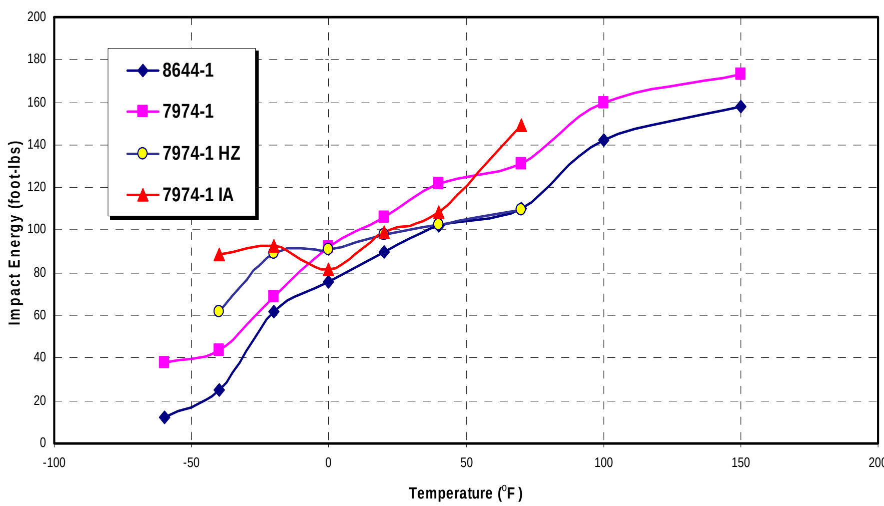
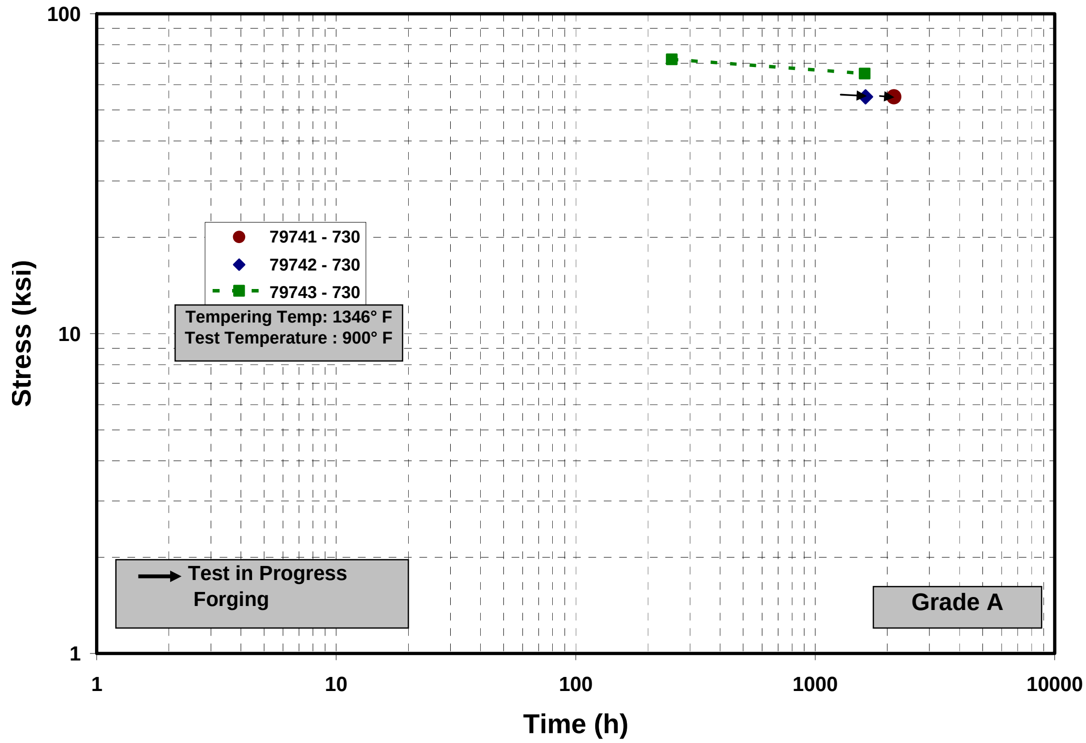


Fig. 4.29. Comparison of Charpy-impact properties of 1-in.-thick plate of Grade A with 6- by 6-in. forgings of Grades A and B. Both plate and forgings were tested in the normalized and tempered conditions (1100 and 730°C).

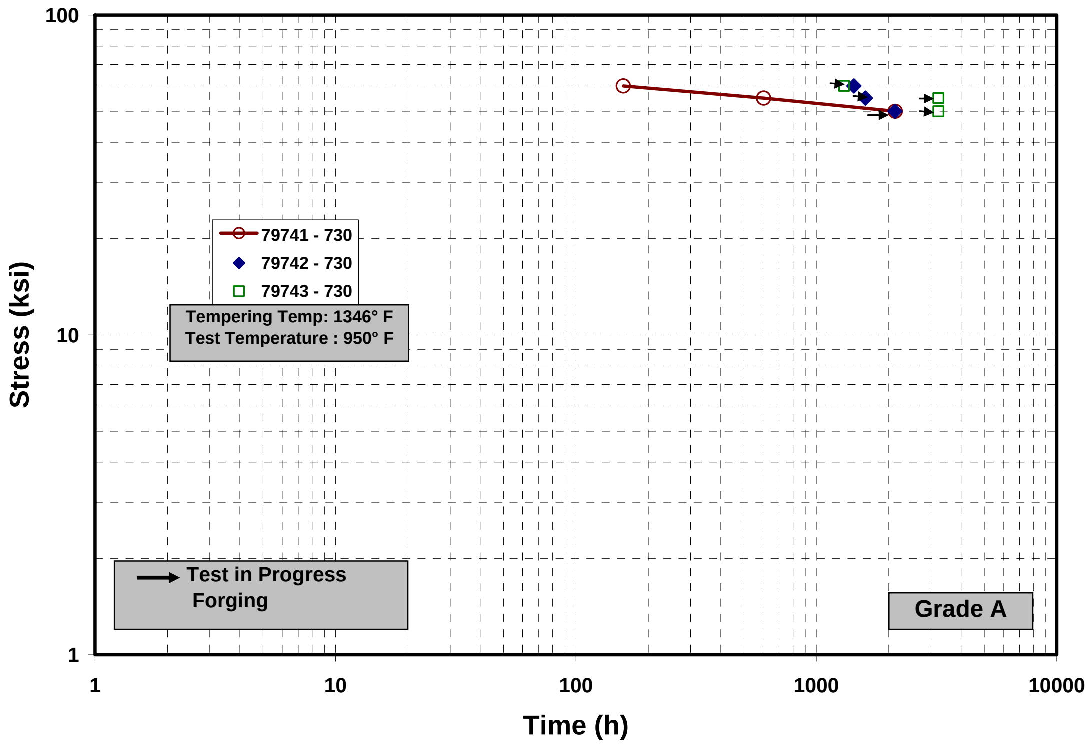
The most commonly accepted method for analyzing the creep data for setting the design-allowable is the Lawson-Miller parameter (LMP). This parameter compresses the data at various test temperatures into a single line or curve. Plots are commonly used to set the 10^5 h creep-rupture strength values for ASME code design stresses. The LMP for creep-rupture data is given as

$$LMP = T(20 + \log t_r) , \qquad (2)$$

where T = test temperature in K and t_r = time to rupture in hours.

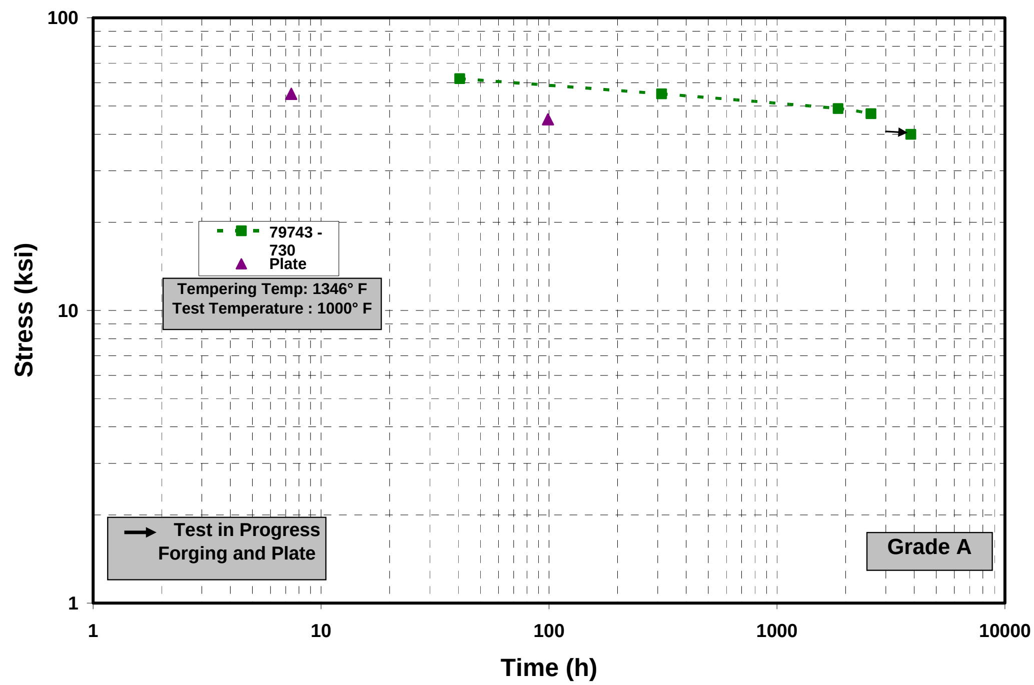


(a)

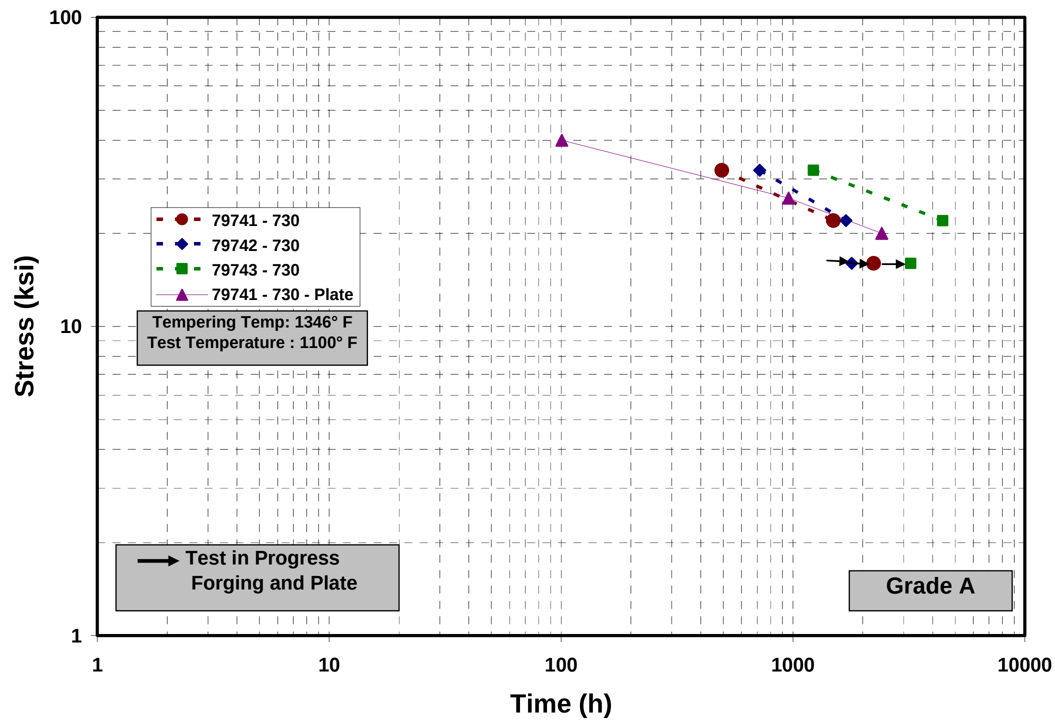


(b)

Fig. 4.30. Isothermal plots of creep-rupture data for three commercial heats of Grade A: (*a*) 900 (482°C) and (*b*) 950°F (510°C). All tests are for forgings and plate tested after tempering at 1345°F (730°C).

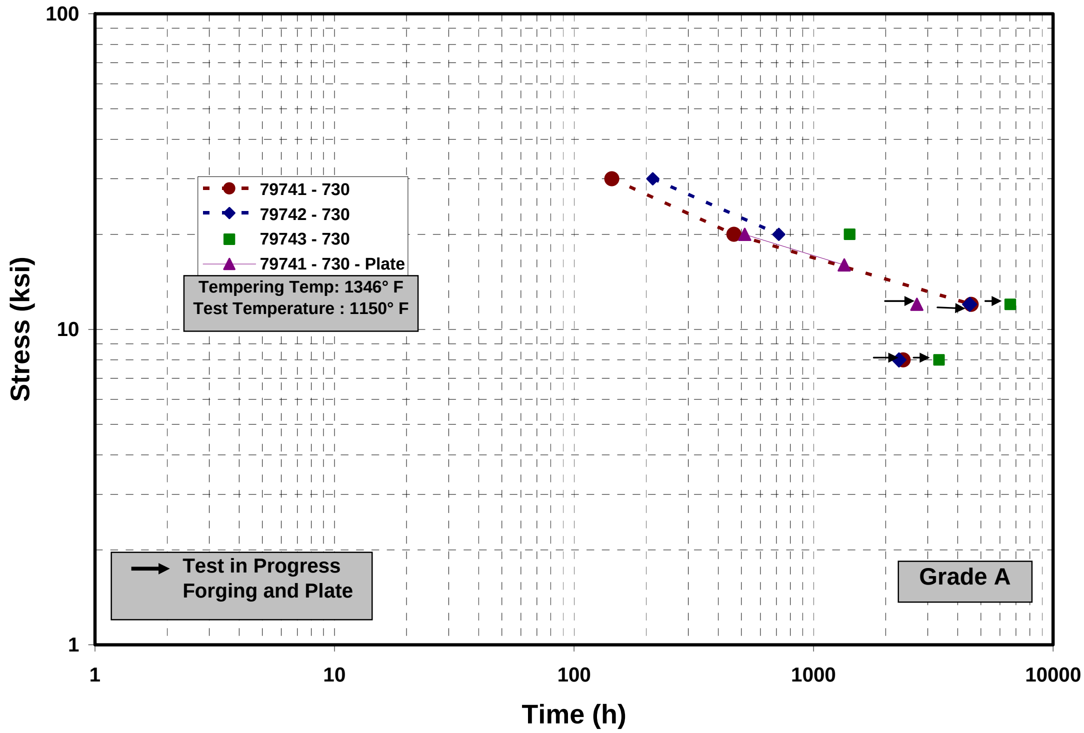


(a)

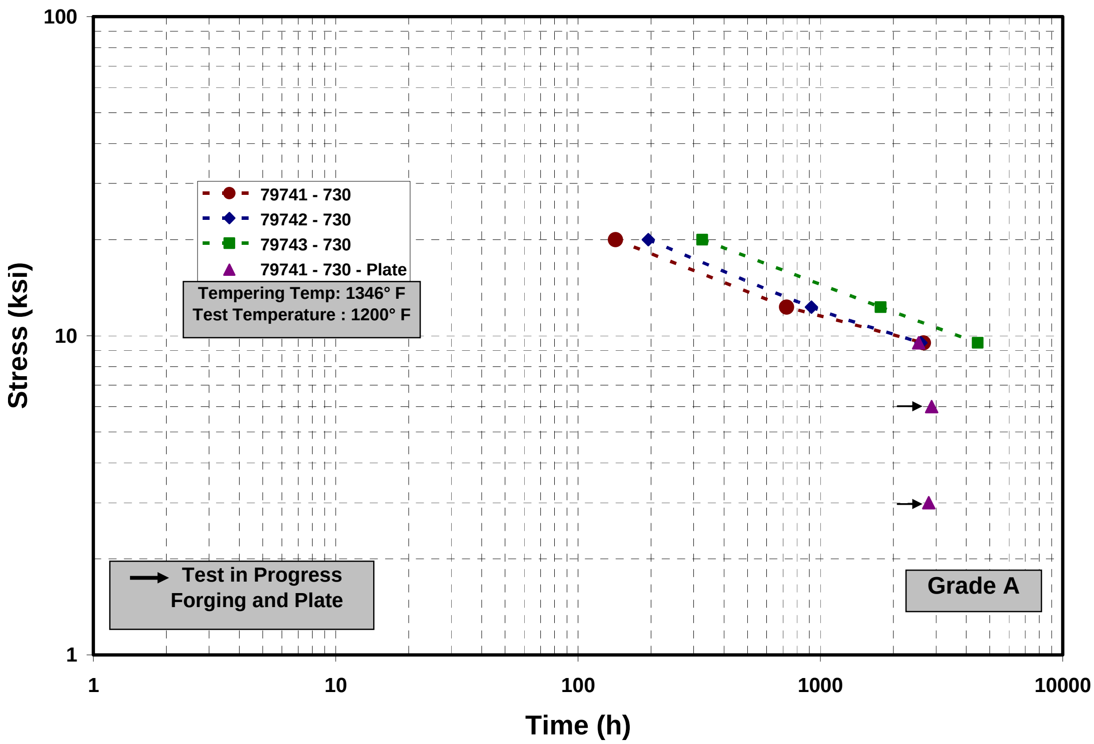


(b)

Fig. 4.31. Isothermal plots of creep-rupture data for three commercial heats of Grade A: (*a*) 1000 (538°C) and (*b*) 1100°F (593°C). All tests are for forgings and plate tested after tempering at 1345°F (730°C).

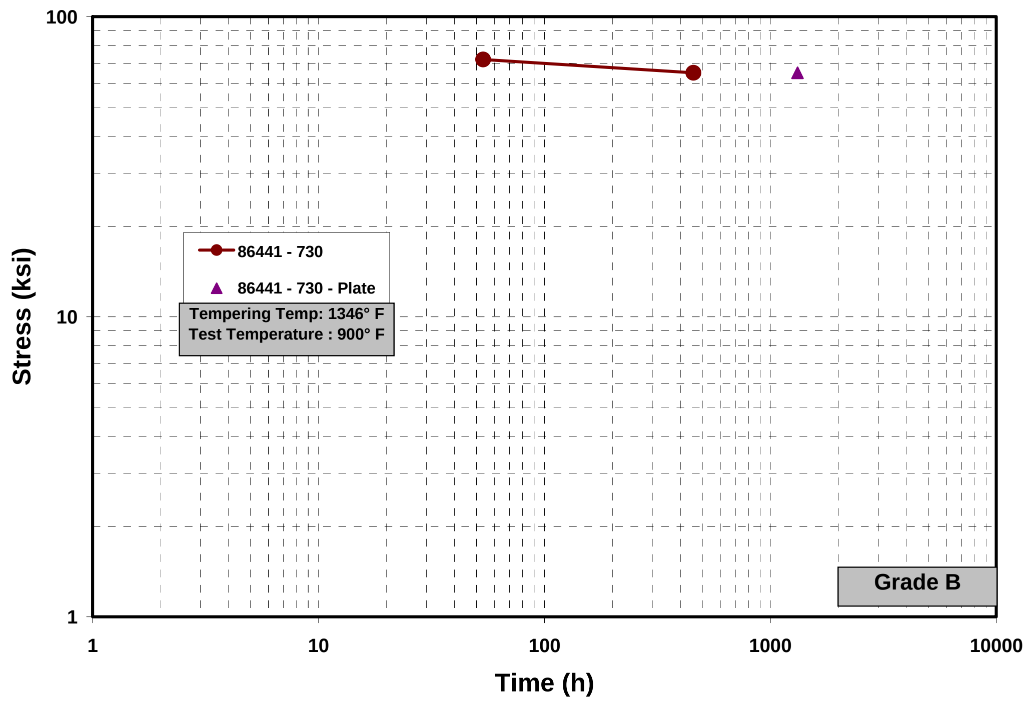


(a)

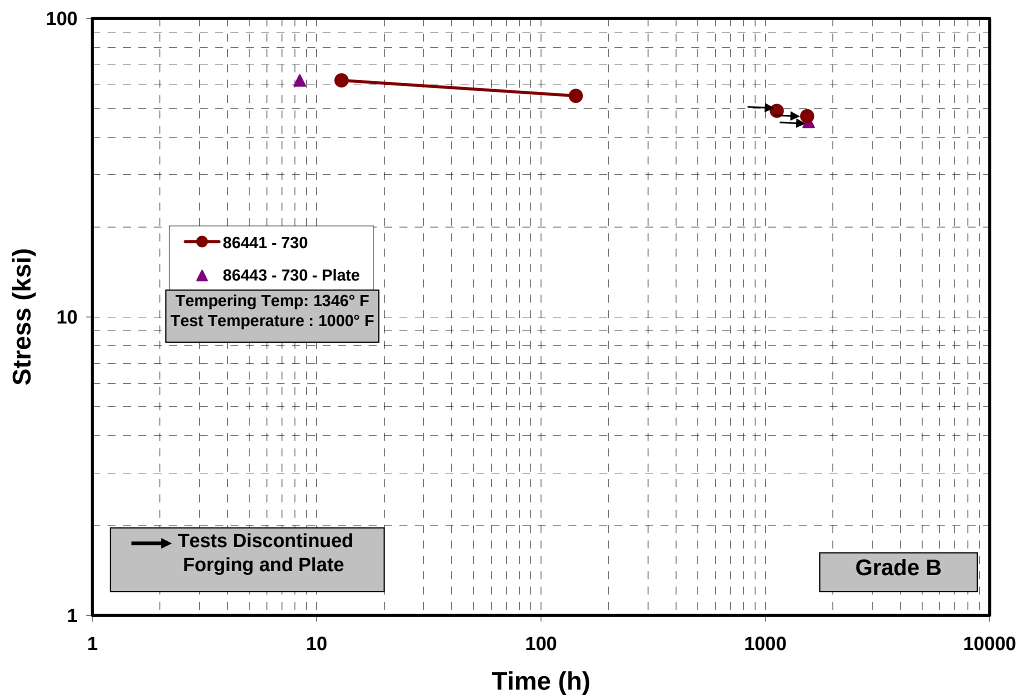


(b)

Fig. 4.32. Isothermal plots of creep-rupture data for three commercial heats of Grade A: (*a*) 1150 (621°C) and (*b*) 1200°F (649°C). All tests are for forgings and plate tested after tempering at 1345°F (730°C).

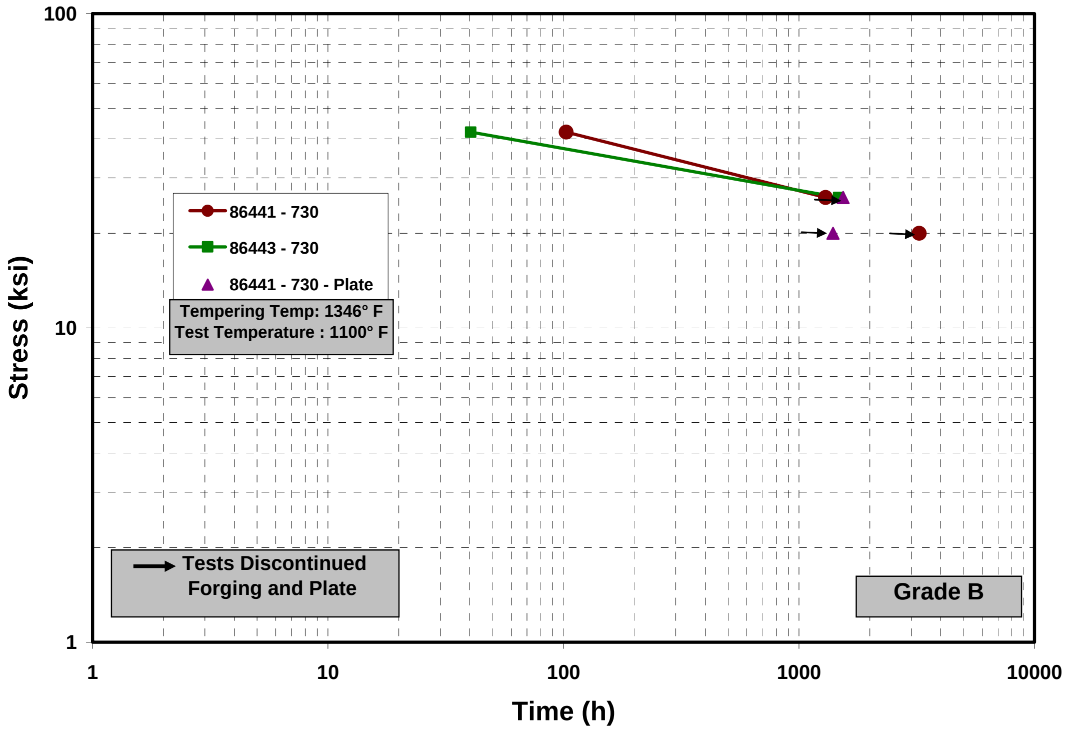


(a)

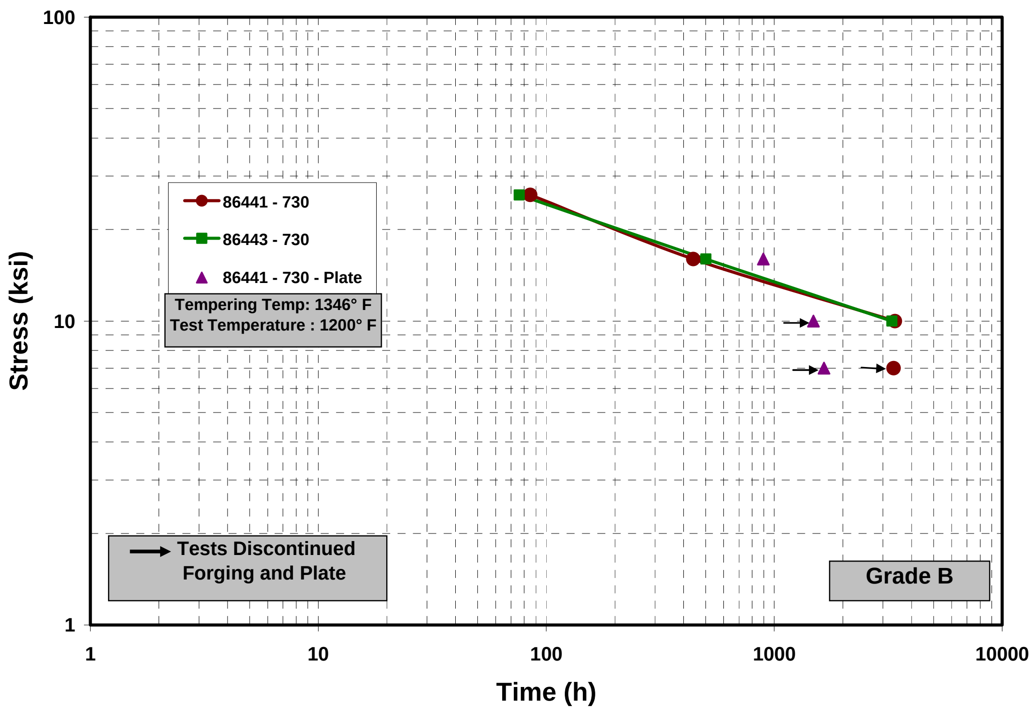


(b)

Fig. 4.33. Isothermal plots of creep-rupture data for three commercial heats of Grade B: (*a*) 900 (482°C) and (*b*) 1000°F (538°C). All tests are for forgings and plate tested after tempering at 1345°F (730°C).



(a)



(b)

Fig. 4.34. Isothermal plots of creep-rupture data for three commercial heats of Grade B: (*a*) 1100 (593°C) and (*b*) 1200°F (649°C). All tests are for forgings and plate tested after tempering at 1345°F (730°C).

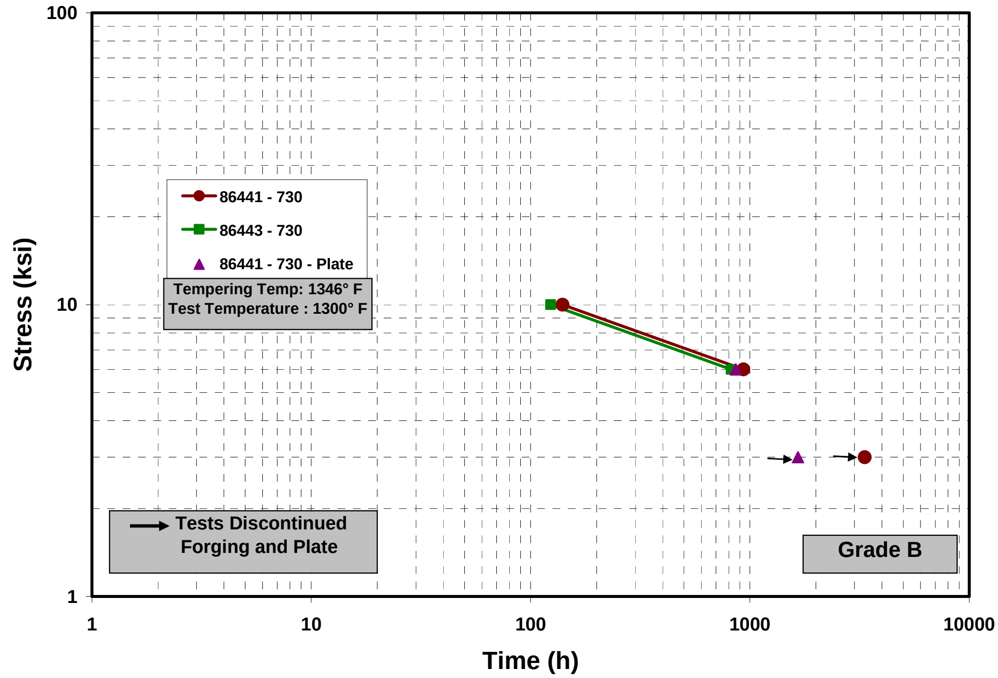


Fig. 4.35. Isothermal plots of creep-rupture data for three commercial heats of Grade B. All tests are for forgings and plate tested after tempering at 1345°F (730°C): test temperature is 1300°F (704°C).

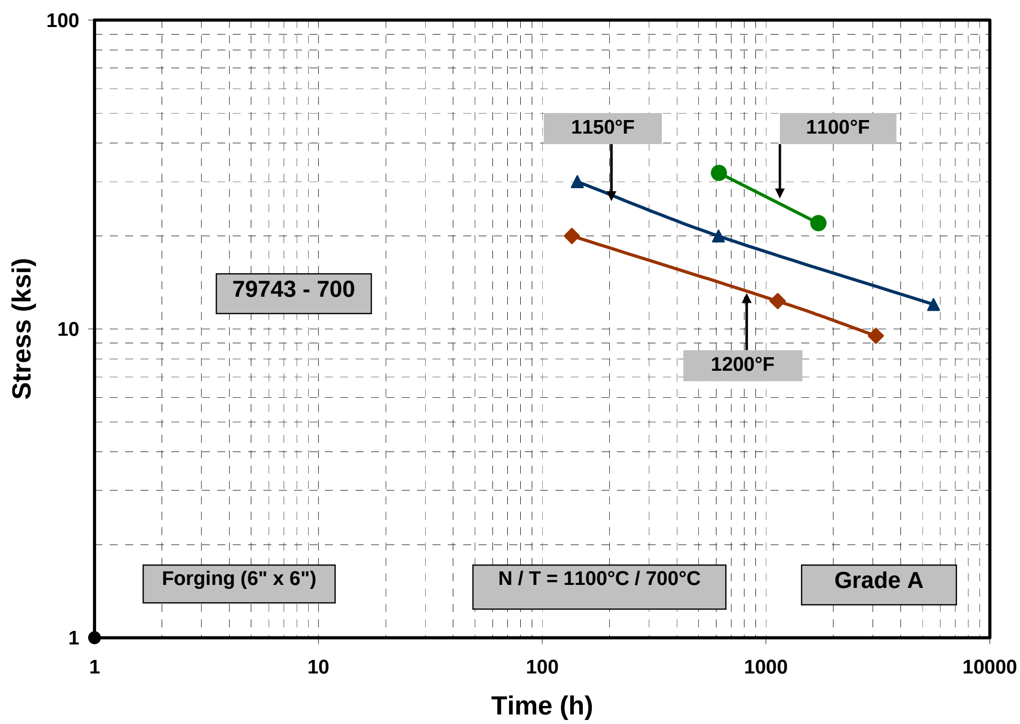


Fig. 4.36. Creep-rupture data for commercial heat 79743 of Grade A tested after tempering at 1292°F (700°C).

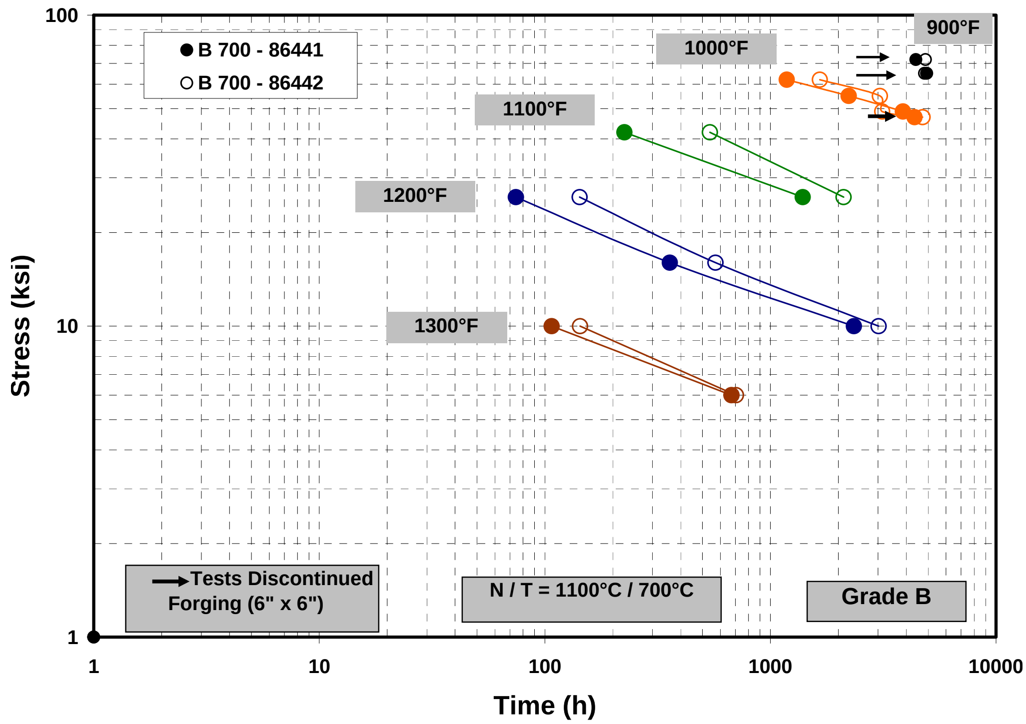


Fig. 4.37. Creep-rupture data for commercial heats 86441 and 86442 of Grade B tested after tempering at 1292°F (700°C).

The LMP plot for all of the creep-rupture data on three commercial heats of Grade A is shown in Fig. 4.38. This plot shows a good collapse of data for temperatures in the range of 900 to 1200°F (482 to 649°C). However, it appears that data are best described by two lines: one for the high-stress region and the other for the low-stress region. The transition from high- to low-stress region appears to occur at approximately 50 ksi. The LMP plot for Grade A is compared with the average values reported for the commercially available alloy T23 in Fig. 4.39. It can be seen from this figure that the creep-rupture strength values for Grade A developed in this project exceed the T23 values up to 10^5 h at 1100°F. At higher temperatures or longer times, the Grade A values match those of T23.

The LMP for all the creep-rupture data on three commercial heats of Grade B is shown in Fig. 4.40. Data for Grade B also show a transition in slope from high- to low-stress region similar to that shown for Grade A in Fig. 4.38. The transition for Grade B occurs at approximately 55 ksi, 5 ksi higher than observed for Grade A. The LMP plot for Grade B is compared with the average values for the commercially available alloy T23 in Fig. 4.41. As this figure shows, the creep-rupture values of Grade B, developed in this project, are higher than T23 for conditions of 10^5 h at 1100°F (593°C). For example, at an LMP value of 20,000, the creep-rupture strength of Grade B is 30 ksi, compared with 20 ksi for T23. However, the creep-rupture strength of Grade B crosses over that of T23 at an LMP corresponding to 10^5 h rupture at 1100°F (593°C). Beyond this crossover point, the Grade B values are somewhat lower than values for T23. These lower values are believed to have resulted from several creep tests carried out at 1300°F (704°C) for Grade B in which a reduction in creep-rupture strength was expected because excessive oxidation caused a reduction in the specimen cross section. Thus, more longer-term data are needed at test temperatures of ≤1200°F (649°C), to further assess the extent of creep-rupture strength enhancement of Grade B as compared to T23.

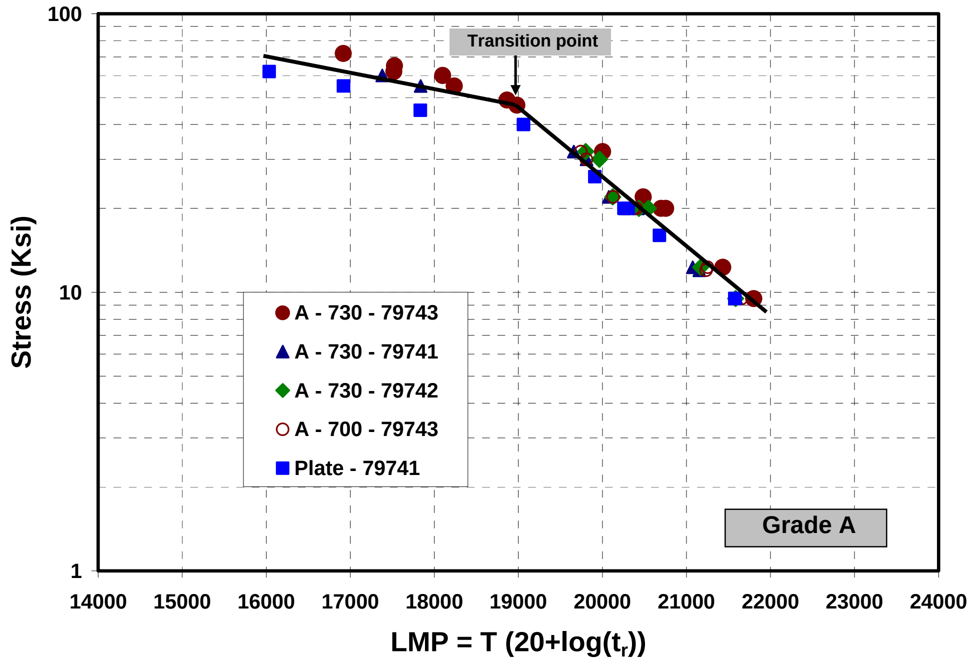


Fig. 4.38. Larson-Miller parameter plot of creep-rupture data for three commercial heats of Grade A. Note the transition point at 50 ksi for a change in slope from a high-stress to a low-stress region.

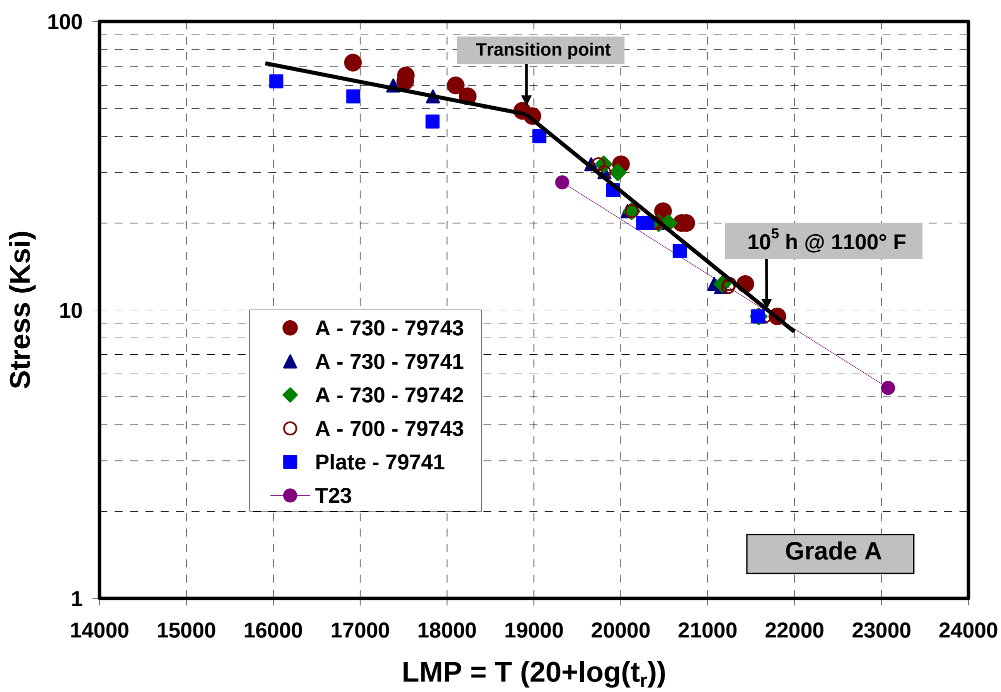


Fig. 4.39. Comparison of Larson-Miller plot for three commercial heats of Grade A, with average values reported for the commercial grade T23. Note the crossover point in strength at 10^5 h at 1100°F (593°C) between Grade A and T23.

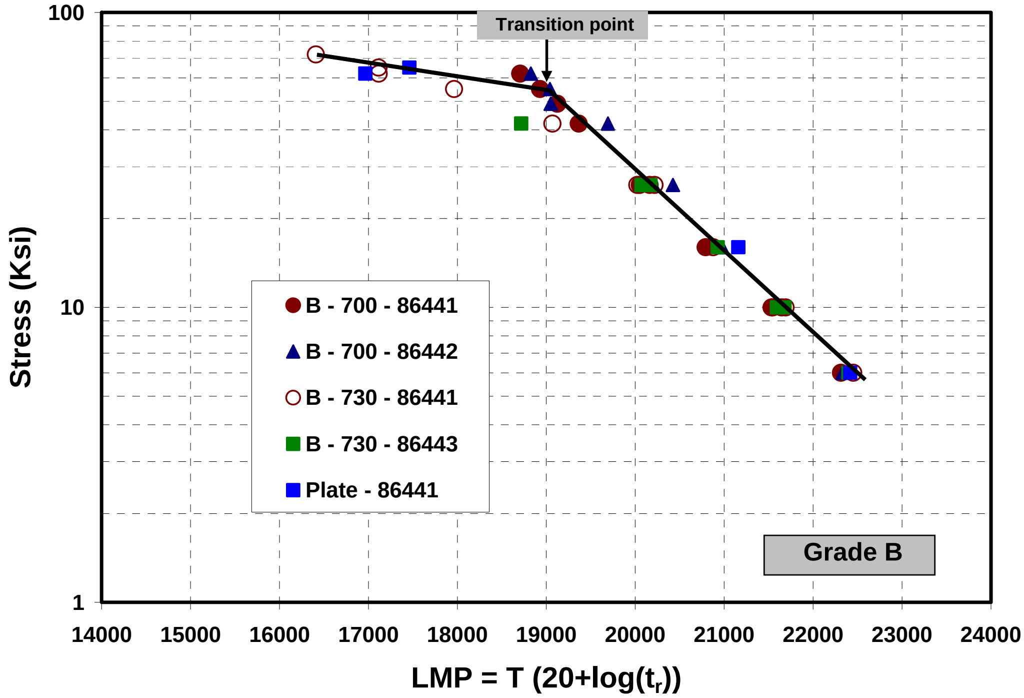


Fig. 4.40. Larson-Miller plot of creep-rupture data for three commercial heats of Grade B. The transition point for a change in slope from high-stress to low-stress region again occurs at 50 ksi.

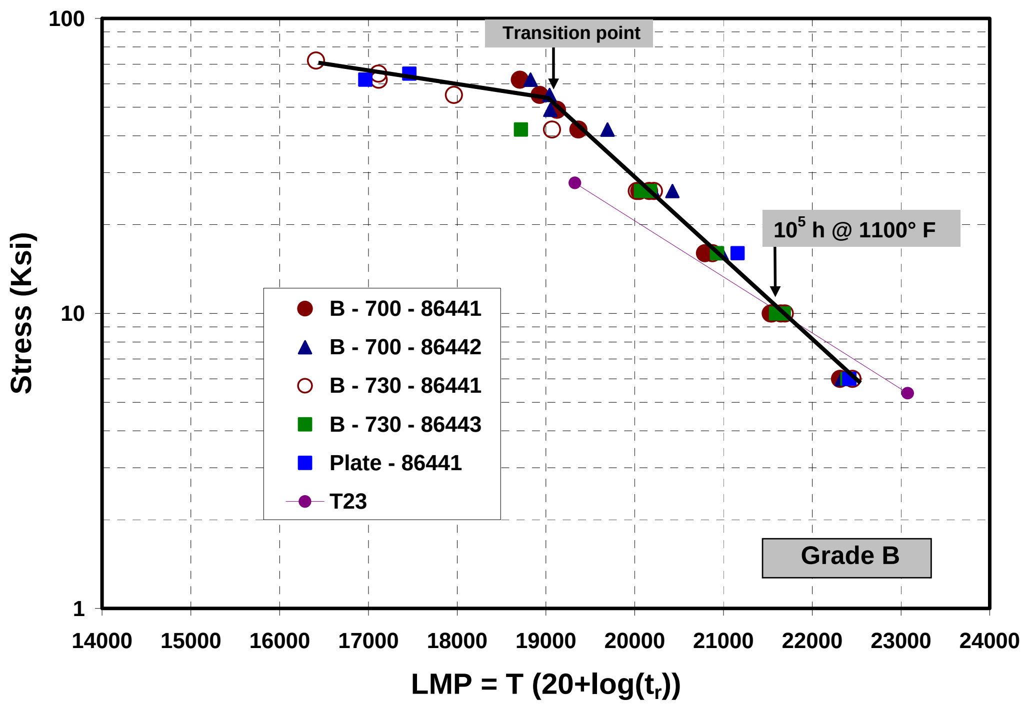


Fig. 4.41. Comparison of Larson-Miller plot for three commercial heats of Grade B, with average values reported for the commercial grade T23. Note the crossover point in strength at 10^5 h at 1100°F (593°C) between Grade B and T23.

The LMP plots of average values of creep-rupture strength for Grades A and B are compared in Fig. 4.42. As can be seen, Grade B has higher creep-rupture strength than Grade A. For LMP values corresponding to 10^5 h rupture at 1100°F (593°C), Grade B falls slightly below Grade A. This is again considered the effect of test temperature on oxidation and a corresponding reduction in creep-rupture strength. All tests on Grade A were at temperatures ≤1200°F. For Grade B, several tests were carried out at 1300°F (704°C).

Creep-rupture elongation and reduction of area for A and B are plotted as a function of LMP in Figs. 4.43–4.46. These figures show the data for all test temperatures and stresses for which creep rupture has already occurred. The following observations can be made on the basis of the data shown in these figures:

- **Grade A.** Creep-rupture elongation for most tests was more than 10% for all test conditions (Fig. 4.43). Two data points fell below 10%, but no detailed analysis is available to explain the cause for the observed values of 6 and 7%. Similarly to the case of total elongation (Fig. 4.44), the reduction of area values for most tests was over 40%, with the exception of three tests between 15 and 25%.

- **Grade B.** The total elongation values for Grade B were mostly over 10% (Fig. 4.45). However, four very-high-stress tests at 1000 and 1100°F (538 and 593°C) showed low values of 1.5 to ~5%. The low values were only for tests on material tempered at 1292°F (700°C). No values for tempering at 1345°F (730°C) fell below 10%. The reduction of area values for Grade B (Fig. 4.46) was typically over 40%. Only five tests showed lower values, ranging from 4 to ~18%. All of these tests were for a tempering temperature of 1292°F (700°C). The reduction of area values for all tests after a tempering temperature of 1345°F (730°C) was over 40%.

In general, the observed elongation and reduction of area values for Grades A and B are considered acceptable.

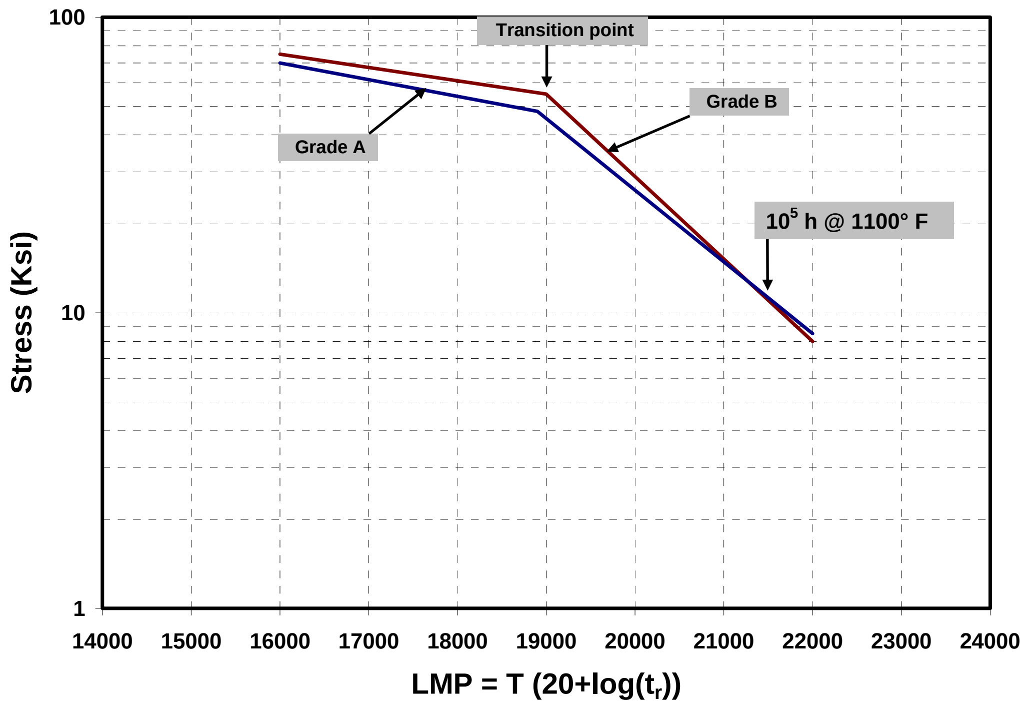


Fig. 4.42. Comparison of average values of creep-rupture strength of Grades A and B.

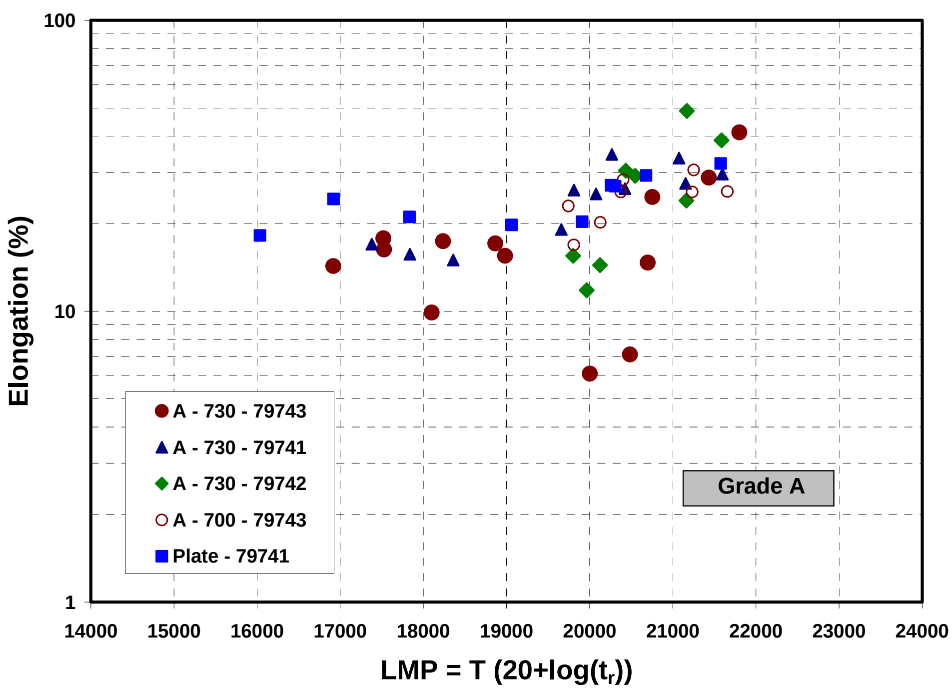


Fig. 4.43. Creep-rupture elongation for creep tests carried out on three commercial heats of Grade A. Data are included for specimens tested after tempering temperatures of 1292 and 1345°F (700 and 730°C).

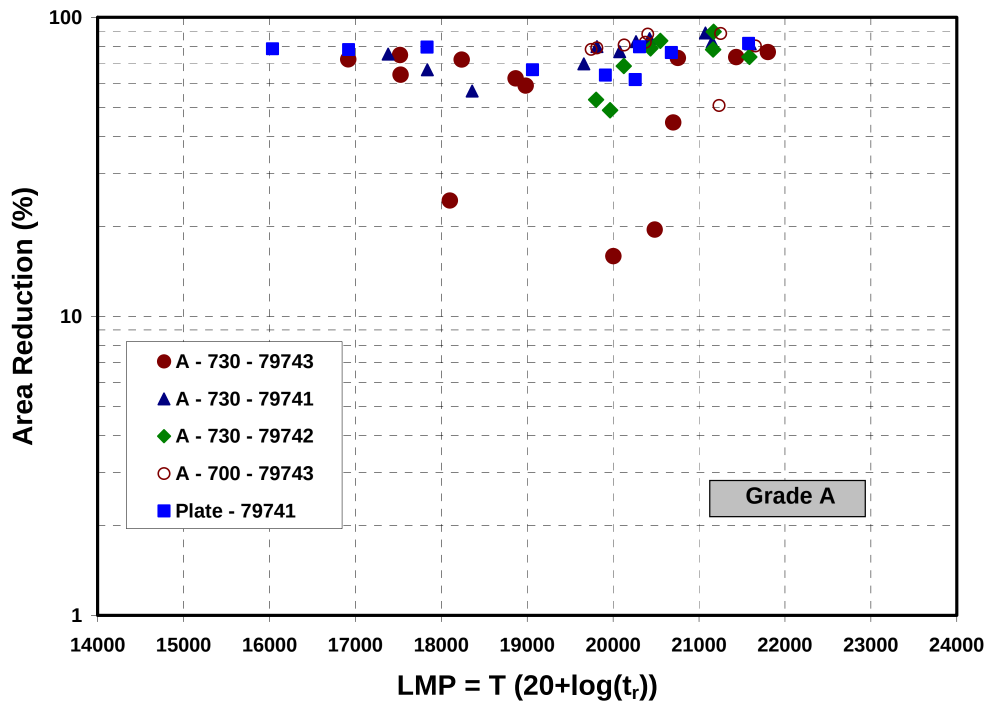


Fig. 4.44. Reduction of area for creep tests carried out on three commercial heats of Grade A. Data are included for specimens tested after tempering temperatures of 1292 and 1345°F (700 and 730°C).

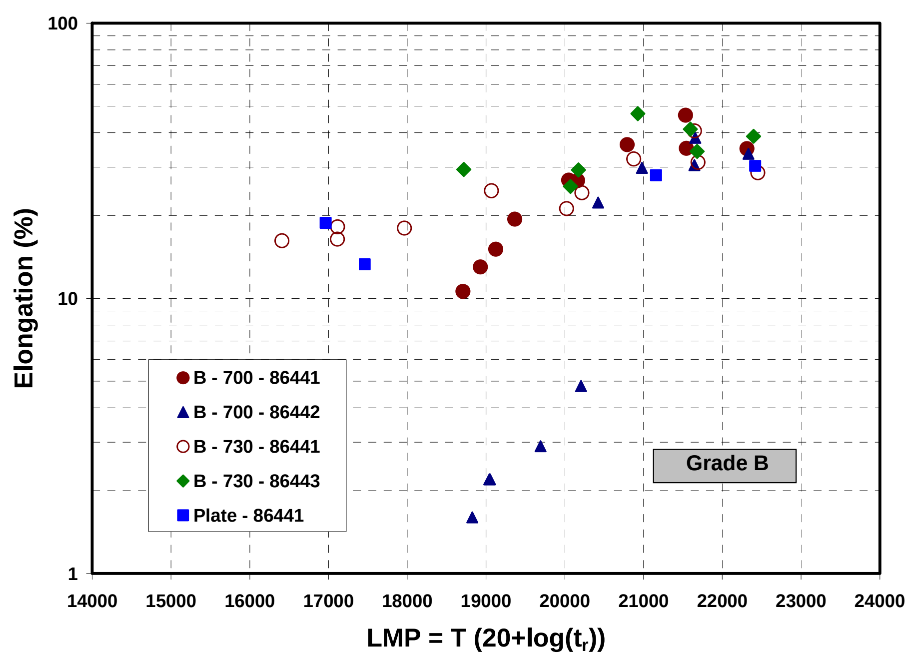


Fig. 4.45. Creep-rupture elongation for creep tests carried out on three commercial heats of Grade B. Data are included for specimens tested after tempering temperatures of 1292 and 1345°F (700 and 730°C).

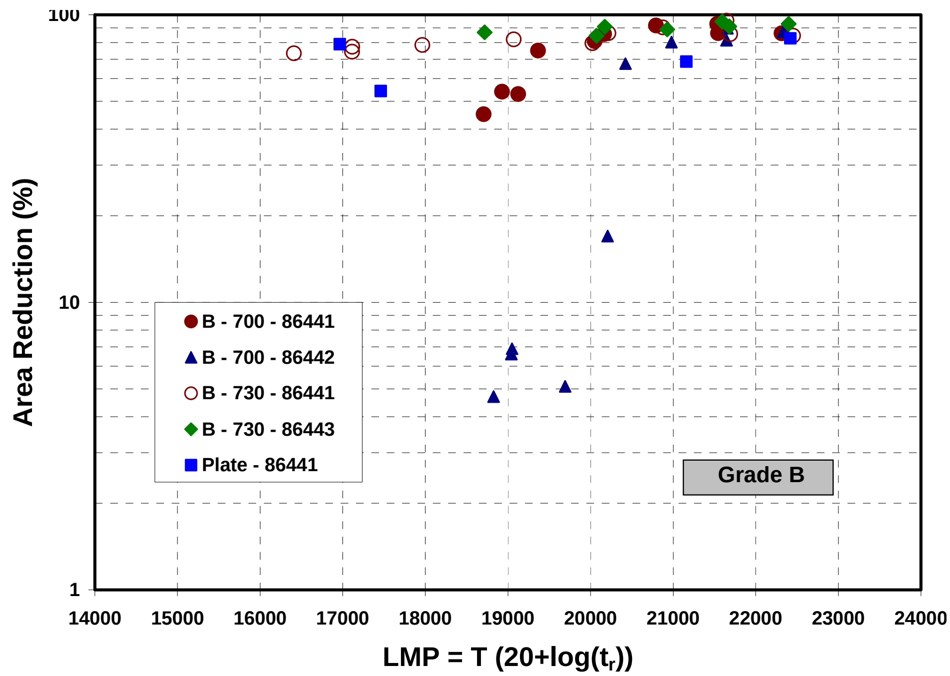


Fig. 4.46. Reduction of area for creep tests carried out on three commercial heats of Grade B. Data are included for specimens tested after tempering temperatures of 1292 and 1345°F (700 and 730°C).

4.7 Weld and Weldment Properties

The most common welding processes used in equipment manufacturing are SA, GTA, and SMA. Of these three processes, SA welding has the highest deposition rate and, thus, is used most in the fabrication of thick-section components. A comparison of the production rate for the SA and GTA processes is shown in Fig. 4.47. For a plate of the same thickness, the SA weld required only 4 passes, while the GTA weld required 14. Other characteristics differentiating the three types of welds include the following:

1. The SA process uses a flux during welding. This process is used for high-production rates.
2. GTA welding uses argon or another inert gas as cover gas. This process is used for specialty welds.
3. The SMA weld uses filler wire coated with a flux similar to the SA process. The SMA process is used for manual welding in cases where the automated SA and GTA processes cannot be used.

One focus of this project was to determine the filler wire composition that would yield acceptable Charpy-impact properties without requiring PWHT. This study was carried out for GTA and SA welds. Data and progress made in each case are discussed in the following sections.

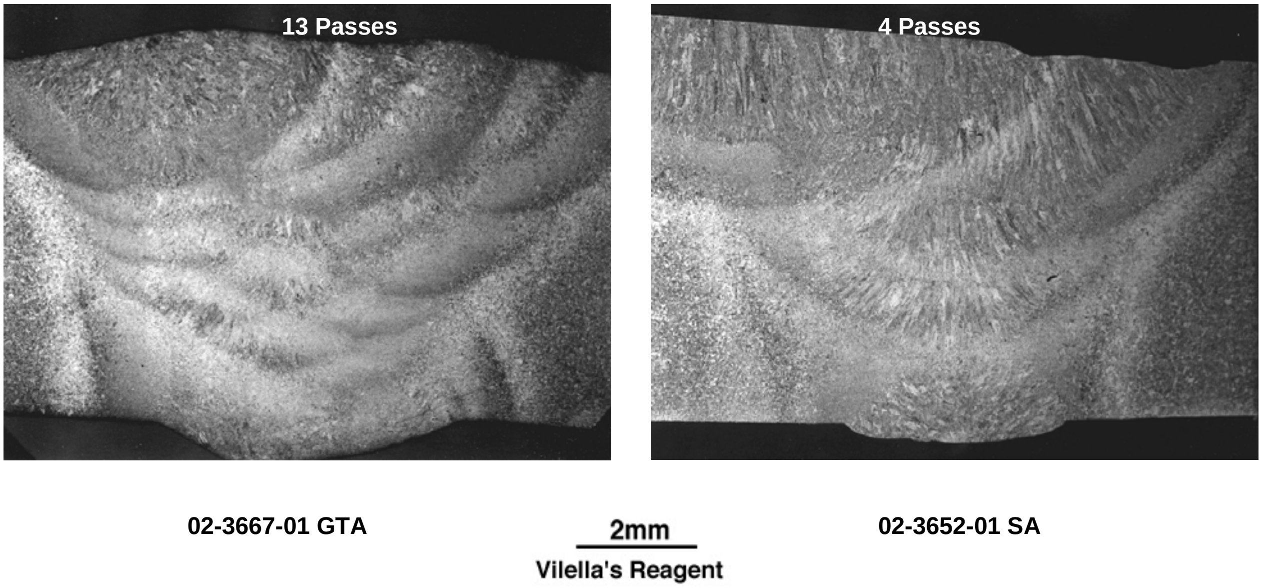


Fig. 4.47. Macrostructure of gas-tungsten-arc (GTA; left) and submerged-arc (SA; right) welds. Note that the SA weld used only one-third the number of passes of the GTA weld.

4.7.1 GTA Welds

Table 4.9 lists the impact properties of GTA welds made in different base metals and with different filler wire compositions. The Charpy-impact data are at room temperature and −40°F. The values for weld and base metal are compared in Table 4.9 and Fig. 4.48.

Table 4.9. Comparison of base metal and gas-tungsten-arc weld impact values (ft-lb)

		Room temperature [a]		−40°F [a]	
Weld ID	Weld type	N	N/T	N	N/T
18687	Base metal	84	124	36	32
18687	GTA[b]	196		172	
18707R2	GTA	118		19	
18692	Base metal	35	105	16	39
18692	GTA[b]	73		16	
18695	Base metal	45	167	36	35
18695	GTA[b]	115		32	
10293	Base metal	39[c]	103	27[c]	5
10293	GTA[b]	29		15	
10293	GTA[d]		184		124

[a] N = normalized; N/T = normalized and tempered.
[b] As-welded data.
[c] Quenched data. All other data are normalized.
[d] Postweld heat-treated at 1292°F (700°C) for 1 h.

Figure 4.48 shows that there are two ways to achieve exceptional impact properties in GTA welds. In the first case, use of a PWHT of 1292°F (700°C) can result in significant improvement in impact values at room temperature (RT) and −40F. In the second case, the filler wire composition can be modified. This was done by using a solid filler wire of heat 18687, which resulted in Charpy-impact properties similar to those obtained in welds that were given PWHT. The chemical analysis of the base and filler wires used for GTA welding is presented in Table 4.10.

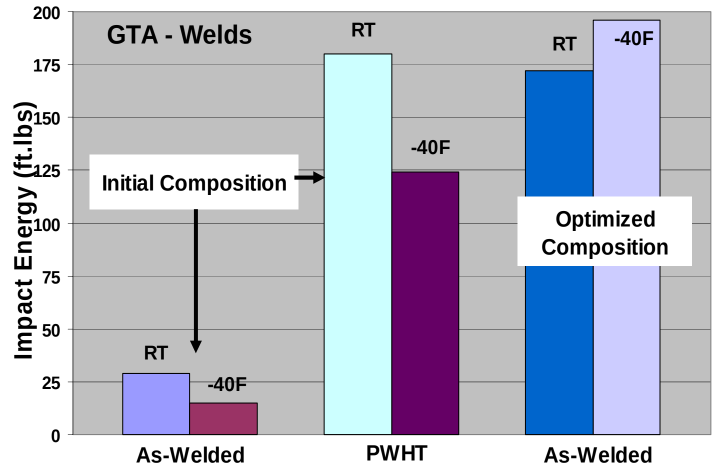


Fig. 4.48. Charpy-impact properties of gas-tungsten-arc welds made with filler wire that requires no postweld heat treatment.

Table 4.10. Chemical analysis of base metal and filler wire compositions used for gas-tungsten-arc welding (wt %)

Element	18687	18692	186595	10293	GTA weld 18687	Weld wire 18707-R2	GTA weld 18692	GTA weld 18695	GTA deposit 10293
C	0.07	0.11	0.095	0.1	0.052	0.1	0.082	0.081	0.058
Mn	0.2	0.29	0.33	0.39	0.2	0.47	0.28	0.34	0.37
P	0.008	0.006	0.008	0.01	0.006	0.006	0.005	0.007	0.004
S	0.005	0.007	0.006	0.004	0.005	0.006	0.006	0.005	0.004
Si	0.21	0.23	0.2	0.16	0.24	0.21	0.26	0.22	0.15
Ni	1	1.13	0.5	0.01	1	2.11	1.12	0.5	0.01
Cr	3.03	3.36	3.03	3.04	3.07	3.01	3.33	3.01	2.92
Mo	0.78	0.84	0.74	0.01	0.77	0.74	0.84	0.75	0.08
V	0.25	0.26	0.23	0.21	0.25	0.23	0.26	0.24	0.23
Cb	0.002	0.005	0.002	0.003	0.003	0.002	0.006	0.003	<0.01
Ti	0.003	0.003	0.003	0.001	0.003	0.003	0.003	0.003	0.003
Co	0.008	0.008	0.006	0.005	0.007	0.009	0.008	0.006	0.008
Cu	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01
Al	0.004	0.002	0.002	0.003	0.004	0.003	0.005	0.002	0.004
B	0.001	<0.001	<0.001	0.001	0.001	0.001	<0.001	<0.001	0.001
W	1.56	1.74	1.54	3.05	1.54	1.52	1.73	1.53	2.84
As	0.001	0.001	0.002	0.001	0.002	0.002	0.003	0.001	<0.001
Sn	0.002	0.003	0.002	0.003	0.002	0.002	0.003	0.003	0.003
Zr	<0.001	<0.001	0.001	0.001	<0.001	<0.001	0.001	0.001	<0.001
N	0.001	<0.001	<0.001	0.004	<0.001	<0.001	0.001	<0.001	0.012
O	0.003	0.003	0.001	0.005	0.002	0.001	0.005	0.001	0.007

4.7.2 SA Welds

The optimization of filler wire compositions that would allow acceptable Charpy-impact properties of 15 ft-lb of energy and 15 mils lateral expansion at room temperature for SA welds without PWHT was challenging because this welding procedure results in an oxygen content in the weld of nearly ten times that observed for the base metal or GTA welds. A significant effort in this area yielded progress in improving the Charpy properties of SA welds without requiring PWHT, as shown in Figs. 4.49 and 4.50. The results shown in Fig. 4.49 are for Charpy-impact properties at room temperature. These data show that the initial filler composition, which is the same as base metal, results in low-impact properties without PWHT; these properties are significantly improved with a PWHT at 1292°F (700°C). The composition of the initial filler wire led to further optimization so that the Charpy-impact properties of energy and mils lateral expansions could be met without PWHT.

The data graphed in Fig. 4.49 show the progress made in meeting the Charpy-impact property requirements through three incrementally improving filler wire compositions. Filler wire composition-III resulted in impact properties that were nearly three times higher than that of the initial composition and met both the energy and mils lateral expansion requirements of SA welds without requiring PWHT.

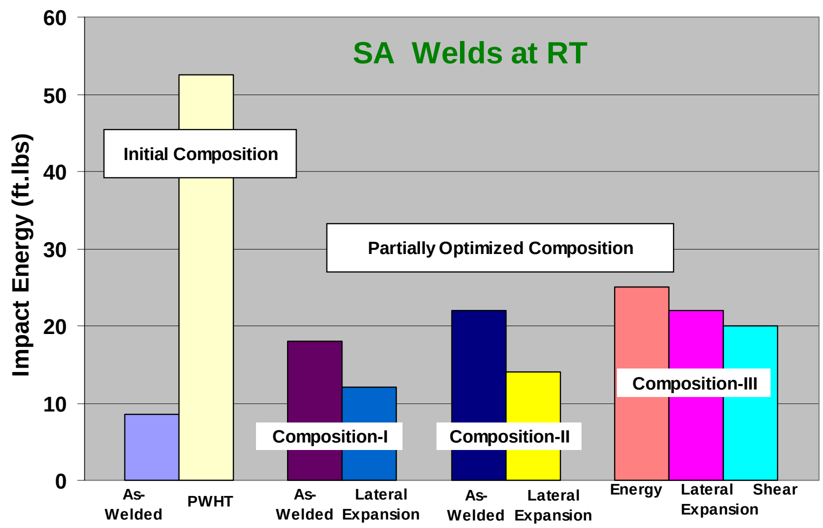


Fig. 4.49. Charpy-impact properties at room temperature (RT) for submerged-arc welds made with various filler wires. Filler wires were used to obtain 15 ft-lb of energy and 15 mil of lateral expansion at room temperature without any postweld heat treatment.

Two of the filler wire compositions that met the Charpy-impact property requirements at room temperature were used to determine the properties at −40°F. Data in Fig. 4.50 at room temperature and at −40°F show that while we could obtain good impact values at room temperature, values at −40°F were less than 10 ft-lb. Tensile properties at room temperature for the weldments made with the filler wires used in Fig. 4.50 are shown in Fig. 4.51. As this figure shows, one of the filler wires, 25A67-10, resulted in failure in the base metal, indicating that the weld made with this wire is stronger than the base metal in the as-welded condition. However, filler wire 25A67-11 resulted in failure in the weld metal, indicating that it is weaker than the base metal. Still, the weldment properties are very impressive, in both cases.

Room-temperature tensile properties of selected GTA and SA welds without PWHT are compared in Table 4.11. Filler wires that resulted in failures in the weld, indicating the weld to be weaker than base metal, generally resulted in acceptable Charpy-impact properties without PWHT. The chemical compositions of filler wires that resulted in acceptable Charpy-impact properties of 15 ft-lb energy and 15 mils of lateral expansion at room temperature are shown in Table 4.12.

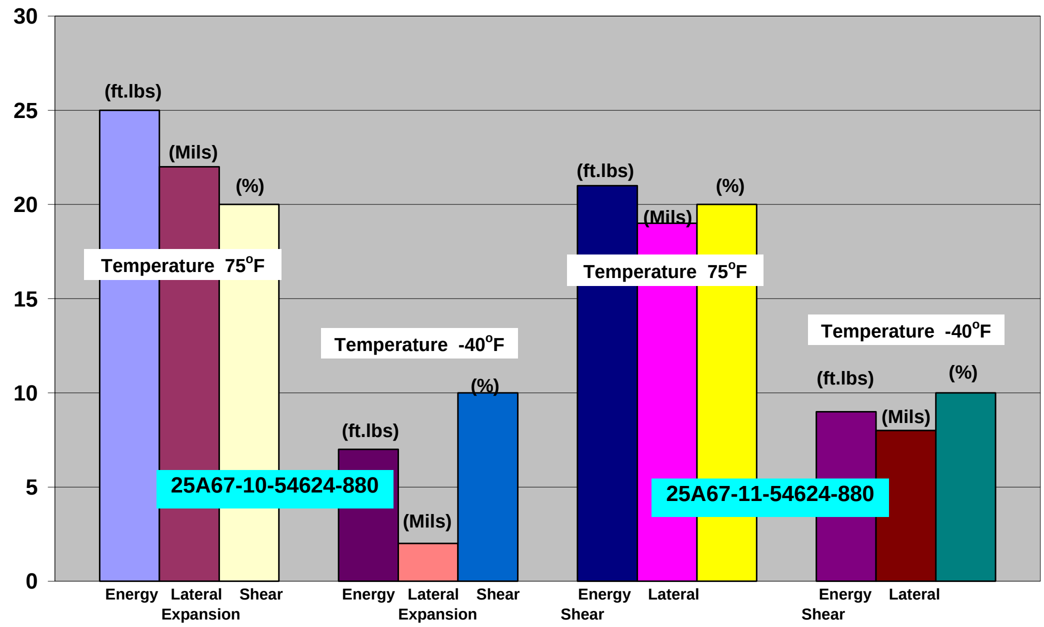


Fig. 4.50. Charpy-impact properties at room temperature and −40F for submerged-arc welds made with two filler wires that exceed the criteria of 15 ft-lb of energy and 15 mil of lateral expansion without requiring postweld heat treatment.

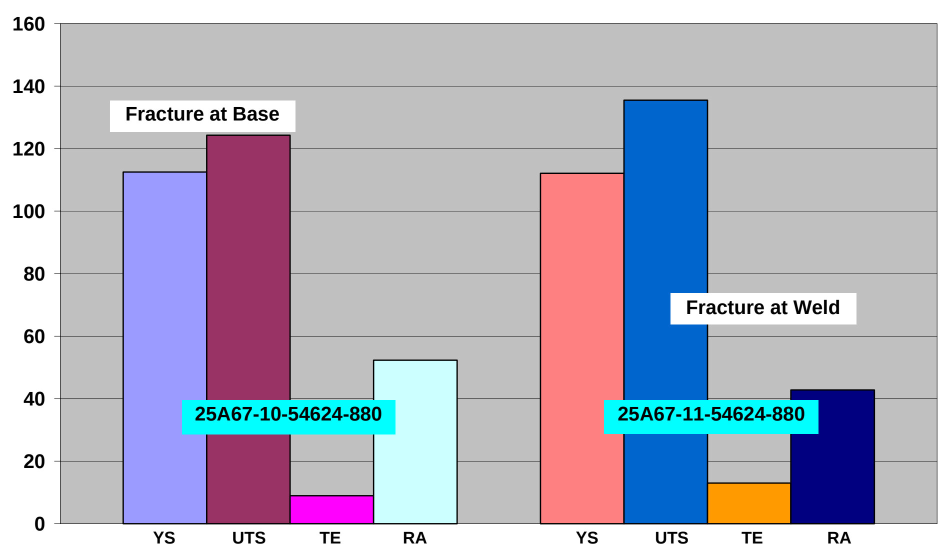


Fig. 4.51. Comparison of tensile properties and fracture locations for submerged-arc welds that met the Charpy-impact requirements without postweld heat treatment.

Table 4.11. Comparison of base metal and weldment tensile properties at room temperature for gas-tungsten-arc and submerged-arc welds without postweld heat treatment

		Strength (ksi)		Percent		
Weld ID	Weld type	Yield	Ultimate tensile	Elongation	Reduction	Failure location
18718	Base metal	129.9	144.6	16.7	74.4	Base metal
18718/ 18707R2	GTA[a]	119.8	134.1	13.3	70.8	Weld metal
10293	Base metal	120.0	156.0	16.0		Base metal
10293/ 10293/ 420TTR	SA[a]	138.0	145.0	14.5	47.6	Base metal
18718	Base metal	129.9	144.6	16.7	74.4	Base metal
18687/ 18660/880	SA[a]	120.3	132.6	12.9	16.0	Weld metal

[a]As-welded condition.

Table 4.12. Chemical analysis of two base metal plates and the submerged-arc weld deposits made with matching fill 10293 and filler wires 25A67-10 and 25A67-11

	Base Metal		SAW Deposit		
Element	54624	10293	54624/ 25A67-10/ 880	54624/ 25A67-11/ 880	10293/ 10293/ 420TTR
C	0.093	0.1	0.025	0.027	0.091
Mn	0.24	0.39	0.63	0.62	0.57
P	0.012	0.01	0.009	0.008	0.004
S	0.01	0.004	0.009	0.009	0.003
Si	0.21	0.16	0.33	0.33	0.2
Ni	1.02	0.01	0.99	0.99	0.01
Cr	3.33	3.04	2.63	2.56	2.85
Mo	0.75	0.01	0.69	0.46	0.01
V	0.24	0.21	0.027	0.029	0.22
Cb	0.007	0.003	—	—	<0.01
Ti	0.027	0.001	—	—	0.005
Co	0.009	0.005	—	—	0.008
Cu	0.020	0.01	—	—	0.01
Al	0.001	0.003	—	—	0.016
B	<0.001	0.001	—	—	0.001
W	1.61	3.05	1.32	1.37	2.98
As	0.001	0.001	—	—	<0.001
Sn	0.002	0.003	—	—	0.003
Zr	<0.001	0.001	—	—	<0.001
N	0.002	0.004	0.009	0.1	0.002
O	0.003	0.005	0.08	0.08	0.029
Ta	<0.01	—	—	—	<0.01

4.7.3 GTA, SA, and SMA Welds and Properties

It was recognized that the GTA welds result in exceptional properties without PWHT and, thus, could be used without PWHT. Although it was demonstrated that acceptable Charpy-impact properties could be obtained for SA welds without PWHT, the project team decided that for consistently acceptable properties, SA welds should be given PWHT. Since SMA welds produce welds of high oxygen composition similar to the composition of the SA welds, SMA welds should also undergo PWHT.

During this project, we also used a neural network-based model for identifying the effects of composition and PWHT on the properties of welds. This model is an extremely useful tool and is described in Appendix C.

A detailed report on the welding and property status of GTA, SA, and SMA welds was recently prepared and is included as Appendix E in this report. This report also makes recommendations for the final filler wire composition that can result in an optimum combination of impact, tensile, and creep properties. The optimum filler compositions have been prepared by Stoody Company and are currently being tested.

5. Accomplishments

This project has accomplished the technical, technology transfer, and commercialization goals described below.

5.1 Technical Goals

A new class of Fe-3Cr-W(V) steels (designated as Grades A and B) were developed during this project. Grade A, which was studied in greater detail, exceeded the goals of the project for its strength, toughness, and PWHT requirements during welding. Both Grades A and B were scaled up to commercial-size heats of 50 tons each and processed commercially into forgings, plate, and tubing. Both alloys were characterized for their mechanical properties, including tensile strength, Charpy-impact toughness, and creep strength. However, we obtained more creep data for Grade A than for Grade B.

Both grades were tested for their response to common welding methods (GTA, SA, and SMA). Grade A was investigated in great detail for weld and weldment properties.

All of the technical goals were met through the efforts of the project team.

5.2 Technology Transfer

The technology of new Fe-3Cr-W(V) steels developed in this project was transferred to industry. Two mechanisms were used:

1. The project team consisted of steel producers; producers of products such as forgings, plate, and tubing; a welding wire producer; component and pressure vessel fabricators; and users. The team partners actively participated in all aspects of this project and thus acquired significant knowledge of the newly developed steels in this project.
2. The technology transfer beyond the team partners was accomplished through presentations at DOE annual project review meetings, three presentations at national and international technical meetings, and publication of two technical papers in conference proceedings. Further technology transfer was accomplished through presentations by industrial partners at certain committee meetings such as ASTM and presentations of data on the new steels to their customers.

5.3 Publications and Patents

Publications from this project are listed below. These publications are reproduced in full in Appendix B of this report. Key presentations from this project are included in Appendix C of this report.

1. V. K. Sikka, R. L. Klueh, P. J. Maziasz, S. Babu, M. L. Santella, M. H. Jawad, J. R. Paules, and K. E. Orie, “Mechanical Properties of New Grades of Fe-3Cr-W Alloys,” pp. 97-106 in *Experience with Creep-Strength Enhanced Ferritic Steels and New and Emerging Computational Methods,* PVP-Vol. 476, ASME, New York, 2004.

2. V. K. Sikka, "High-Strength Fe-3Cr-W(Mo) Steel for Petrochemical Applications," in *Proceedings of 2004 NPRA Maintenance Conference* (published as conference proceedings CD) May 25–28, 2004, San Antonio, Texas.
3. Kenneth Orie, "Mechanical Property Evaluation of New Fe-3Cr-Mo-W(Ta) Steel," ISG Plate, Coatesville, Penn., March 26, 2004.
4. Standard Specification for Pressure Vessel Plates, Alloy Steel, Chromium-Tungsten-Molybdenum-Vanadium and Chromium-Tungsten-Molybdenum-Vanadium-Tantalum, submitted by Ken Orie at ISG Plate to ASTM for approval, May 2004.

In addition to publications and presentations, two patent disclosures were made as a result of this project. These patent disclosures are listed below.

1. A new invention disclosure (ID 1156, S-99,347) entitled "Improved Cr-W-V Bainitic/Ferritic Steel Composition" was filed on September 19, 2002.
2. The invention (ID 1156C), retitled "CR-W-V Bainitic/Ferritic Steel Compositions," has been filed in the U.S. Patent Office and foreign (PCT), December 16, 2003.

5.4 Commercialization

Significant progress towards commercialization of the new steels developed in this project was made through the following steps:

1. Obtained approval of specifications in ASTM for both Grades A and B
2. Made progress toward obtaining ASME Pressure Vessel and Boiler Code approved design-allowable stresses for Grade A by submitting its comprehensive mechanical properties data package to the code committees
3. Retained Dr. Maan Jawad as a consultant to the project for participating at the ASME Code Committee Review meetings to answer any questions that might arise during deliberations
4. Ensured further commercialization through visits by Dr. Jawad to various companies and by making their system design engineers familiar with the advantages of using the new steels

6. Summary and Conclusions

6.1 Summary

This project developed a new class of Fe-3Cr-W(V) ferritic steels for chemical processing equipment such as hydrocrackers, hydrotreaters, and heat recovery systems. The key property targets for the new steels were (1) 50% higher tensile strength at temperatures up to 932–1112°F (500–600°C) than currently available materials in the class; (2) a potential for not requiring PWHT for certain welding processes; (3) a reduction in equipment weight by 25%; and (4) resulting impact properties of approximately 100 ft-lb of upper shelf energy and a DBTT of −10°F. The competing commercially available alloys in this class include the widely used 2.25Cr-1Mo steel (also known as Grade 22) and the recently available Grades T23 and T24.

The research and development work was conducted by a team consisting of chemical and petrochemical companies (ExxonMobil Chemical Company, BP Amoco, and DuPont); materials producers (ISG Plate, Ellwood Materials Technologies Company, Plymouth Tube Company, and Ellwood National Forge); a component fabricator and welding process developer (Nooter Fabrication Services Inc.); a weld wire producer and process developer (Stoody Company); a heat recovery unit construction company (Nooter-Eriksen); and a national laboratory (ORNL). Industry participated by (1) identifying reactor vessels and other components that can take advantage of the new steel, (2) testing components, (3) assisting in conducting production-size heats of the new steel, (4) assisting in component fabrication and process development, and (5) developing the welding process. Welding wire suppliers produced small batches of wire for trials by Nooter and ORNL. Industry representatives also provided guidance and direction to the project through active participation in identifying and monitoring project deliverables and in writing technical progress reports.

The project identified two compositions with Fe-3Cr-W(V) as the base. These compositions were designated as Grades A and B, sometimes referred to as Grades 315 and 315T. Grades A and B differ only in that the latter contains 0.10 wt % Ta. Both grades were scaled up to commercial heats of 50 ton each. Ingots from both heats were processed (using commercial practice) into forgings, plate, and tubing.

Detailed mechanical property characterization was carried out on both Grades A and B. The most expensive of the mechanical tests was creep strength testing. Because of the budget constraints, the long-term creep strength tests are continuing on Grade A only. A significant effort was devoted to the development of the welding process and weldment properties for the new steel. The steel compositions and mechanical properties database were used to prepare data packages for obtaining ASTM specifications and ASME code approvals for the new steels.

6.2 Conclusions

The following are the important conclusions from this project:

1. Through this project, an industry-ORNL team has developed two U.S. versions of high-strength steels based on Fe-3Cr-W(V) composition (Grades A and B). Grade B has higher creep strength than Grade A, but its higher strength comes through the addition of 0.1 wt % Ta, which adds to the cost of the alloy.

2. The newly developed Grade A steel, which was investigated in more detail than Grade B, showed the attributes described in Table 6.1, as compared with the commonly used 2.25Cr-1Mo steel and a recent high-strength version from Japan known as T23:

Table 6.1. Comparison of the new Grade A steel composition with two commercial steels

	Comparison of Grade A Fe-3Cr-W(V) steel with	
Property	2.25Cr-1Mo steel	T23 steel
Yield strength at room temperature	60% higher	25% higher
Yield strength at high temperatures	110% higher at 900°F (482°C)	45% higher at 1110°F (600°C)
Tensile strength at room temperature	50% higher	33% higher
Tensile strength at high temperatures	50% higher at 900°F (482°C)	33% higher at 1110°F (600°C)
Charpy-impact upper shelf energy	*a*	*a*
Ductile-to-brittle transition temperature	*b*	*b*
Creep-rupture strength	—	35% higher for 10^5h at 932ºF (500ºC) Same for 10^5h at 1100ºF (590ºC)

[a]Values of upper shelf energy in the range of 50 to 100 ft-lb. No comparable data available.
[b]Ductile-to-brittle transition temperature of −20 to −40ºF. No comparable data available.

3. Grade B steel, investigated less detail than Grade A, showed the following attributes:

   a. Tensile property improvements were similar to those described for Grade A.
   b. Impact properties were similar to the impact properties of Grade A.
   c. Grade B showed 10–20% higher creep rupture strength than Grade A for conditions causing rupture in 10^5 h at temperatures ≤1100°F (593°C). However, for higher test temperatures, Grade B had a slightly lower creep-rupture strength than Grade A.
   d. Limited welding trials with Grade B showed no unusual problems. We anticipate that the weld wire for this grade of steel will require a higher tantalum content in order to obtain the target value.

4. Grades A and B have been shown to be scalable to 50-ton heats by standard electric furnace melting techniques. Furthermore, both grades can be processed by commercial methods to forgings, plate, and tubing.
5. The new steels are used in normalized and tempered (N/T) conditions. The N/T treatment consists of austenitizing at 2012°F (1100°C), followed by air cooling to room temperature and tempering at 1345°F (730°C).
6. A significant number of creep tests at temperatures ranging from 900 to 1300°F (482 to 704°C) were conducted on both grades. Several creep tests exceeding 5000 h have been conducted for Grade A. Long-term creep testing of Grade B was discontinued because of lack of funds.
7. Alloy composition, heat treatment, and tensile property data on Grades A and B were used to obtain their ASTM specifications. Both grades are included in ASTM Specification A1041-04. This is the first step in making newly developed steel grades available for recommendation by equipment designers for the construction of chemical processing equipment.

8. A detailed mechanical property database on Grade A was compiled and submitted to ASME Pressure Vessel and Piping Code committees. This package will be used to establish the design-allowable stresses for the new steel. This is the second step in making the newly developed steel available for recommendation by the equipment designers for the construction of chemical processing equipment.
9. Commercial use of the new steels requires introducing them to potential users. This was accomplished through presentations about the new steels at national technical meetings sponsored by ASME, ASM International, and others. Part of the commercialization will also occur because steel producers, welding wire producers, component and system fabricators, and steel users were part of this project.

6.3 Commercialization Aspects (Plans, Status, Barriers)

A plan that identified steps needed for commercialization of the new steels was developed. The steps identified were (1) getting specifications of the new steels approved in ASTM, (2) getting ASME Pressure Vessel and Boiler Code–approved allowable-design stresses for the new steels, (3) making systems designers familiar with the properties of the new steels so that they can be specified as a material of choice, and (4) providing test material and welding filler for fabricators to become familiar in the use of the new steels.

Progress made towards the commercialization was as follows:

1. Both Grades A and B were approved for inclusion in ASTM specifications. The new alloys are listed in Specification A1041-04.
2. Design-allowable stresses for the alloy have to be set by ASME Boiler and Pressure Vessel Code committees. Setting of the design allowables by ASME requires the submission of a detailed mechanical properties data package for review and analysis by the code committees. The data package for the advanced alloy developed in this study was submitted in August 2004 (see Appendix A). Typically, 12 to 24 months are needed for code bodies to review all of the information and perform analysis to set the design-allowable stresses. In order to expedite the ASME code approval process, we have subcontracted Dr. Maan Jawad of Global Engineering (previously with Nooter Corporation) to actively pursue the process by participating in ASME Code Committee meetings on a regular basis and responding to any questions that may be asked.
3. New alloys need to be specified by equipment designers. In addition to obtaining approvals from ASTM and ASME code, a parallel activity is needed to educate equipment designers about the benefits of the new alloy. This activity was partially accomplished by presenting papers at technical conferences and having the industrial partners of this project share information on the new alloy within their companies (for the users) and with their customers (for the alloy producers). We are also relying on our consultant, Dr. Jawad, to further this cause by visiting individual companies and making presentations about this alloy. Because of his design background at Nooter Corporation and his familiarity with both chemical and heat recovery systems, we anticipate that his involvement will further reduce the time until the new alloy is in commercial use.
4. In addition to approvals by ASTM and ASME, and designers specifying the new alloy as material of choice, it has to be commercially available at a competitive price in various product forms (forgings, plate, tubing, and piping). Furthermore, the welding consumables such as filler wire, flux, and electrodes need to be available commercially. The team members of this project are capable of meeting both of these requirements as they arise. The

component fabricators have been contacting ORNL to receive the plate samples from the newly developed alloy so that they can develop their own procedures for bending, forming, and welding. The plate samples are currently being offered at no cost to U.S.-based companies for their use. Based on these trials, these companies will be ready to build equipment when the need arises.

In summary, all elements essential for commercialization of the new alloy are in place, and further technology transfer is necessary.

7. Recommendations

This project has accomplished nearly all proposed aspects. However, the following is a list of recommendations that can further take advantage of this project:

1. Provide support to continue long-term creep testing of Grade A. These data are essential for obtaining ASME code approval and gaining confidence from users in the long-term stability of the new steels.
2. Provide support to initiate the creep tests on Grade B.
3. Provide support for installing components from the new steel in commercial production conditions. Successful installation and operation under production conditions develops user confidence in trying new steels. One example of this installation could include tubing in heat recovery boilers.
4. Although progress on welding process and filler wire development was made during this project, there is a need to develop a significant amount of mechanical property data on weldment. This effort is needed initially for welds in 2- to 4-in.-thick plates of Grade A and subsequently for welds in Grade B.
5. The welding process also needs to be demonstrated for actual components such as tube-to-tube or tube-to-tube sheet. Again, this is required initially for Grade A, followed by Grade B.
6. In order to be competitive in the global market, the United States needs to stay active in further development of high-strength steels. The new tools of thermodynamic and kinetic modeling and the experience in developing steels in this project will make future developments somewhat easier.

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Appendix A

ASME Code Data Package

ASME Code Data Package

(Second draft)
August 11, 2004

Vinod K. Sikka

Background

This ASME code package is a new grade of FeCrW alloy, designated as Grade 315 by ASTM (specification approval applied for).

The alloy is recommended for applications as chemical reactor vessels, piping and tubing for boilers and heat recovery systems. The alloy is recommended as a higher strength replacement for commonly used Grade 22 (Fe-2.25 Cr-Mo) and recently introduced Grade T23. The current alloy composition was developed at the Oak Ridge National Laboratory and many aspects of scale-up were carried out by companies such as Ellwood Quality Steel, ISG Plate, Stoody Company, and Nooter Corporation.

This package provides the following information:

1. Chemical analysis range and actual analysis of three commercial heats produced of the alloy composition

2. Heat-treatment transformation diagram for the alloy

3. Effect of heat treatment on tensile properties to set the minimum properties

4. Tables of tensile yield properties

5. Tensile and yield property plots as a function of temperature for three commercial heats

6. Stress-strain plots for each test

BC04-1063 **3/93**

Chemical Analysis Specifications

Grade A Chemical Analysis

Heat Nos.	Production Method
79741	Electric Furnace
79742	Electroslag Remelted
79743	Vacuum Arc Remelted

Element	Range	79741	79742	79743
C	0.08-0.12	0.099	0.11	0.11
Mn	0.25-0.45	0.34	0.33	0.25
P	0.01 Max	0.009	0.008	0.008
S	0.01 Max	0.003	0.001	0.001
Si	0.15-0.4	0.21	0.15	0.21
Ni	0.25 Max	0.15	0.15	0.15
Cr	2.8-3.2	2.97	2.95	2.97
Mo	0.65-0.85	0.73	0.74	0.74
V	0.2-0.3	0.22	0.22	0.22
Cb		0.002	0.001	0.002
Ti		0.003	0.003	0.003
Co		0.014	0.013	0.013
Cu		0.11	0.11	0.1
Al		0.008	0.005	0.008
B	0.001 Max	<0.001	<0.001	<0.001
W	1.35-1.65	1.68	1.67	1.68
As		0.005	0.007	0.007
Sn		0.008	0.008	0.008
Zr		<0.001	<0.001	<0.001
N		0.009	0.013	0.004
O		0.004	0.001	<0.001
Ta			<0.001	<0.01

BC04-1063 **5/93**

ASTM Specification Draft

BC04-1063 **6/93**

A 1041-04

To: **ASTM A01.11 Members**

From: **Ken Orie, TG Chairman**

Subject: **New Standard AXXXX/AXXXXM**

WK#: **WK 3558**

Rationale: **New standard providing higher strength Cr Mo W V steel consisting of two grades, one of which contains tantalum.**

Item:

A 1041-04

Standard Specification for

Standard Specification for Pressure Vessel Plates, Alloy Steel, Chromium-Tungsten-Molybdenum-Vanadium and Chromium-Tungsten-Molybdenum-Vanadium-Tantalum[1]

This standard is issued under the fixed designation A XXXX/AXXXM; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification covers chromium-tungsten–molybdenum-vanadium, with or without tantalum, alloy steel plates intended primarily for welded boilers and pressure vessels designed for elevated temperature service.

1.2 Plates are available under this specification in two grades having different alloy contents as follows:

Grade	Nominal Chromium Content, %	Nominal Tungsten Content, %	Nominal Molybdenum Content, %	Nominal Vanadium Content, %	Nominal Tantalum Content, %
315	3.00	1.50	0.75	0.25	
315T	3.00	1.50	0.75	0.25	0.10

1.3 The maximum thickness of plates is limited only by the capacity of the composition to meet the specified mechanical property requirements.

1.4 The specification is expressed in both inch-pound units and in SI units; however, unless the order specifies the applicable "M" specification designation (SI units), the plates are furnished to inch-pound units.

1.5 The values stated in either inch-pound units or SI units are to be regarded separately as standard. Within the text, the SI units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system is to be used independently of the other.

2. Referenced Documents

2.1 *ASTM Standards:*

A 20/A 20M Specification for General Requirements for Steel Plates for Pressure Vessels[1]

A 370 Test Methods and Definitions for Mechanical Testing of Steel Products[2]

A 435/A 435M Specification for Straight-Beam Ultrasonic Examination of Steel Plates[2]

A 577/A 577M Specification for Ultrasonic Angle-Beam Examination of Steel Plates[2]

A 578/A 578M Specification for Straight-Beam Ultrasonic Examination of Plain and Clad Steel Plates for Special Applications[2]

3. General Requirements

3.1 Product furnished to this specification shall conform to Specification A 20/A 20M, including any supplementary requirements indicated in the purchase order or contract. Failure to comply with the general requirements of Specification A 20/A 20M constitutes nonconformance with this specification. In case of conflict between the requirements of this specification and Specification A 20/A 20M, the requirements of this specification shall prevail.

3.2 In addition to the basic requirements of this specification, certain supplementary requirements are available if additional control, testing, or examination is required to meet end use requirements. The purchaser is referred to the listed supplementary requirements in this specification and to the detailed requirements in Specification A 20/A 20M.

4. Materials and Manufacture

4.1 *Steelmaking Practice*—The steel shall be killed and shall conform to the fine austenitic grain size requirements of Specification A20/A20M.

5. Heat Treatment

5.1 Except as allowed by 5.2, all plates shall be normalized at 1950 to 2050 °F [1065 to 1120 °C] and then tempered at 1290 to 1400 °F [700 to 760 °C].

5.2 Plates ordered without the heat treatment required by 5.1 shall be furnished in either the stress-relieved or annealed condition, and the purchaser shall be responsible for the heat treatment of such plates to conform to 5.1.

6. Chemical Composition

6.1 The steel shall conform to the requirements for chemical composition given in Table 1.

7. Mechanical Properties

7.1 *Tension Test*—The plates, as represented by the tension test specimens, shall conform to the applicable requirements given in Table 2.

8. Keywords

8.1 elevated temperature service, creep resistance, high-strength, tantalum, chromium, molybdenum, tungsten, vanadium, pressure vessels, hydrogen service, alloy steel plates

TABLE 1 Chemical Requirements

NOTE—Where ". . . " appears in this table, there is no requirement.

	Composition, %	
Element	Grade 315	Grade 315T
Carbon:		
Heat Analysis	0.08-0.12	0.08-0.12
Product Analysis	0.07–0.13	0.07–0.13
Manganese:		
Heat Analysis	0.25-0.45	0.25-0.45
Product Analysis	0.20-0.50	0.20-0.50
Phosphorus, max:		
Heat Analysis	0.010	0.010
Product Analysis	0.015	0.015
Sulfur, max:		
Heat Analysis	0.010	0.010
Product Analysis	0.012	0.012
Silicon:		
Heat Analysis	0.15-0.40	0.15-0.40
Product Analysis	0.10-0.45	0.10-0.45
Nickel, max:		
Heat Analysis	0.25	0.25
Product Analysis	0.30	0.30

Chromium:		
Heat Analysis	2.8-3.2	2.8-3.2
Product Analysis	2.7-3.3	2.7-3.3
Molybdenum:		
Heat Analysis	0.65-0.85	0.65-0.85
Product Analysis	0.60-0.90	0.60-0.90
Nickel, max:		
Heat Analysis	0.25	0.25
Vanadium:		
Heat Analysis	0.20–0.30	0.20–0.30
Product Analysis	0.18–0.33	0.18–0.33
Boron, max:		
Heat Analysis	0.0007	0.0007
Tantalum:		
Heat Analysis	. . .	0.07-0.13
Product Analysis	. . .	0.06-0.14
Tungsten:		
Heat Analysis	1.35-1.65	1.35-1.65
Product Analysis	1.30–1.70	1.30–1.70

TABLE 2 Tensile Requirements

	Grade 315 and 315T
Tensile Strength, ksi [MPa]	105 to 135 [725 to 930]
Yield Strength, Min ksi [MPa]	85 [585]
Elongation in 2 in. [50 mm], %, Min	16

SUPPLEMENTARY REQUIREMENTS

Supplementary requirements shall not apply unless specified in the order. A list of standardized supplementary requirements for use at the option of the purchaser is included in Specification A 20/A 20M. Several of those considered suitable for use with this specification are listed below by title. Other tests may be performed by agreement between the supplier and the purchaser.

S1 Vacuum Treatment

S2 Product Analysis

S3 Simulated Post-Weld Heat Treatment of Mechanical Test Coupons

S4 Additional Tension Test

S5 Charpy V-Notch Impact Test

S6 Drop-Weight Test (for Plates 0.625 in. [16 mm] Over in Thickness]

S7 High-Temperature Tension Tests

S8 Ultrasonic Examination in Accordance with Specification A 435/A 435M

S9 Magnetic Particle Examination

S11Ultrasonic Examination in Accordance with Specification A 577/A 577M

S12Ultrasonic Examination in Accordance with Specification A 578/A 578M

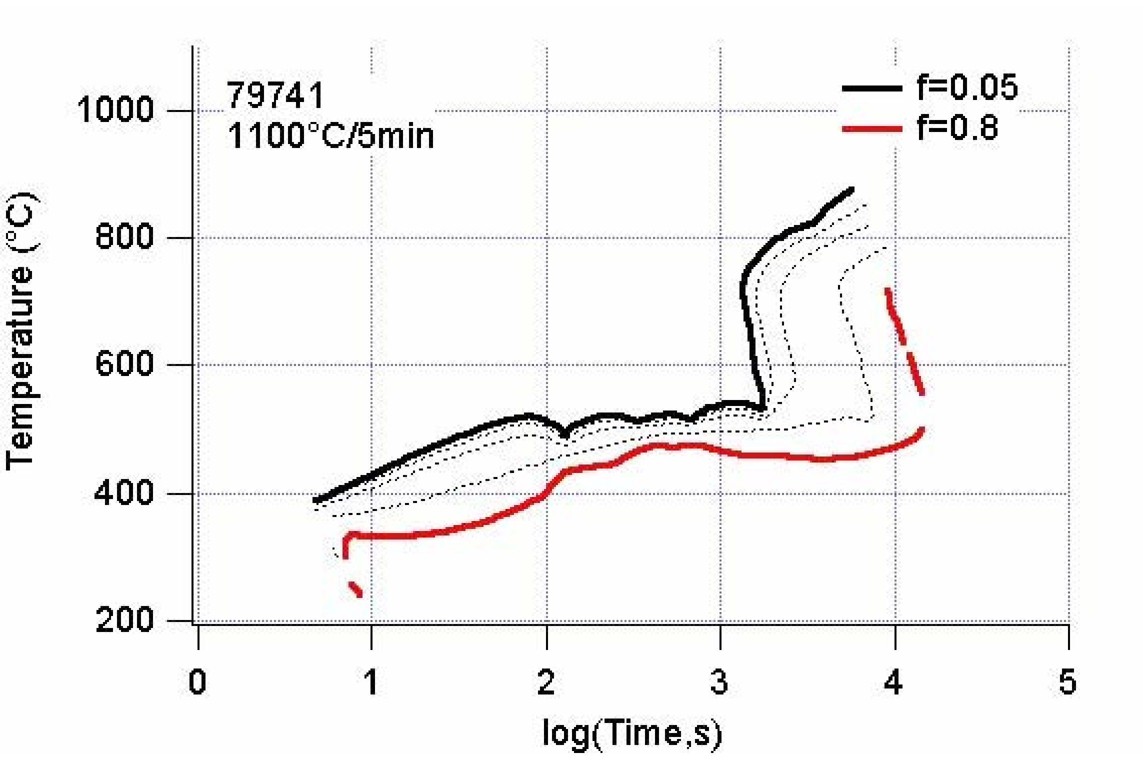
BC04-1063 **11/93**

A 1041-04

Heat Treatment Diagram

A 1041-04

CCT DIAGRAM FOR GRADE 315 (HEAT 79741)

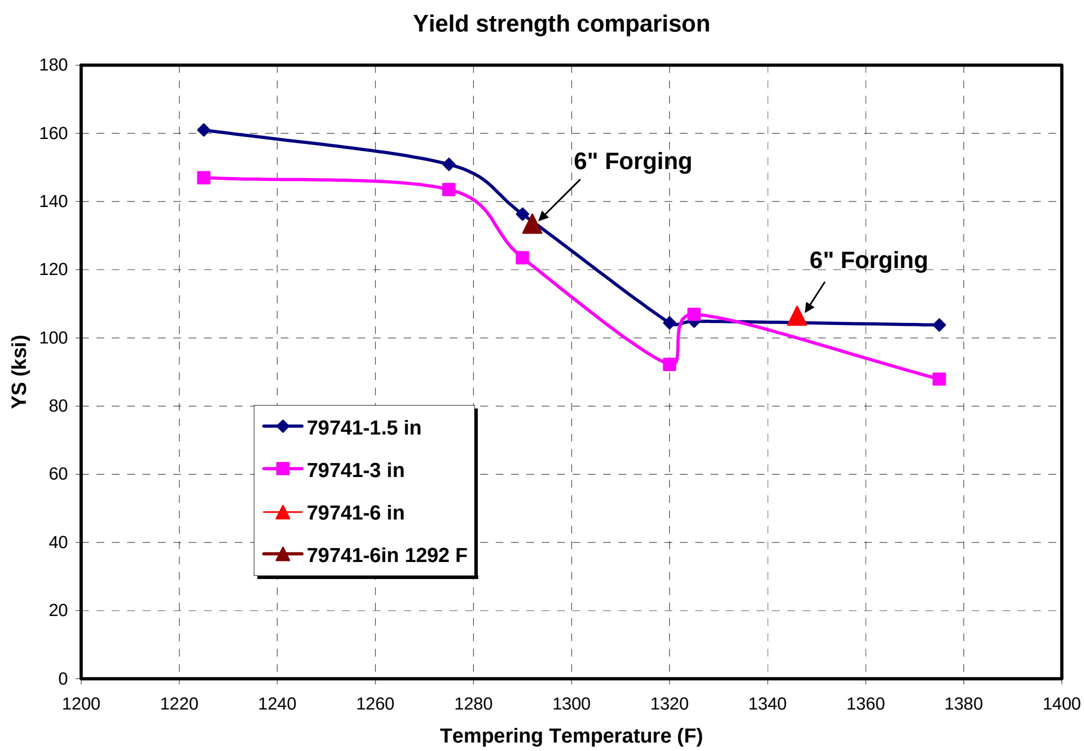


A 1041-04

Effect of Tempering on Room-Temperature Tensile Properties

BC04-1063 **14/93**

A 1041-04



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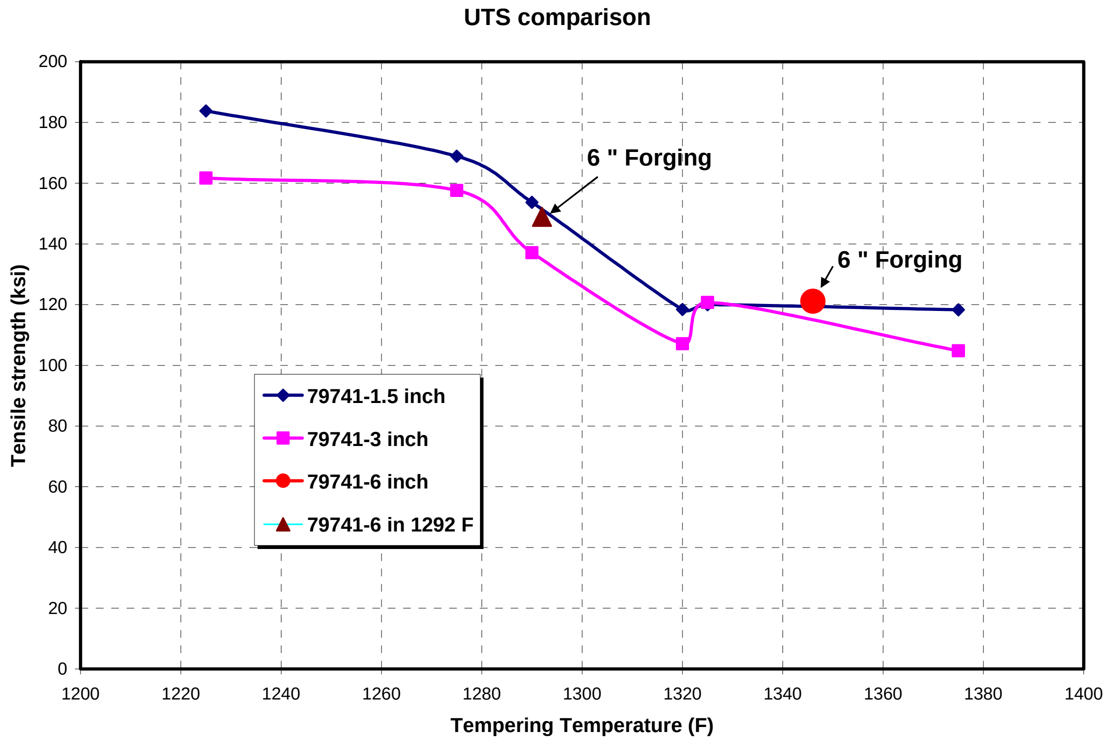
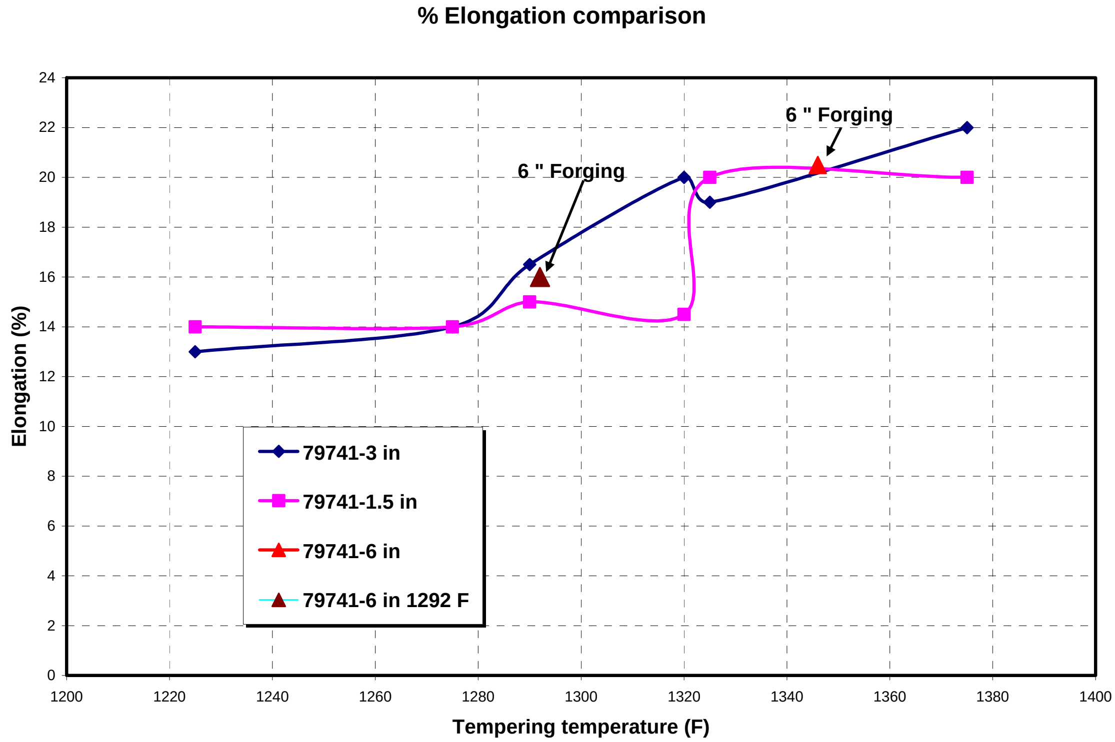

UTS comparison
Tensile strength (ksi)
Tempering Temperature (F)
6 " Forging
6 " Forging
79741-1.5 inch
79741-3 inch
79741-6 inch
79741-6 in 1292 F
200
180
160
140
120
100
80
60
40
20
0
1200
1220
1240
1260
1280
1300
1320
1340
1360
1380
1400

BC04-1063 **16/93**

A 1041-04



A 1041-04

Tensile Properties Data

A 1041-04

7974-1-EF,Tempered at 1346 F
Longitudinal, round,elevated temperature,reduced section tensiles

Test Temp.(°F)	Yield strength (ksi)	Ultimate tensile strength (ksi)	Total elongation (in %)	Reduction in area (%)
70	104.6	120	20.5	66.8
70	106.5	121.1	20	68.2
200	106.6	118.7	20	67.5
400	104.2	114.9	21	68.8
600	98.9	107.4	19	66.6
800	94.5	102.7	16.5	61.5
900	92	99.7	16.5	60.8
1000	89.3	97.3	15.5	61.7
1100	79.4	81.4	20	74.1
1200	78.9	80.4	18	76
1300	57.3	60.6	22	78

A 1041-04

Heat No. **7974-2**
Heat Treatment Normalised/Tempered @ 1346 F/ 1 hr
Specimen Longitudinal

Specimen ID	Test temperature (ºF)	Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Total Elongation (%)	Reduction in area (%)
1	70	116.9	137.4	19	57.1
6	70	120	137.4	19	57.7
2	200	118.7	134.5	18.5	56.6
3	400	116	129.7	17	51
4	600	111.7	123.4	13	34.7
5	800	102.1	114.6	15	46.3
7	900	101.5	107.9	18	58.9
8	1000	94.8	104.3	17.5	59.4
9	1100	93.1	99	18	64
10	1200	79.7	86.3	15	48.1
11	1300	62.6	67.1	17	53.3

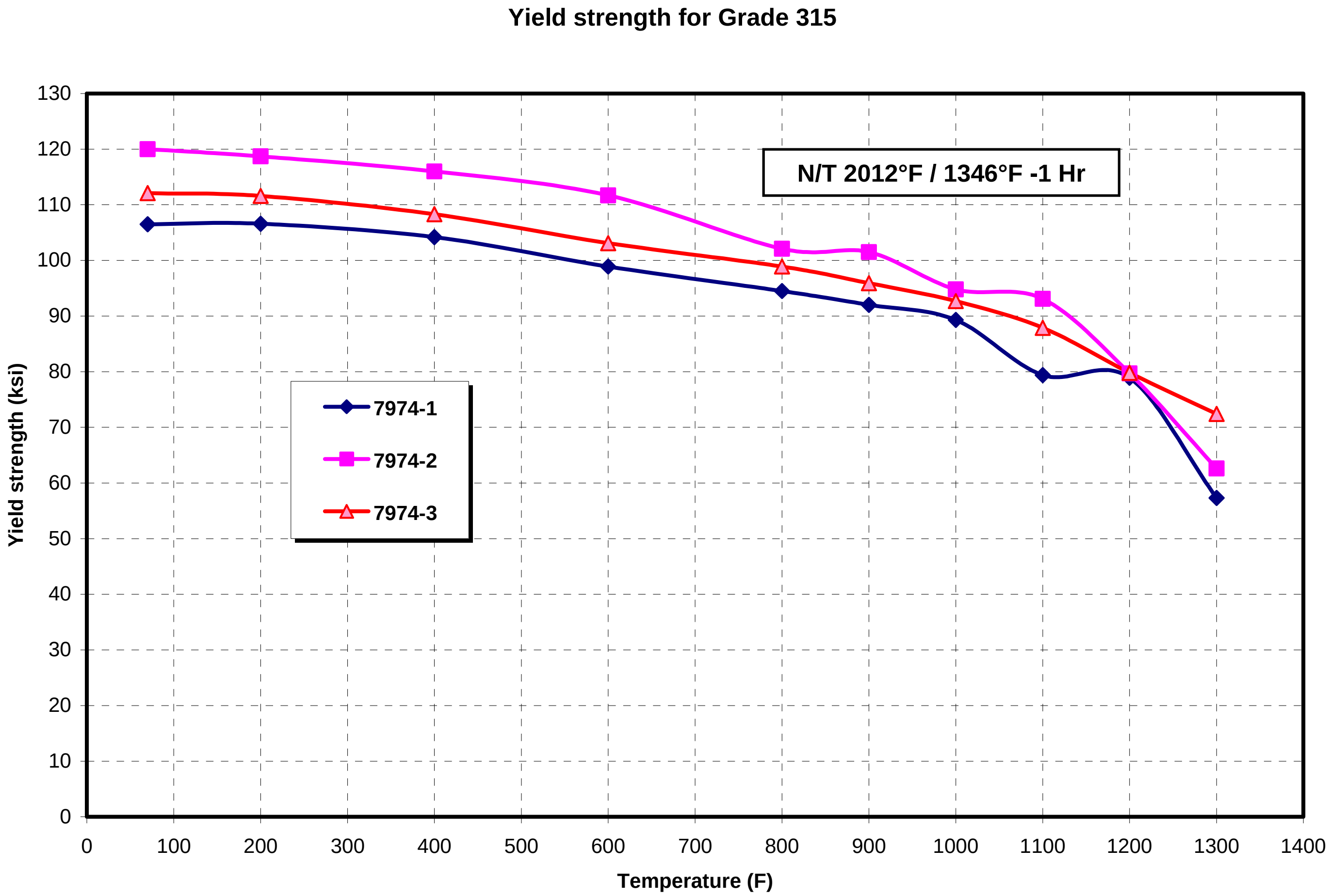
A 1041-04

Heat No. 7974-3
Heat Treatment Normalised/Tempered @ 1346 F/ 1 hr
Specimen Longitudinal

Specimen ID	Test temperature (ºF)	Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Total Elongation (%)	Reduction In area (%)
1	70	113.6	125.9	18.5	63.3
6	70	112.1	125.1	19.5	65.6
2	200	111.6	122.7	19	63.3
3	400	108.3	119.5	20	67.2
4	600	103.1	111.8	18	66.5
5	800	98.9	107.5	19.5	68.8
7	900	95.9	102.5	15.5	60.6
8	1000	92.7	98.4	17.5	63
9	1100	87.9	90.5	18	69.7
10	1200	79.8	80.2	19	75.2
11	1300	72.4	75	19	76

BC04-1063 **21/93**

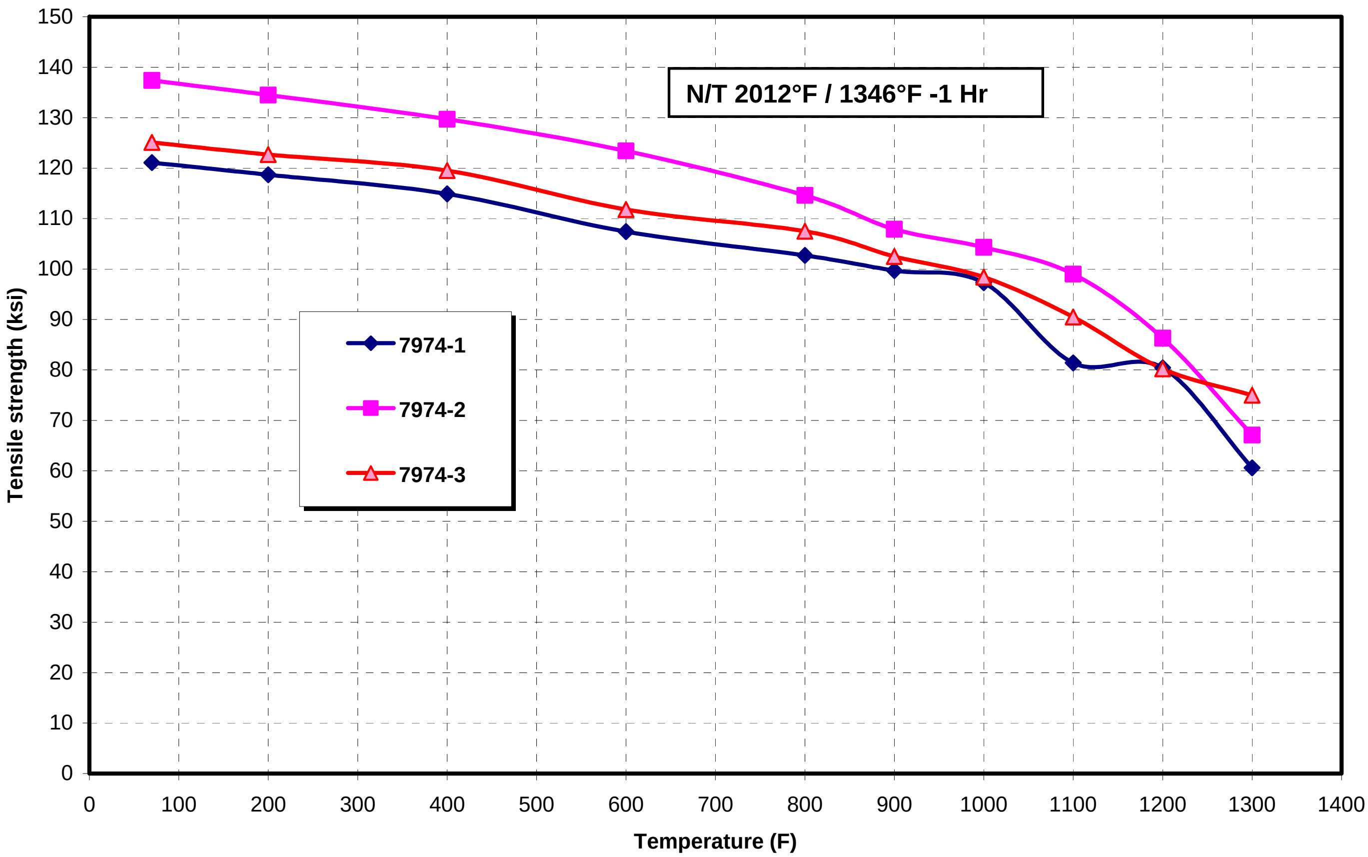
A 1041-04



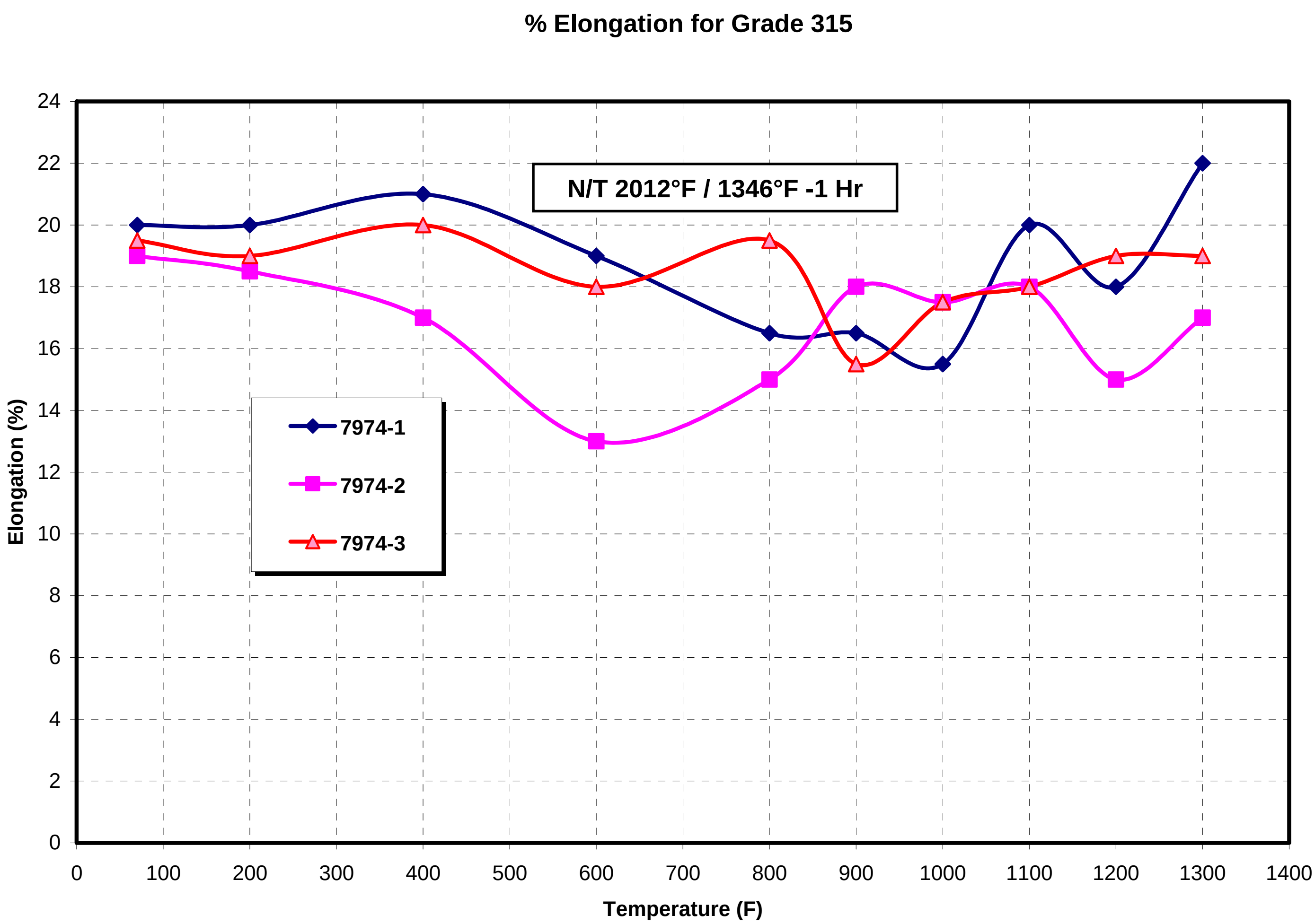
BC04-1063 **22/93**

A 1041-04

Tensile strength prop. for Grade 315



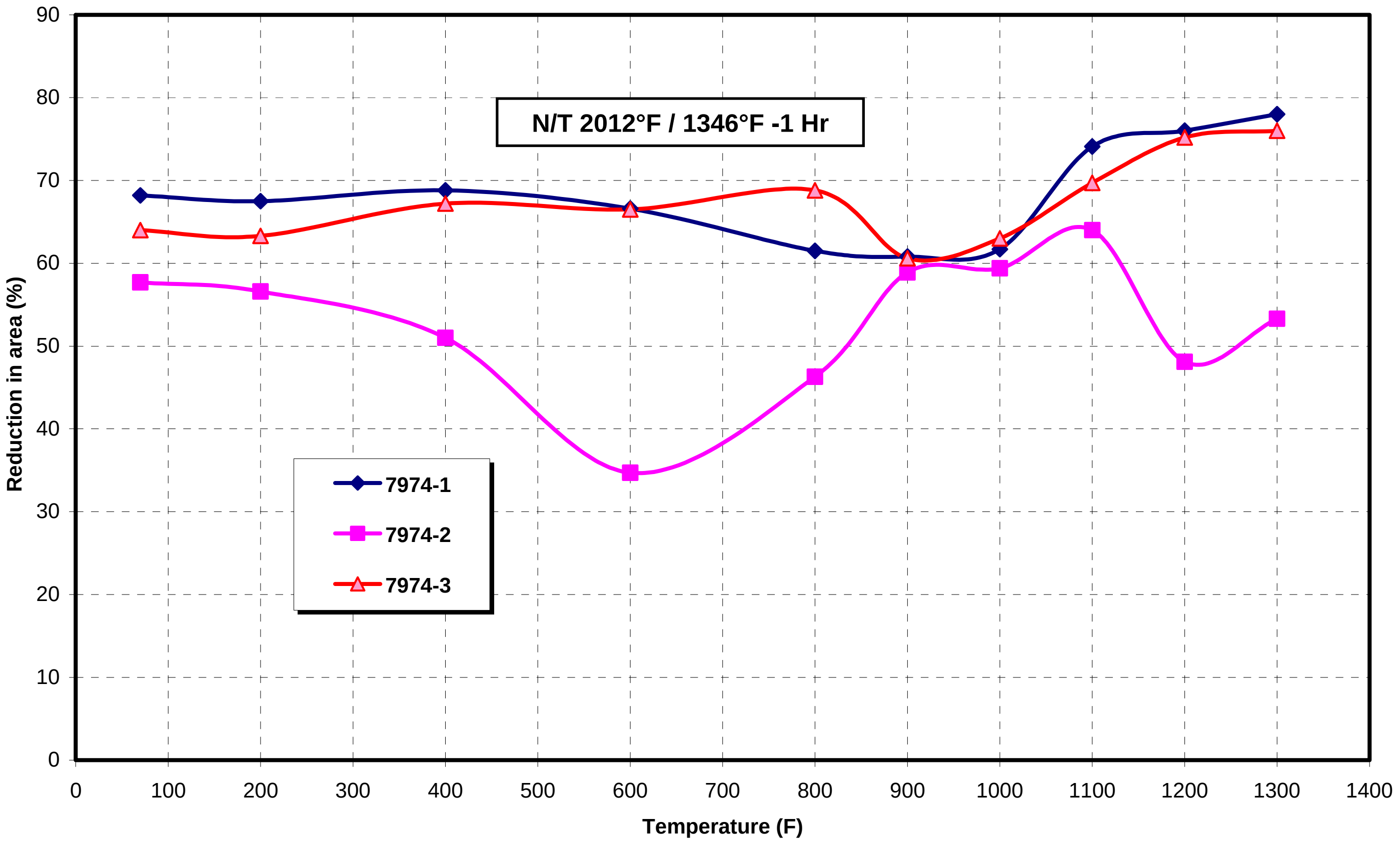
A 1041-04


% Elongation for Grade 315
N/T 2012°F / 1346°F -1 Hr
Elongation (%)
Temperature (F)
7974-1
7974-2
7974-3
0
2
4
6
8
10
12
14
16
18
20
22
24
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400

BC04-1063 **24/93**

A 1041-04

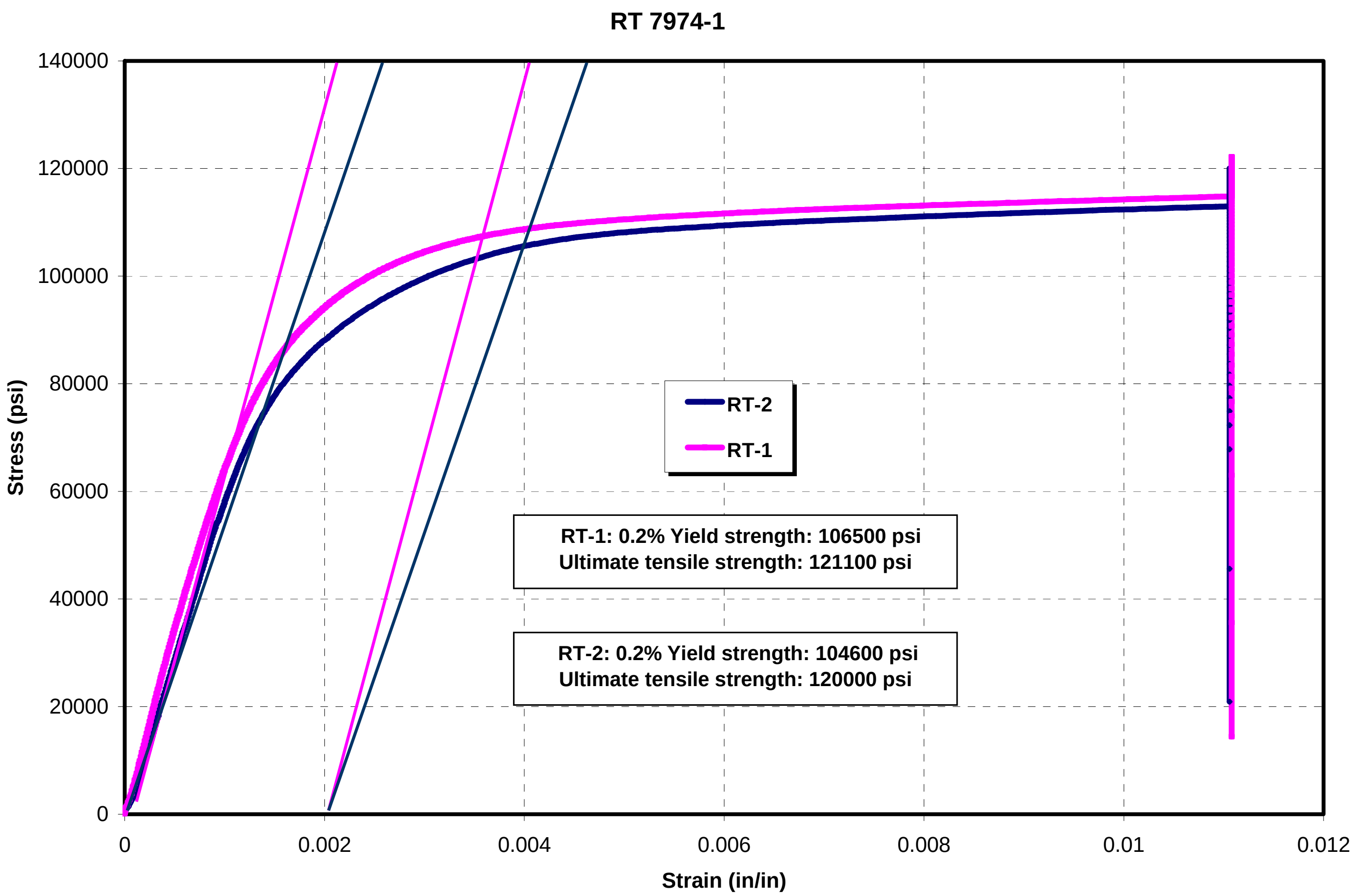
% Reduction in area for Grade 315



A 1041-04

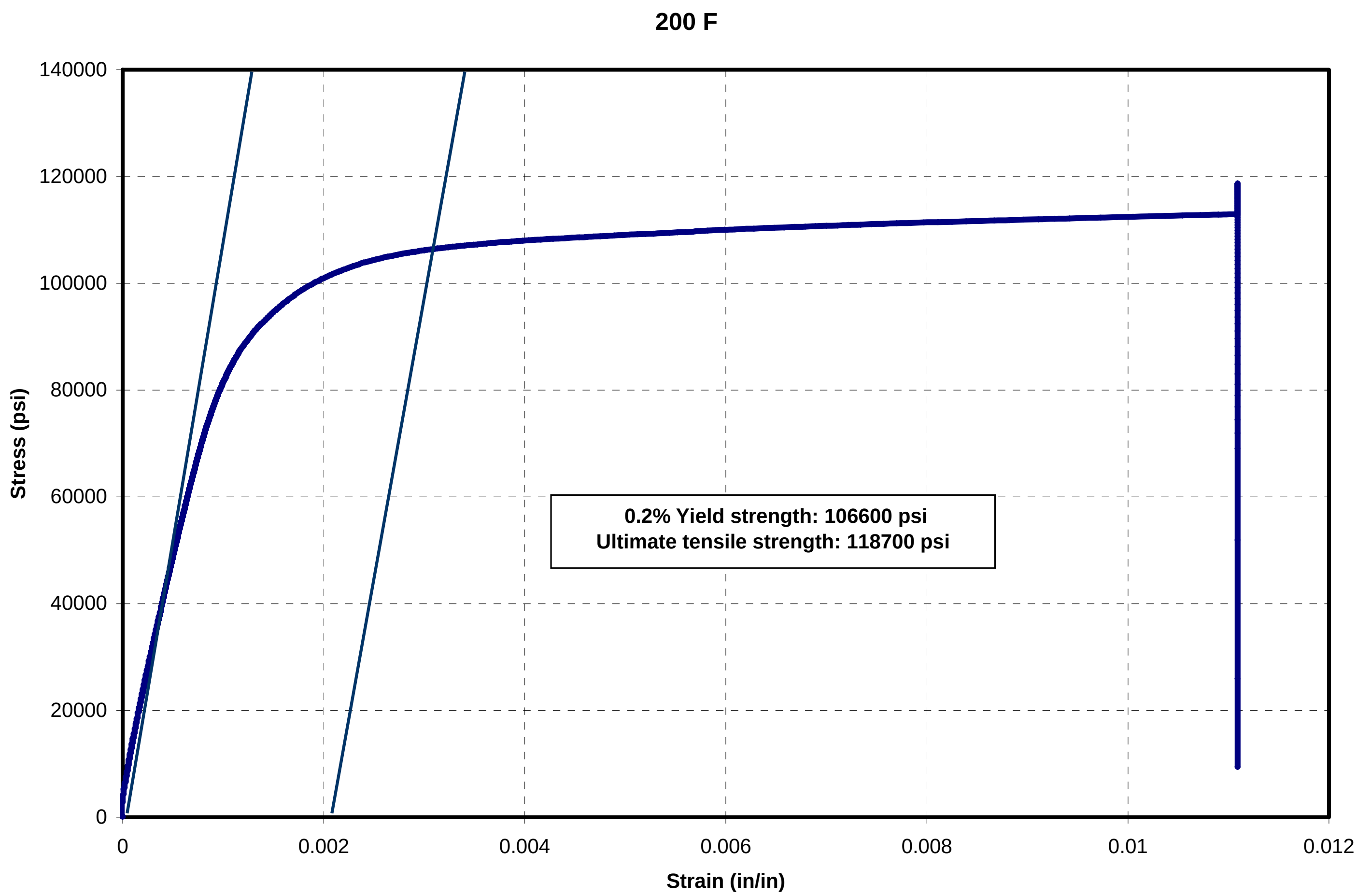
Stress-Strain Plots for Various Test Temperatures

A 1041-04


RT 7974-1
Stress (psi)
Strain (in/in)
140000
120000
100000
80000
60000
40000
20000
0
0
0.002
0.004
0.006
0.008
0.01
0.012
RT-2
RT-1
RT-1: 0.2% Yield strength: 106500 psi
Ultimate tensile strength: 121100 psi
RT-2: 0.2% Yield strength: 104600 psi
Ultimate tensile strength: 120000 psi

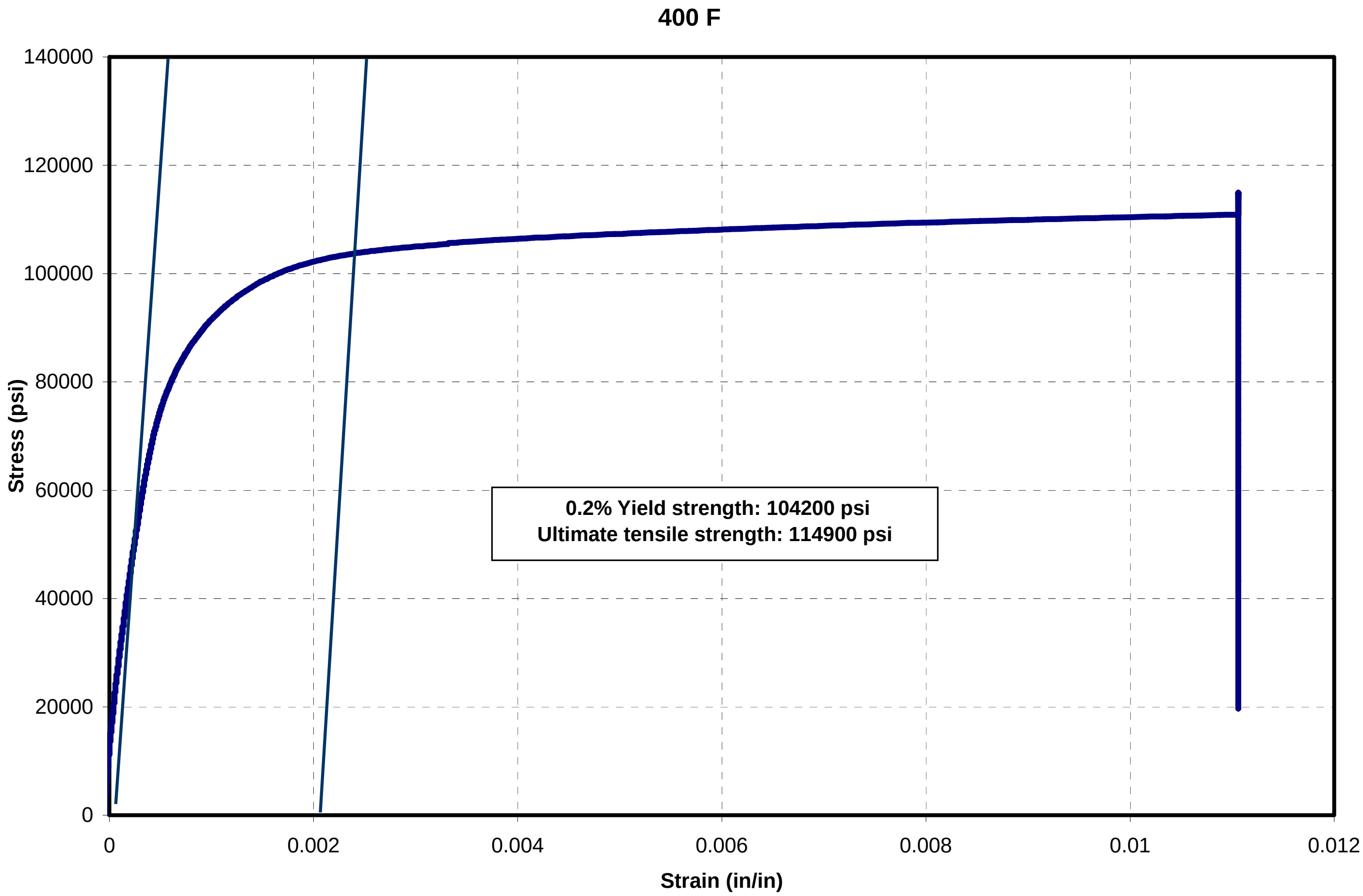
BC04-1063 **27/93**

A 1041-04



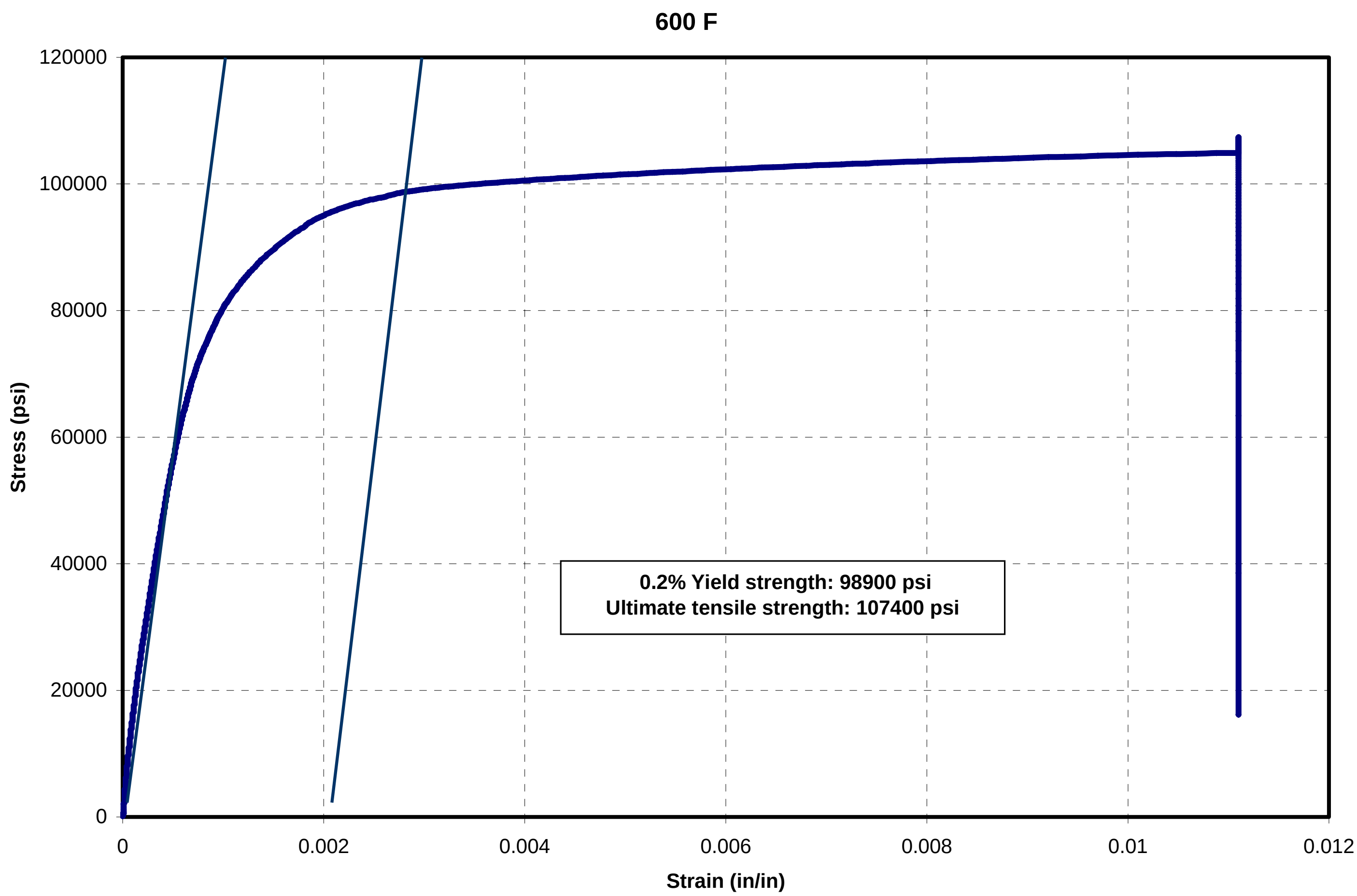
BC04-1063 **28/93**

A 1041-04



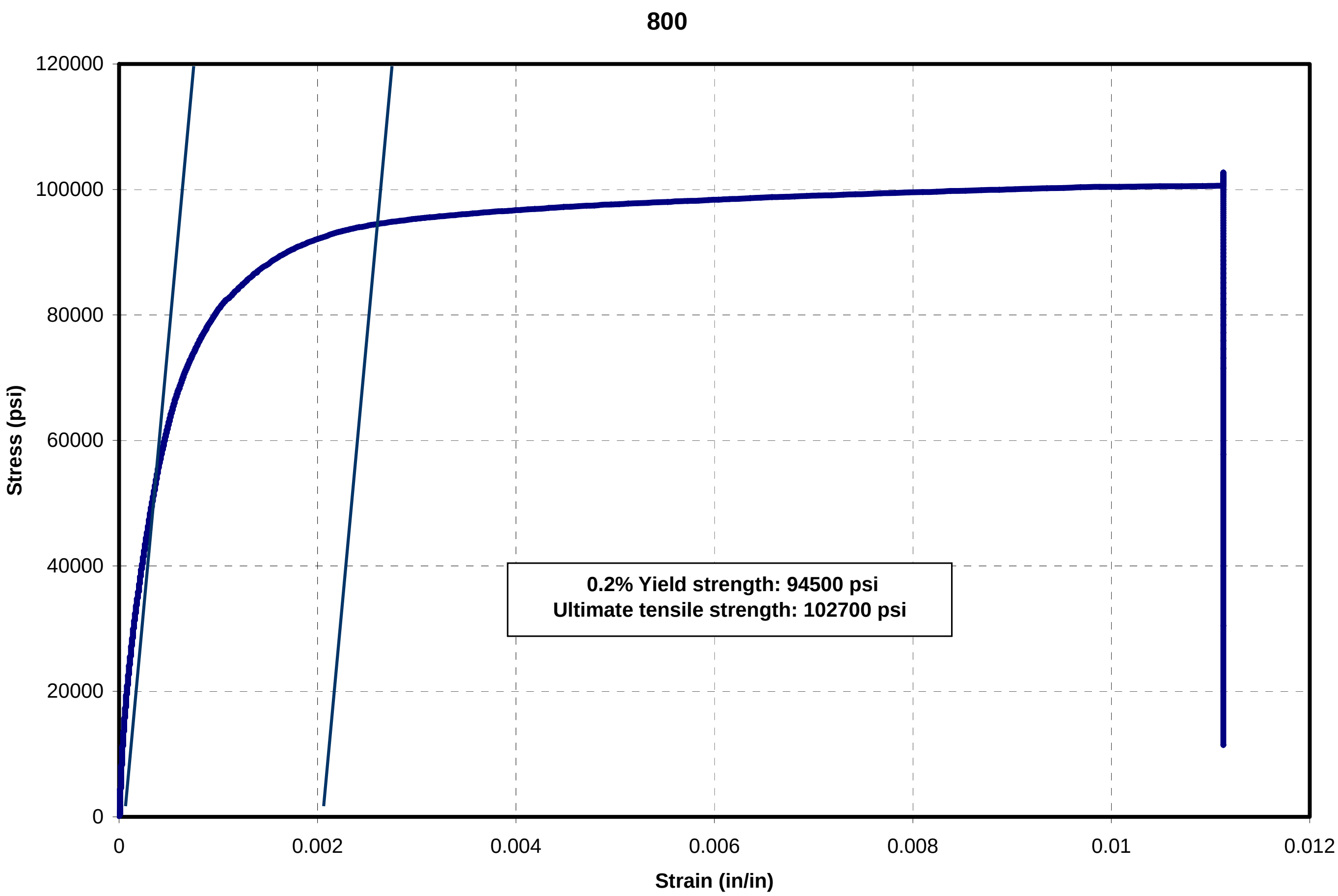
BC04-1063 **29/93**

A 1041-04



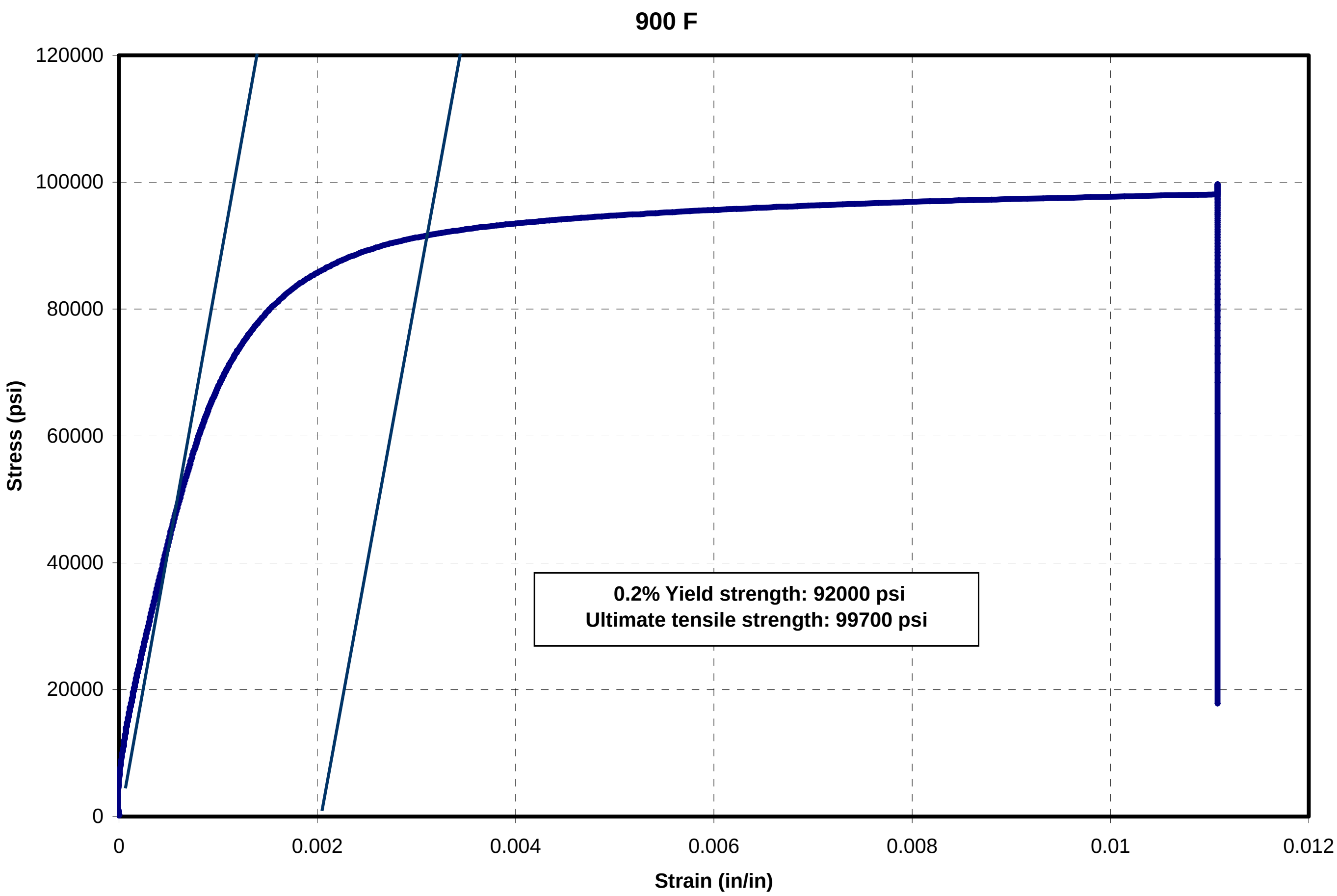
BC04-1063 **30/93**

A 1041-04



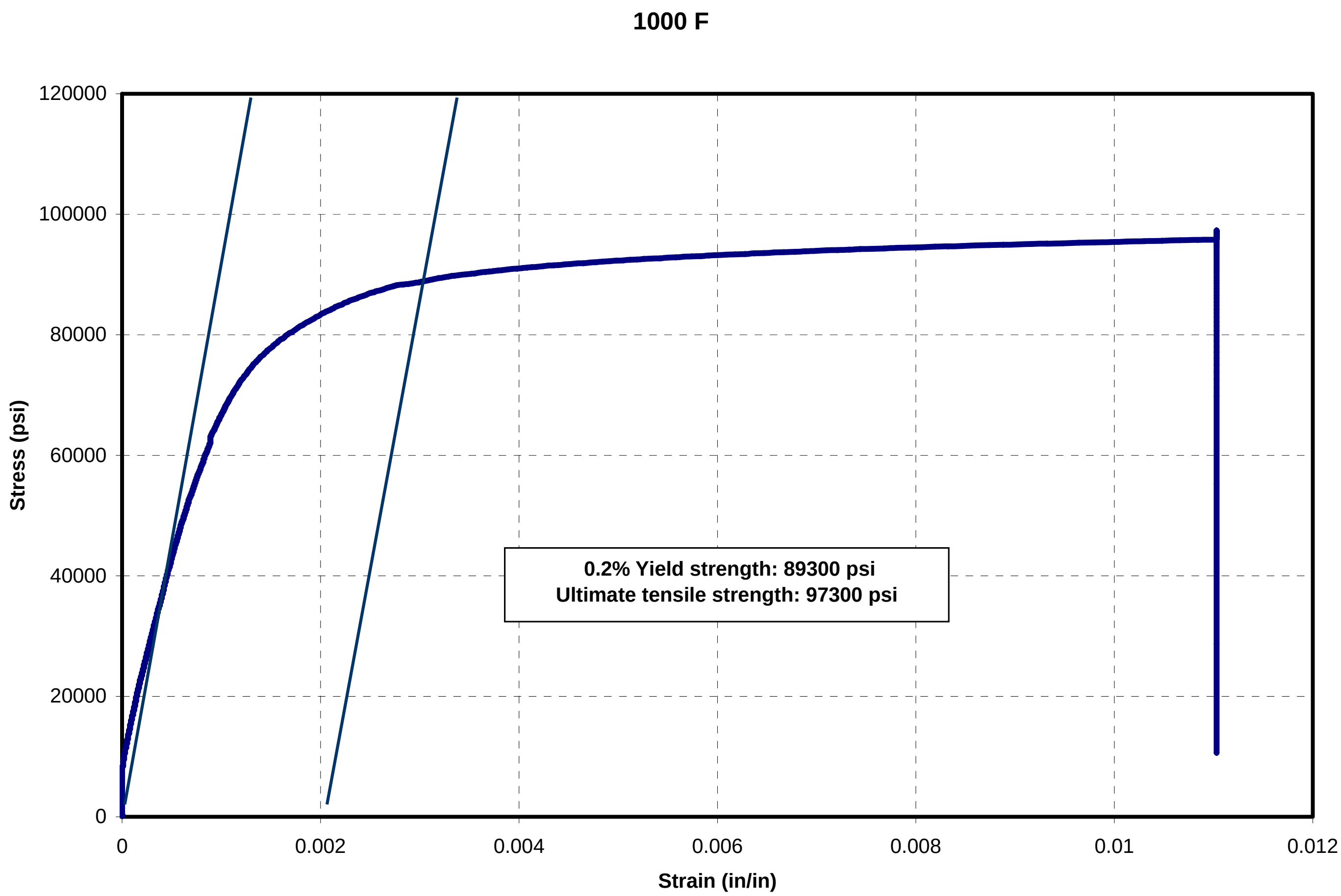
BC04-1063 **31/93**

A 1041-04



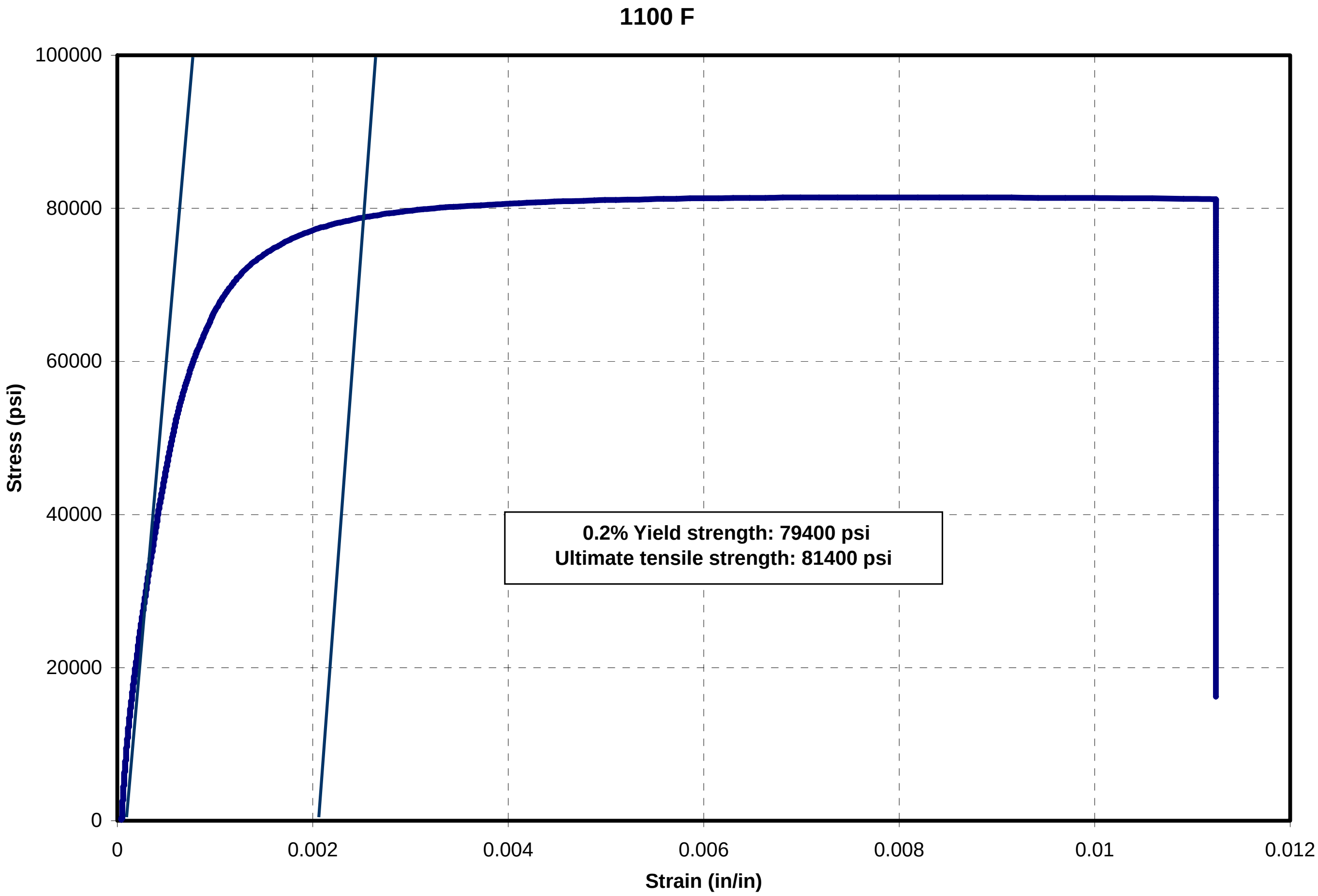
BC04-1063 **32/93**

A 1041-04



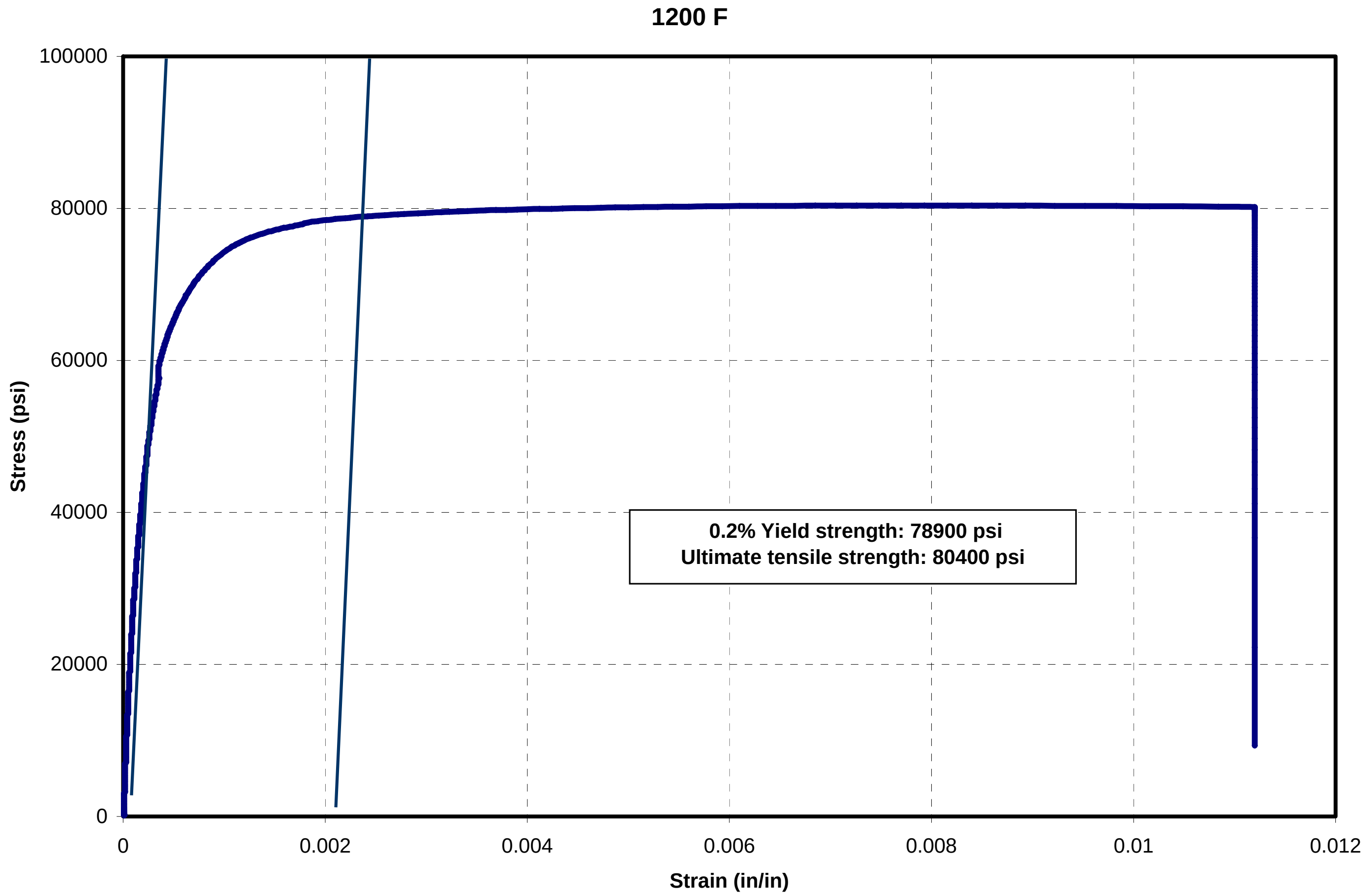
BC04-1063 **33/93**

A 1041-04



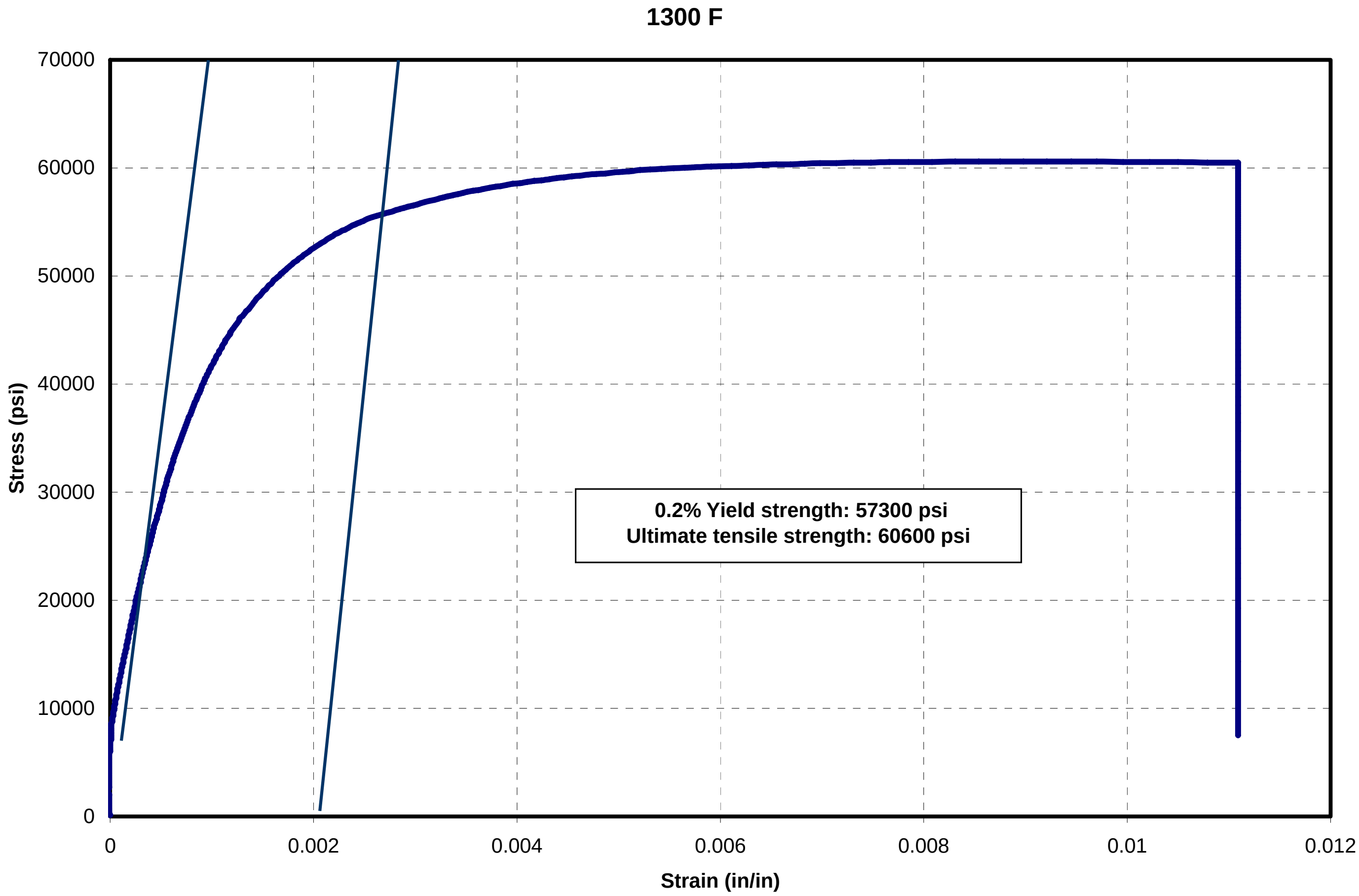
BC04-1063 **34/93**

A 1041-04



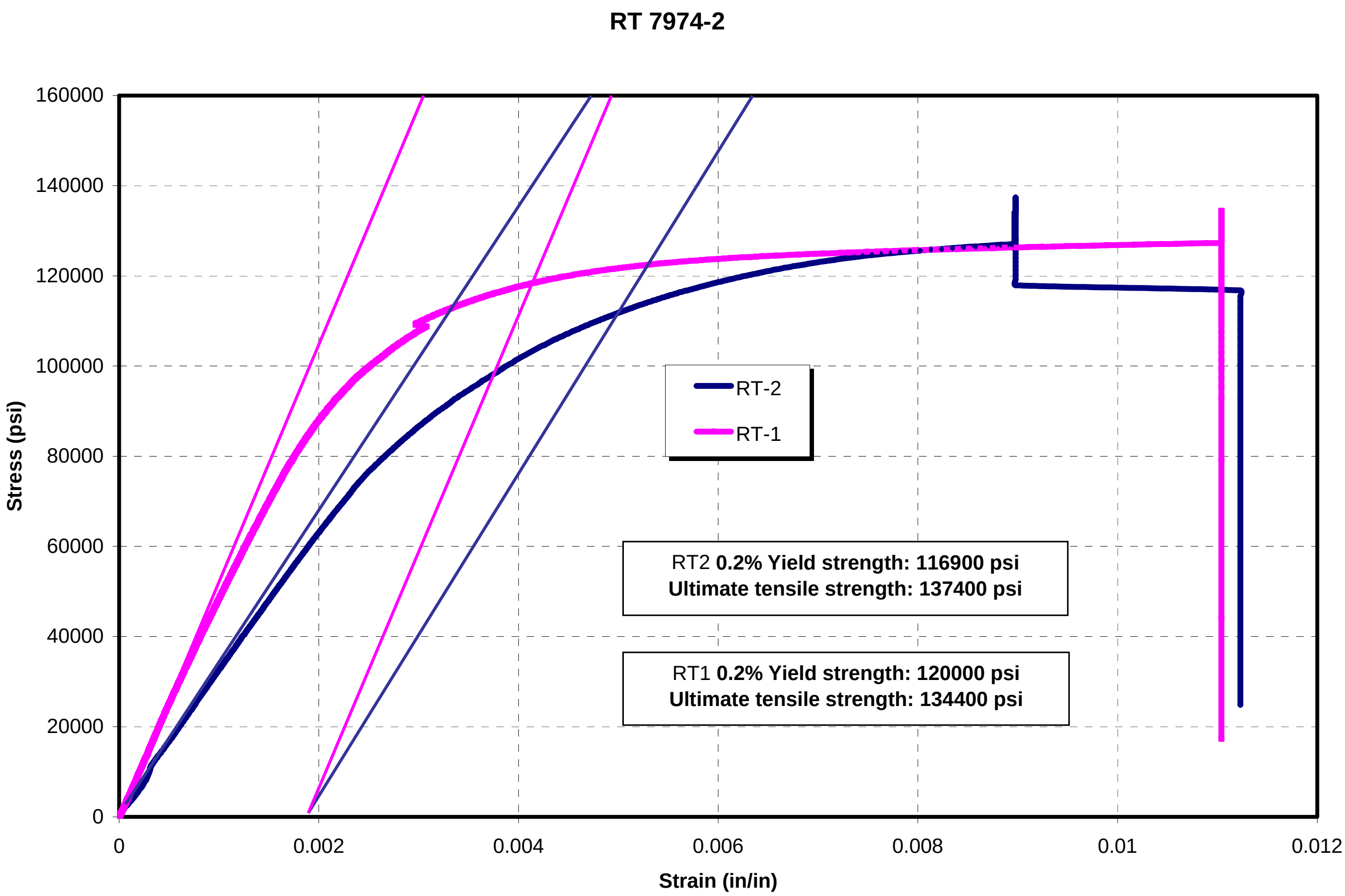
BC04-1063 **35/93**

A 1041-04



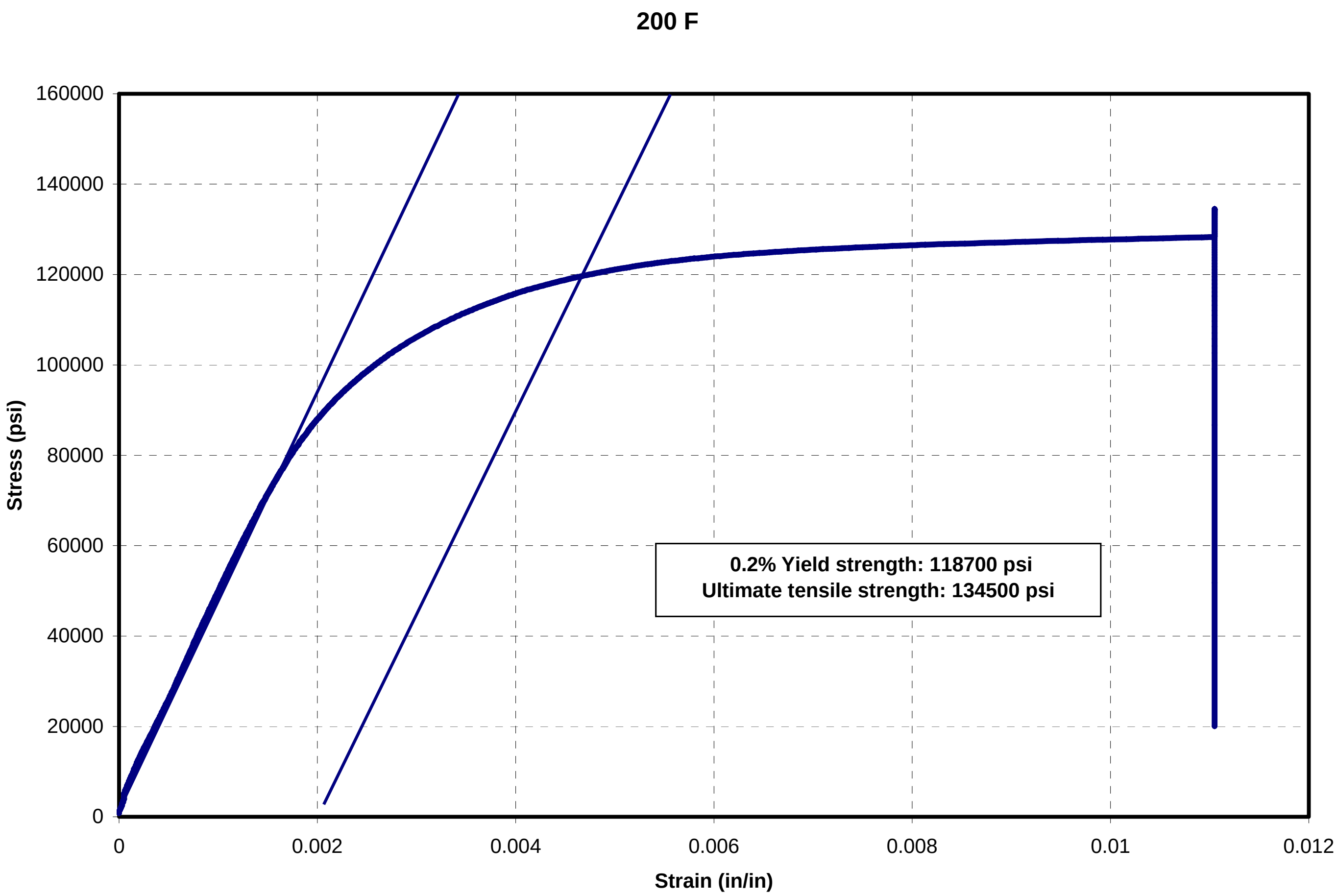
BC04-1063 **36/93**

A 1041-04



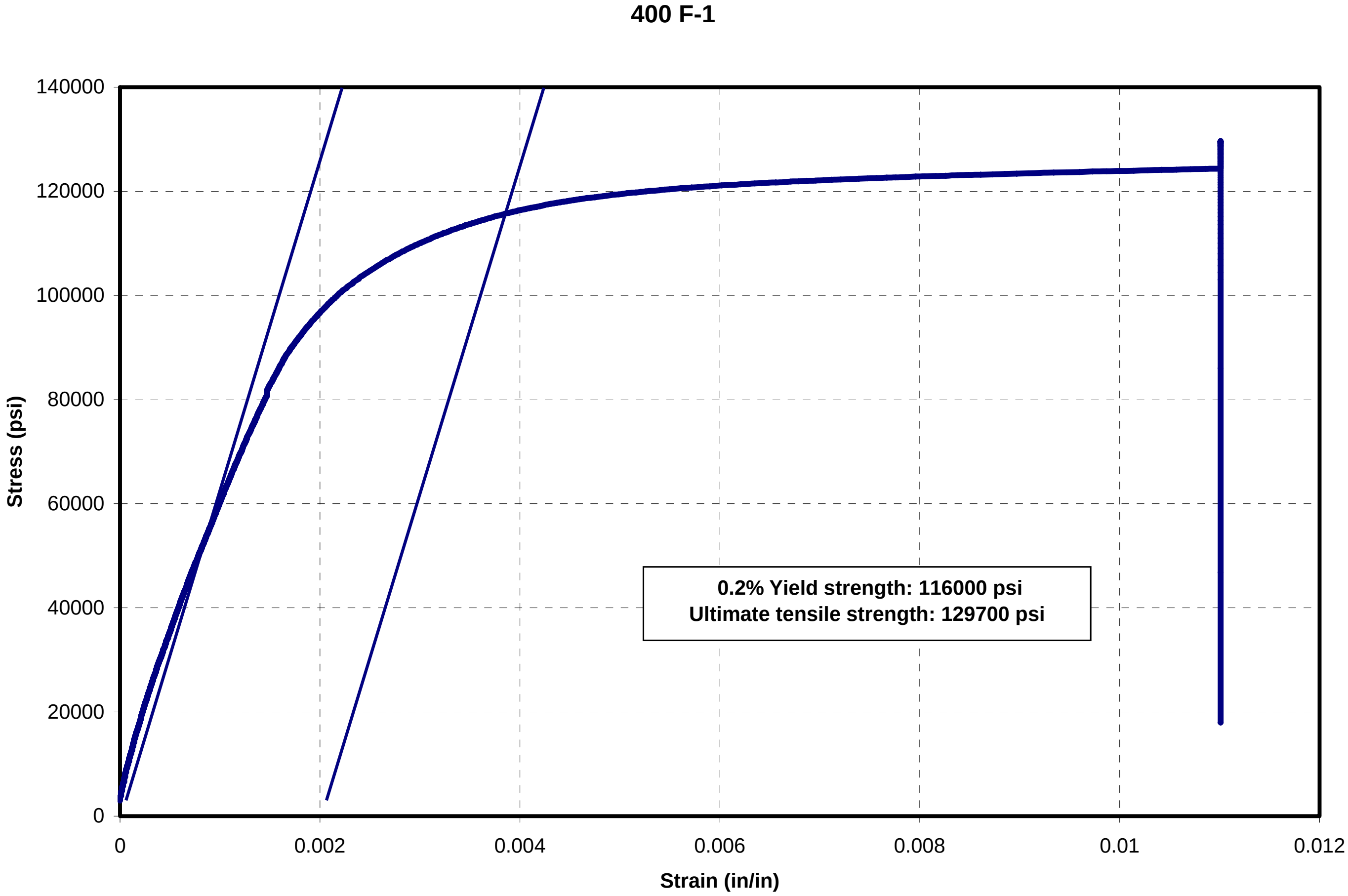
BC04-1063 **37/93**

A 1041-04

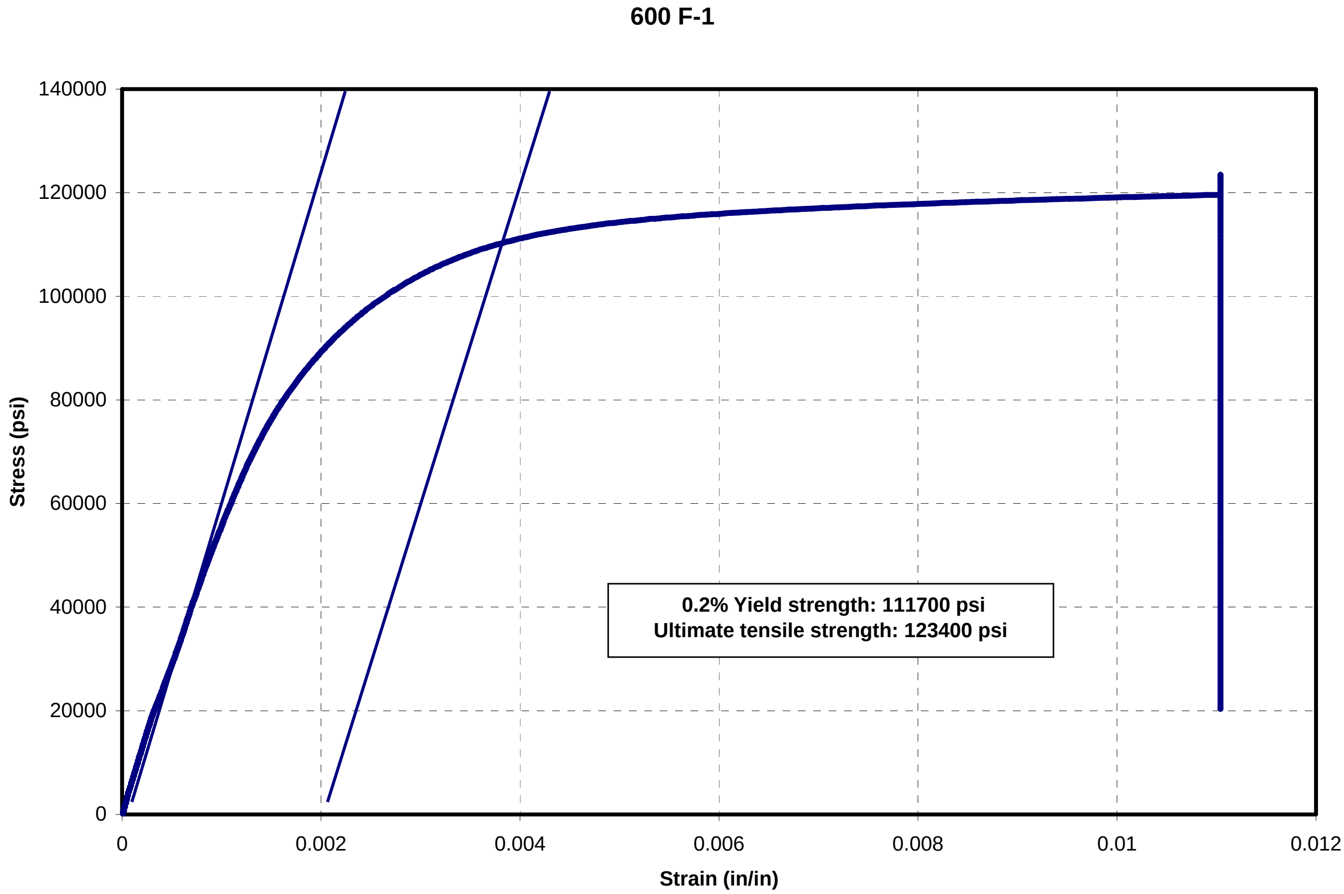


BC04-1063 **38/93**

A 1041-04

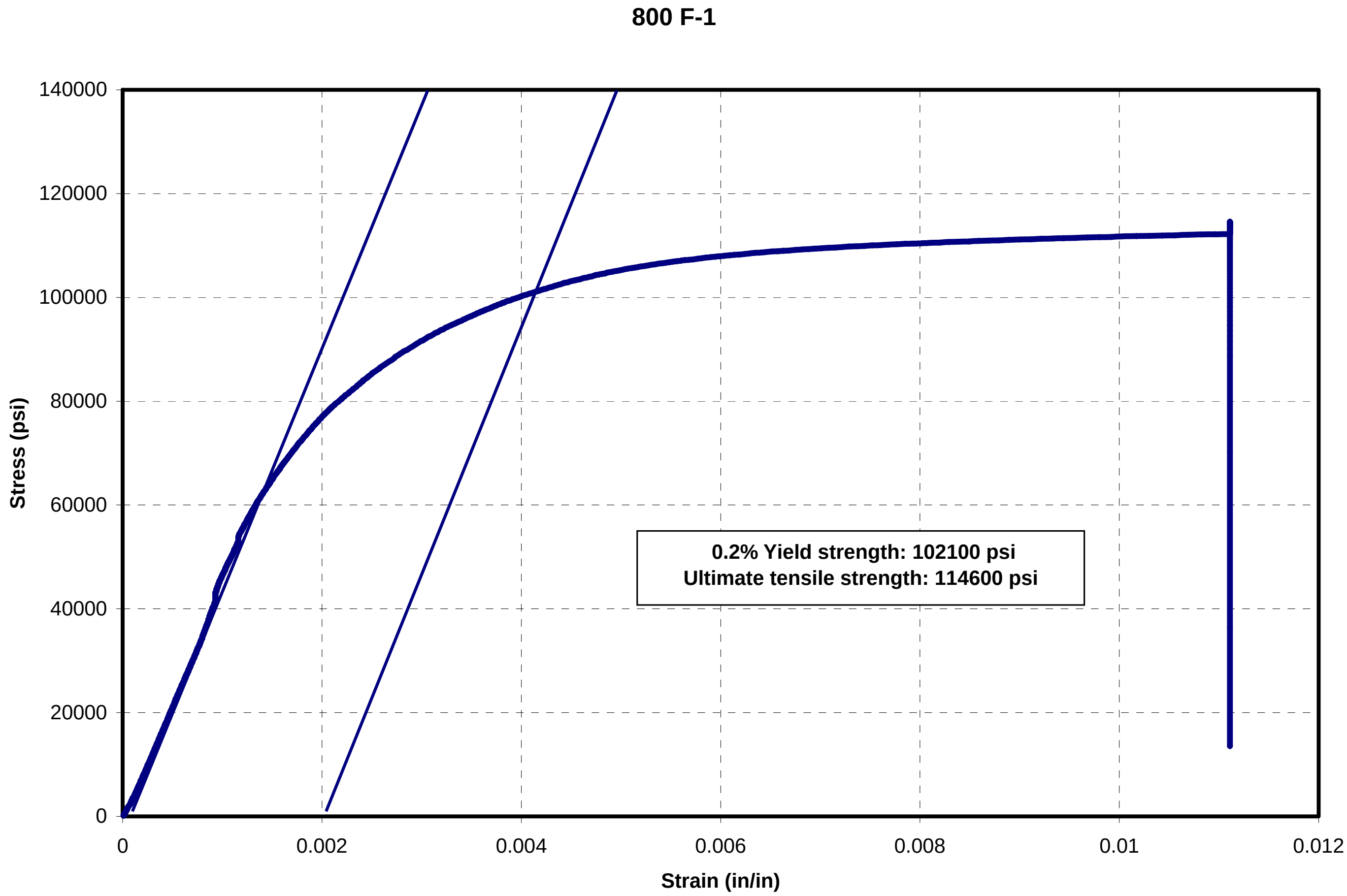


A 1041-04


600 F-1
0.2% Yield strength: 111700 psi
Ultimate tensile strength: 123400 psi
Stress (psi)
Strain (in/in)
140000
120000
100000
80000
60000
40000
20000
0
0
0.002
0.004
0.006
0.008
0.01
0.012

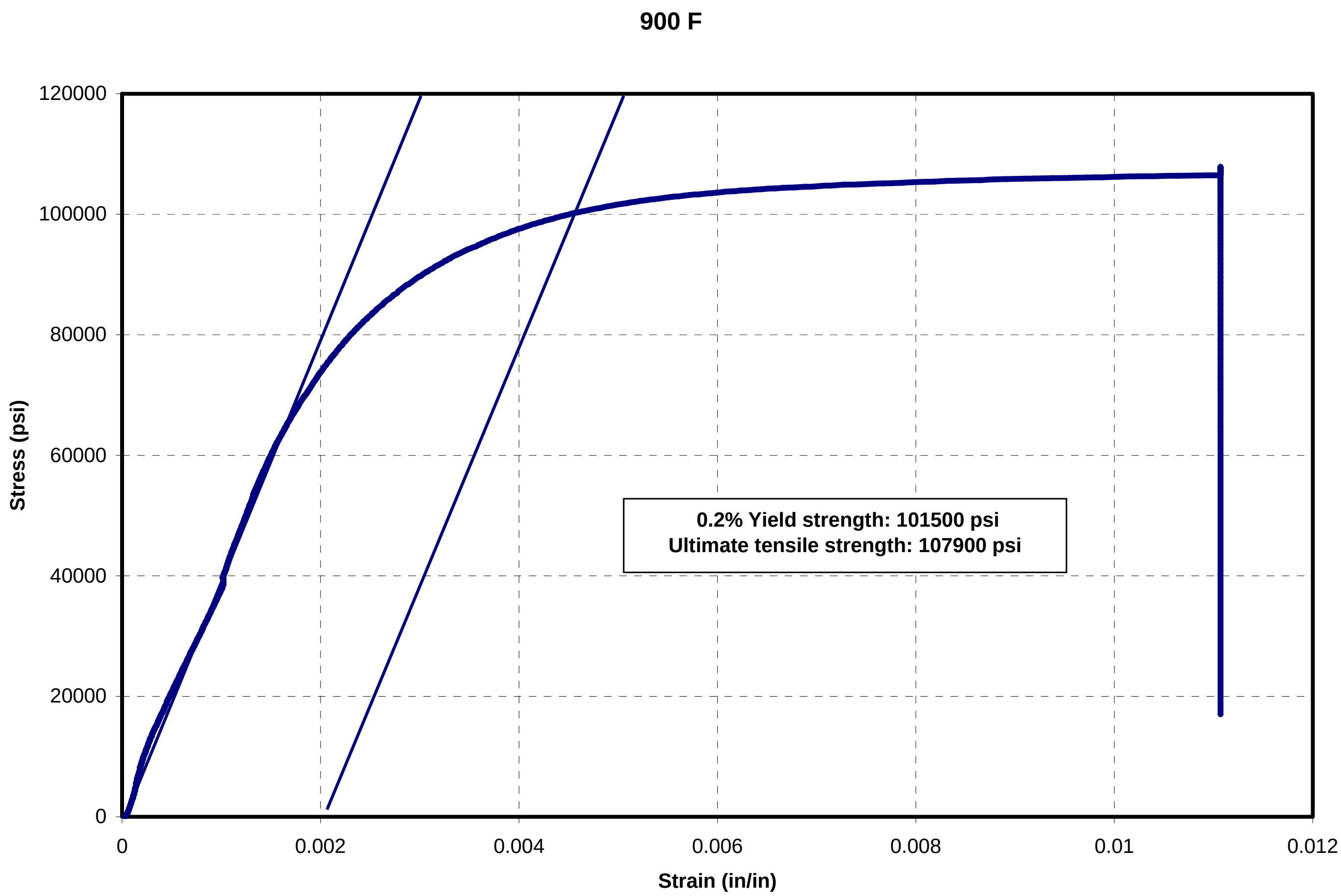
BC04-1063 **40/93**

A 1041-04



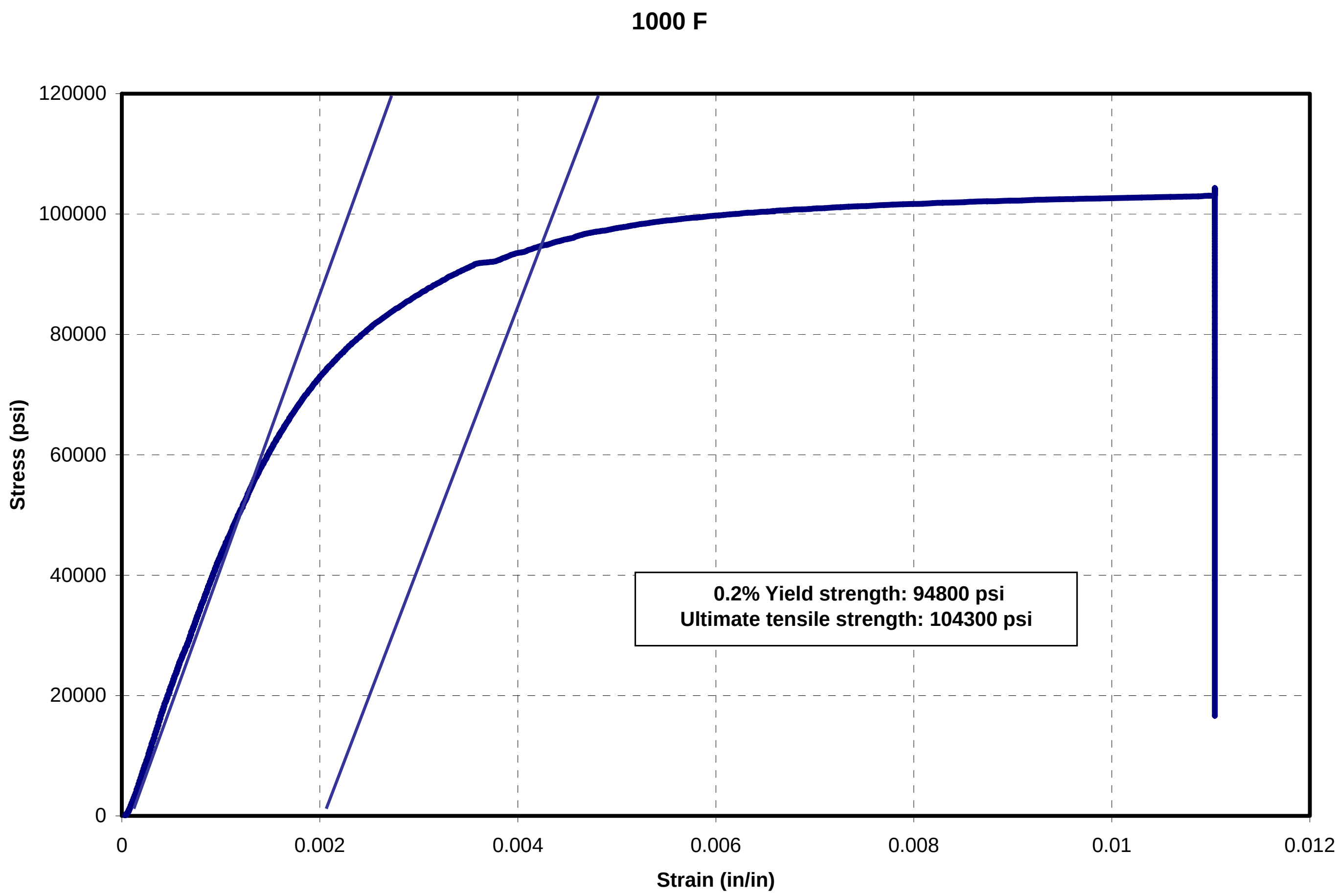
BC04-1063 **41/93**

A 1041-04



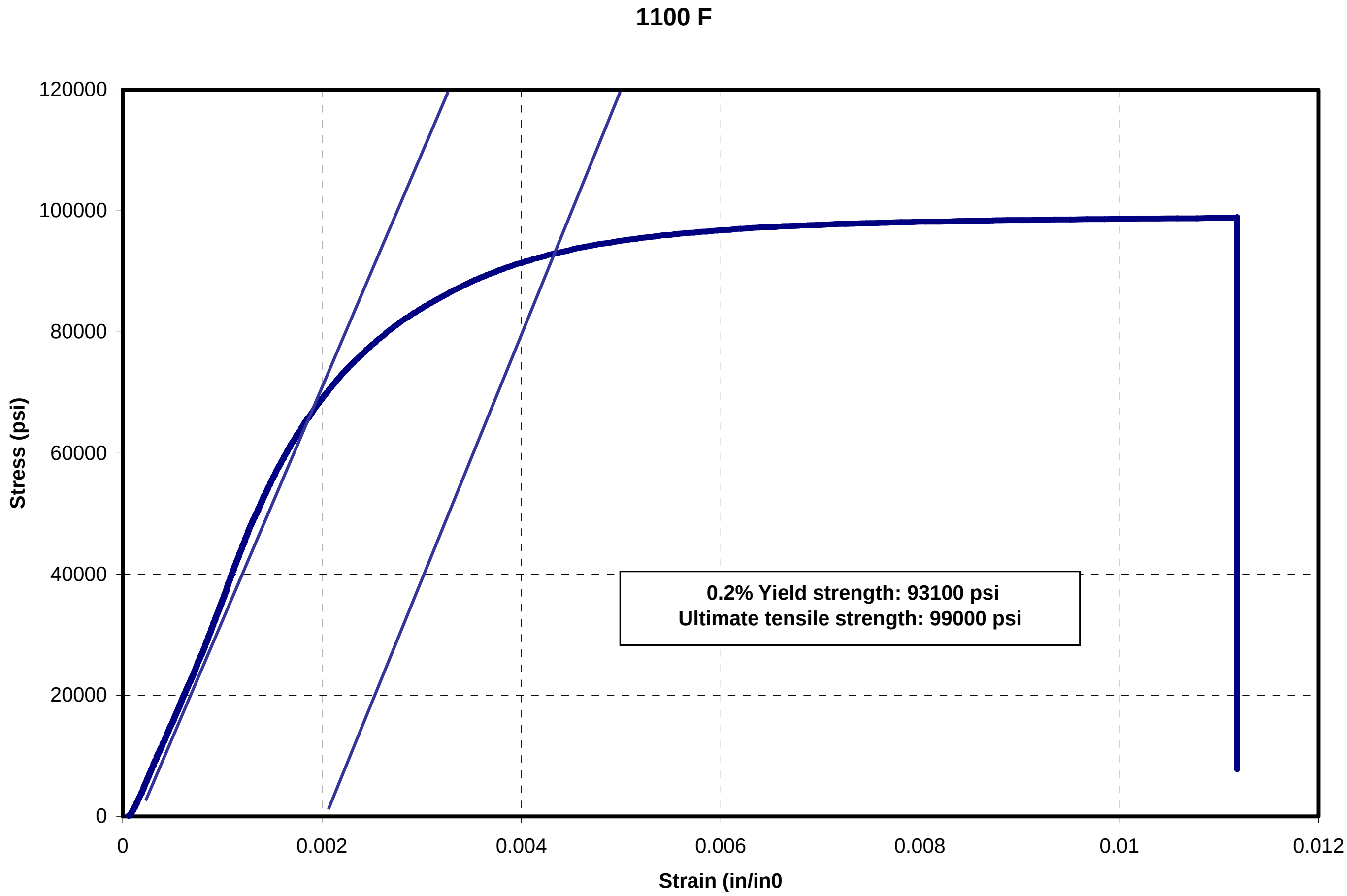
BC04-1063 **42/93**

A 1041-04



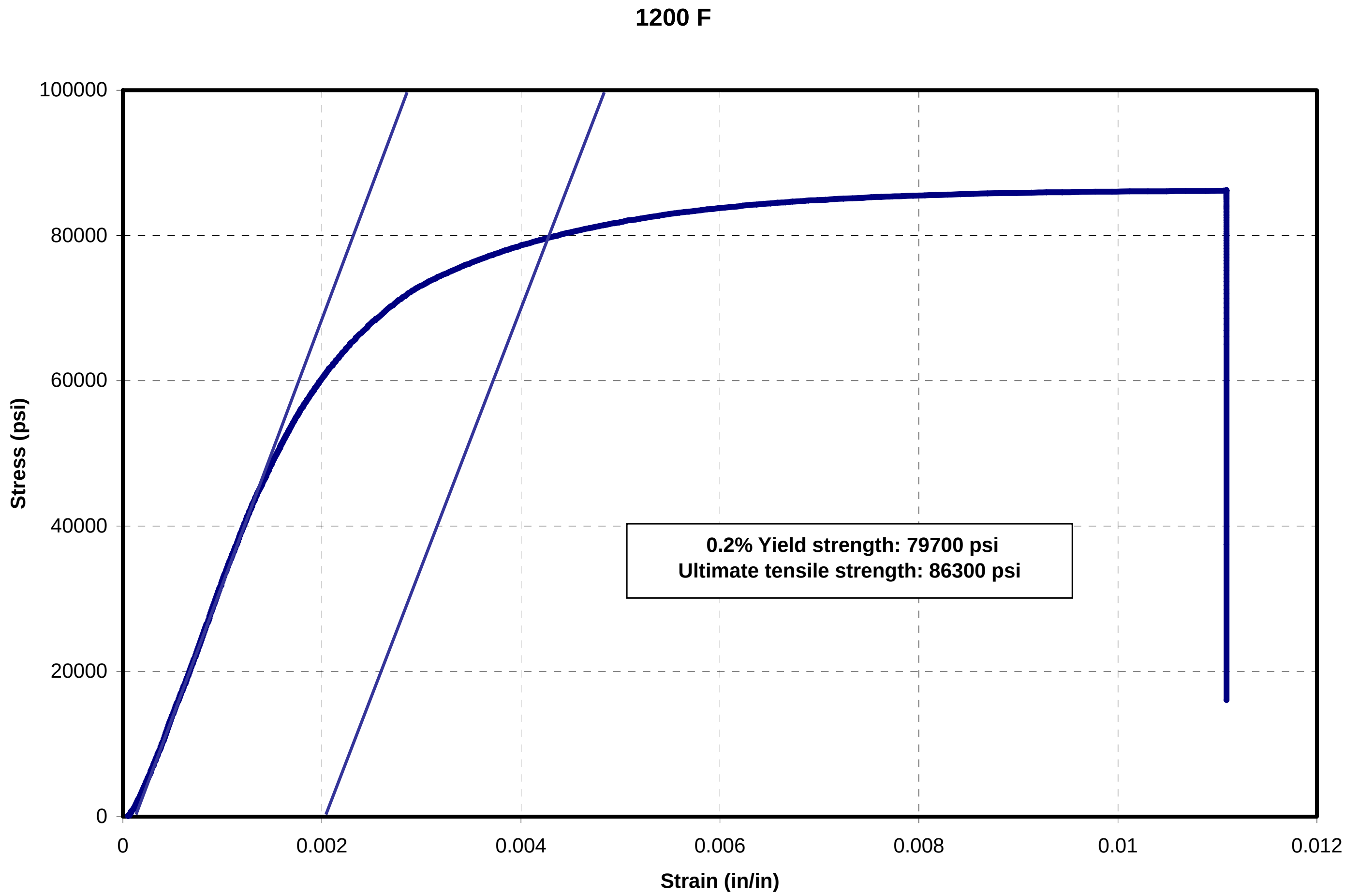
BC04-1063 **43/93**

A 1041-04



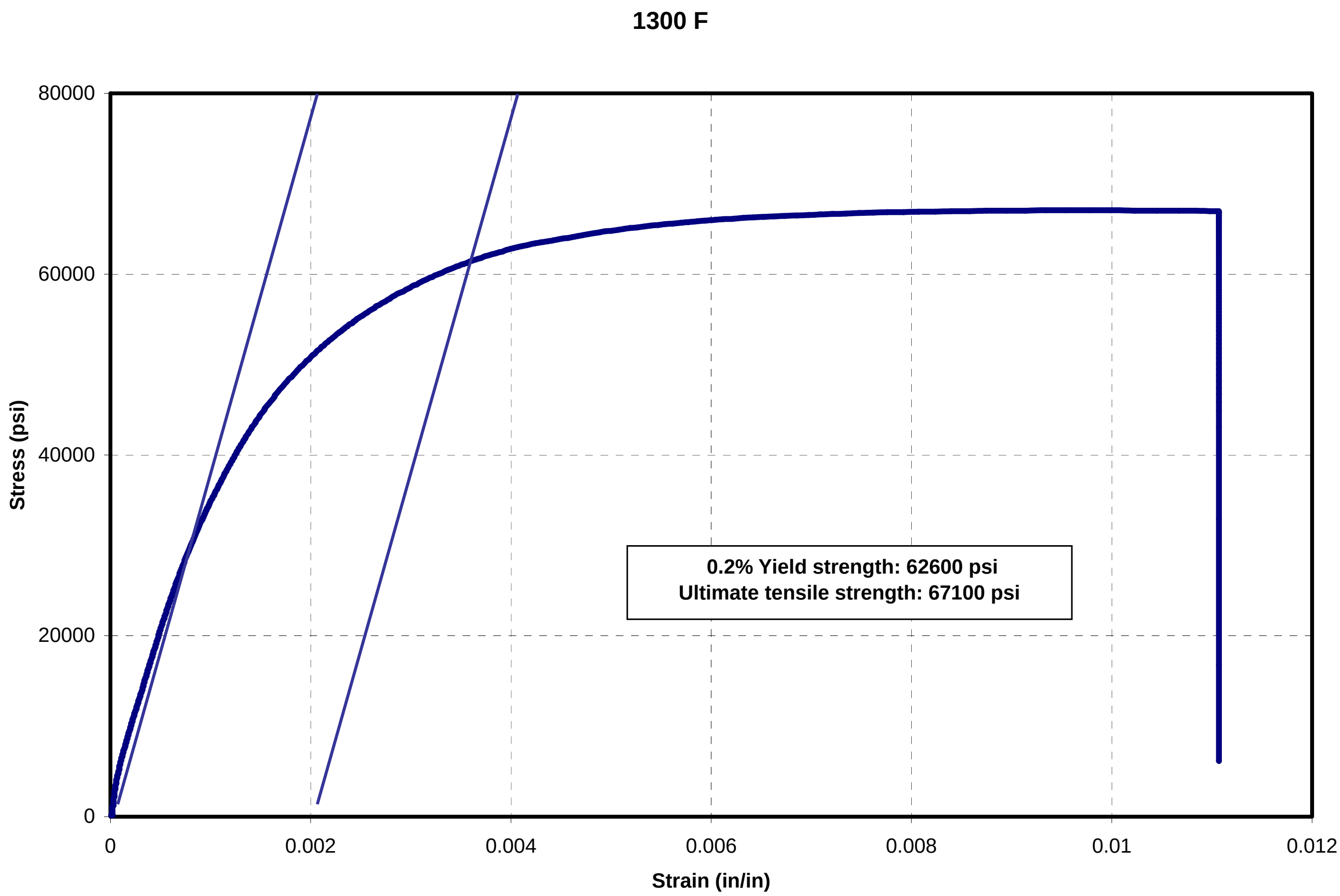
BC04-1063 **44/93**

A 1041-04



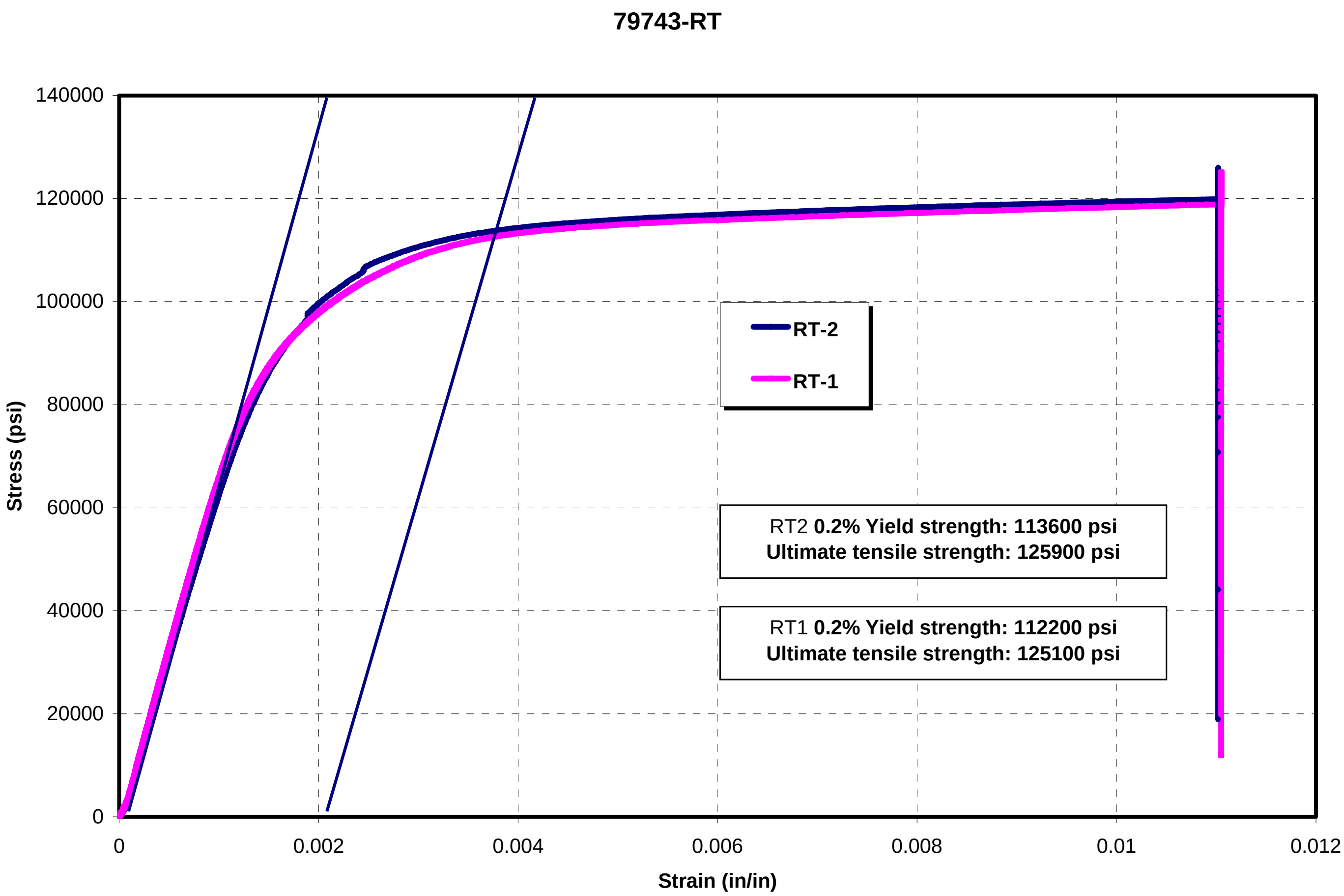
BC04-1063 **45/93**

A 1041-04



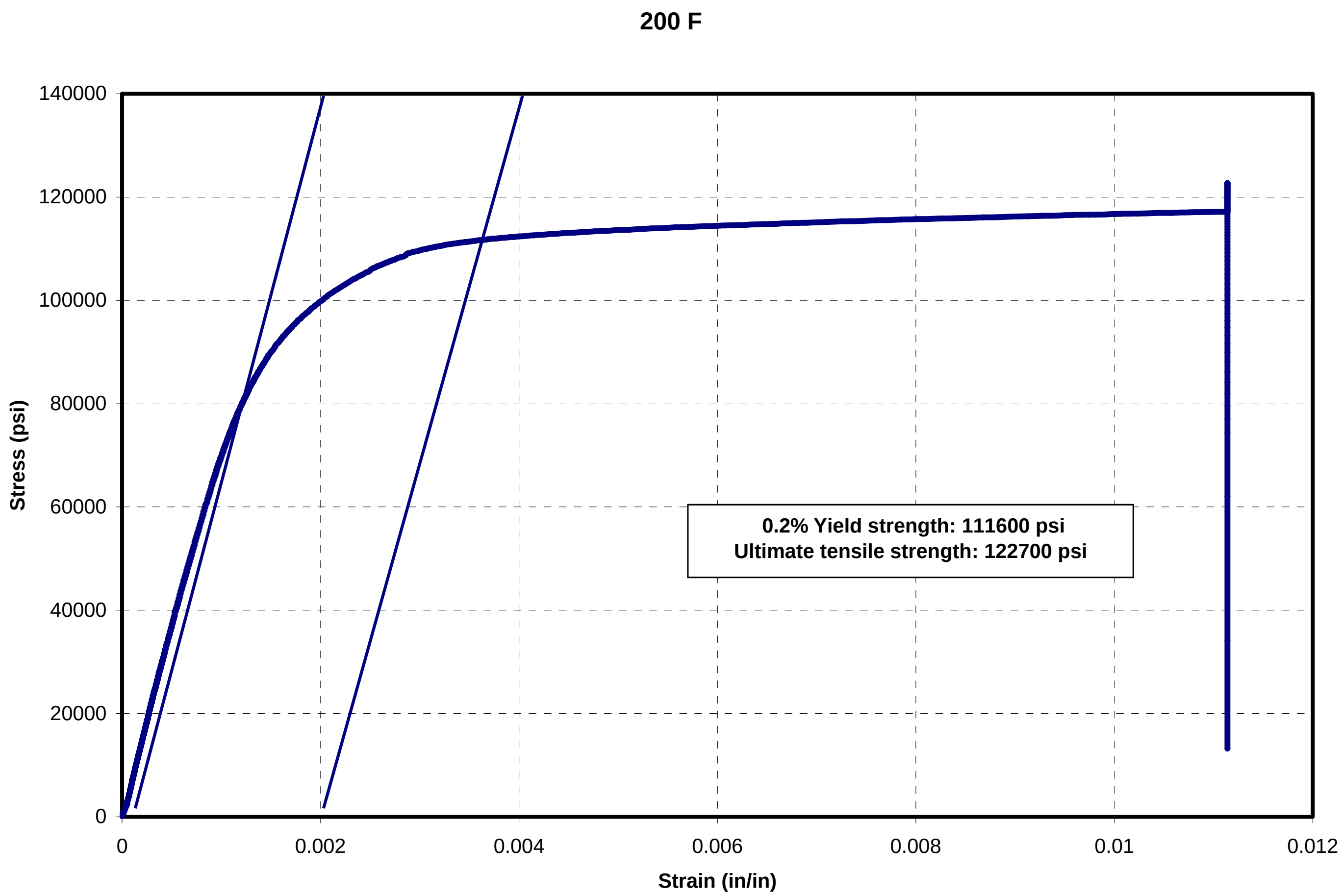
BC04-1063 **46/93**

A 1041-04



BC04-1063 **47/93**

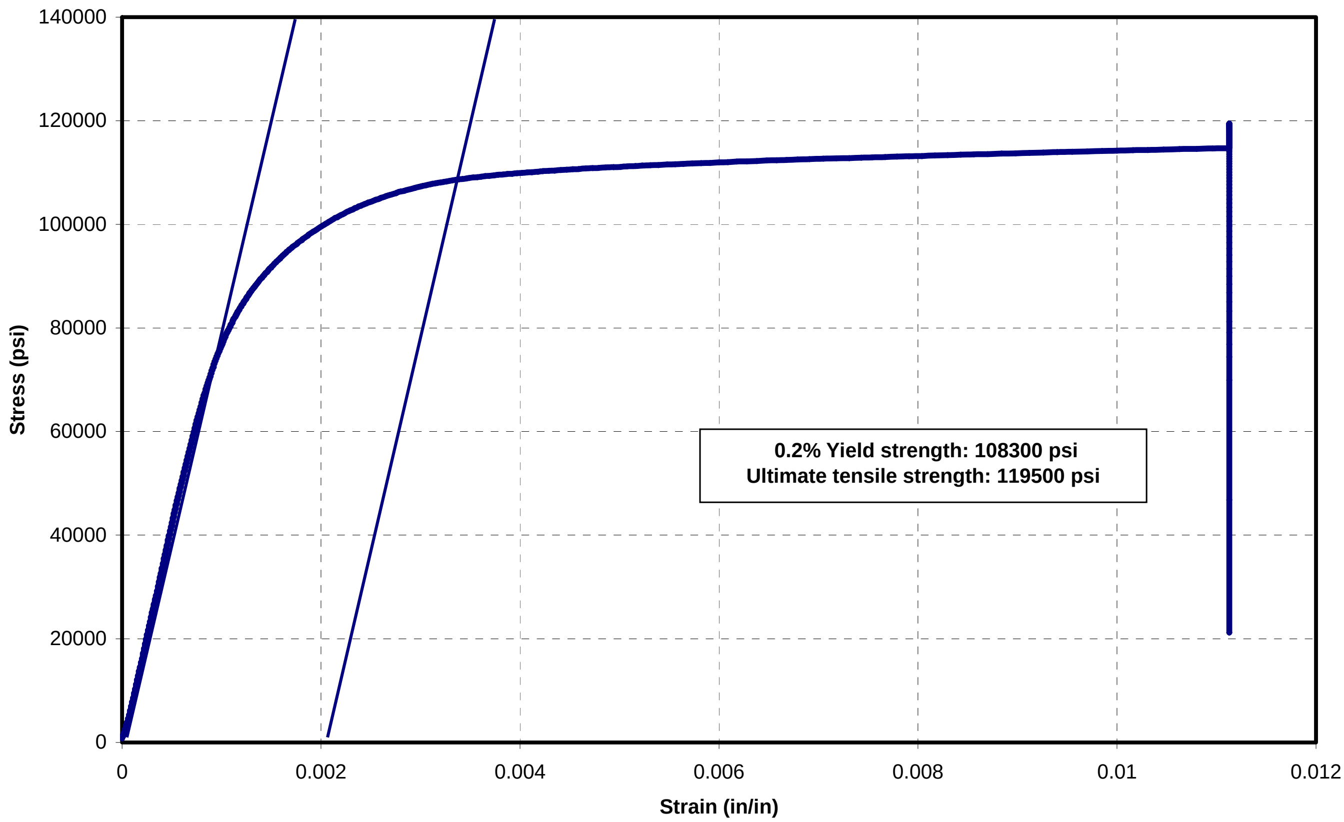
A 1041-04



BC04-1063 **48/93**

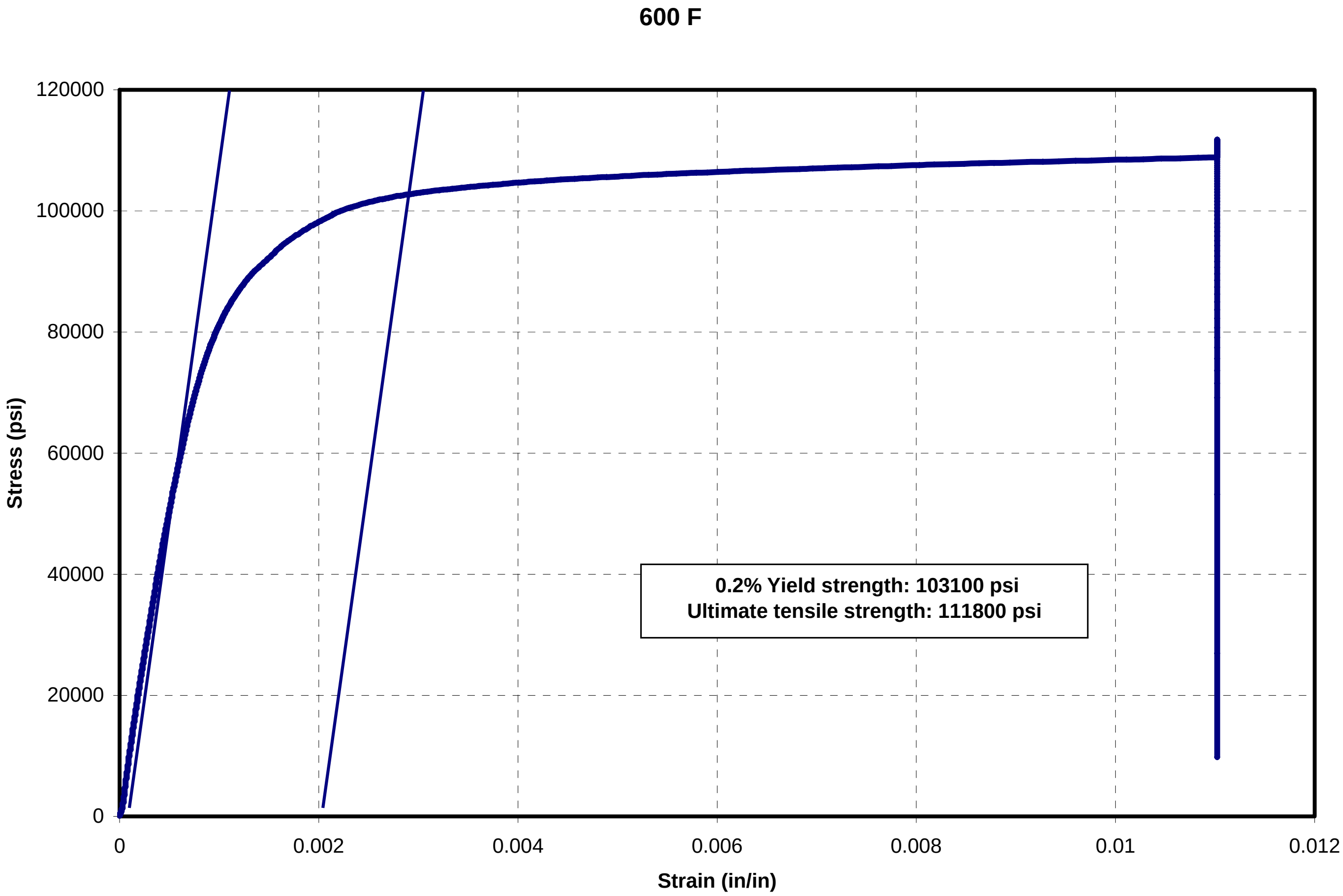
A 1041-04

400 F



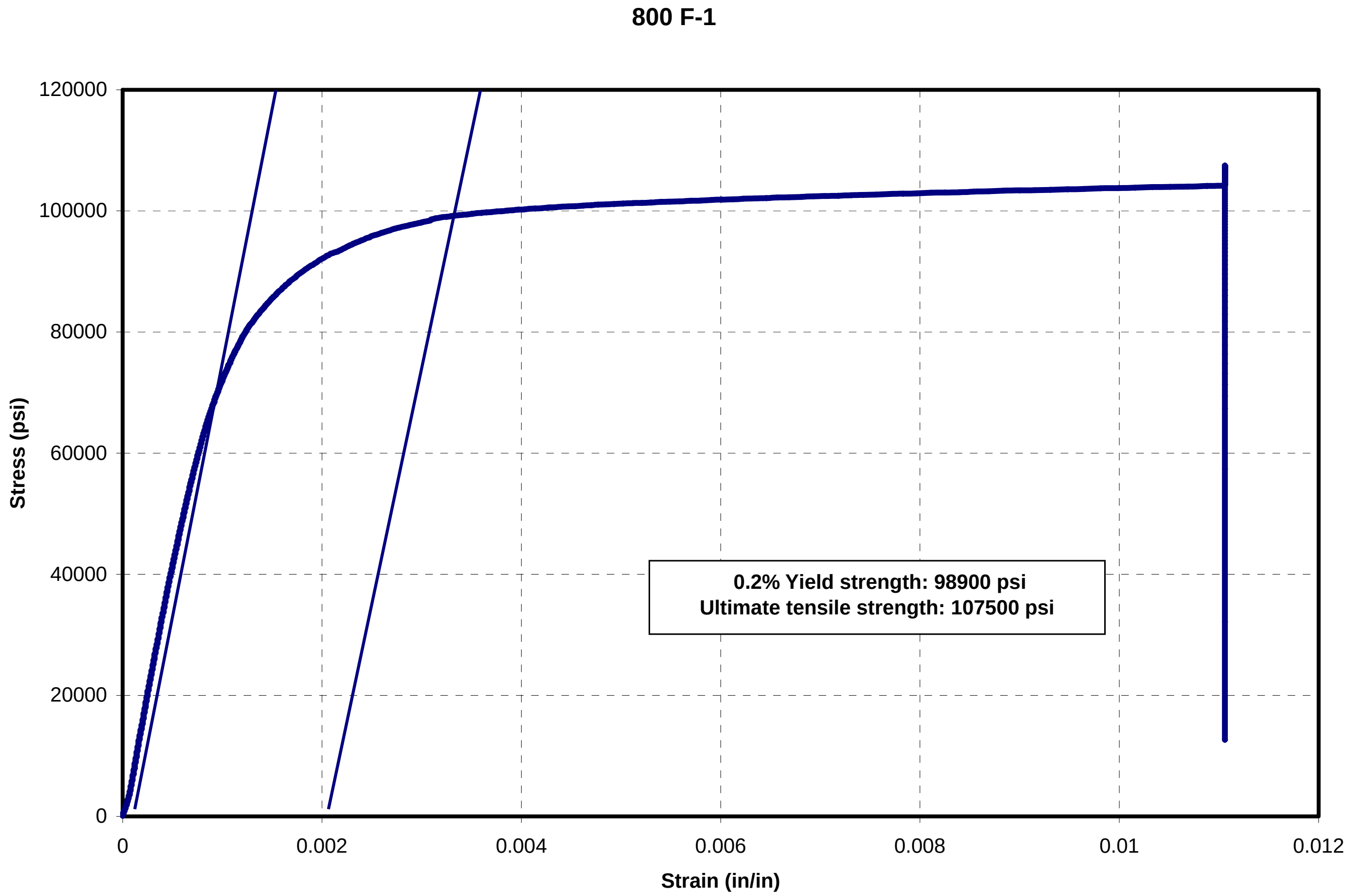
BC04-1063 **49/93**

A 1041-04



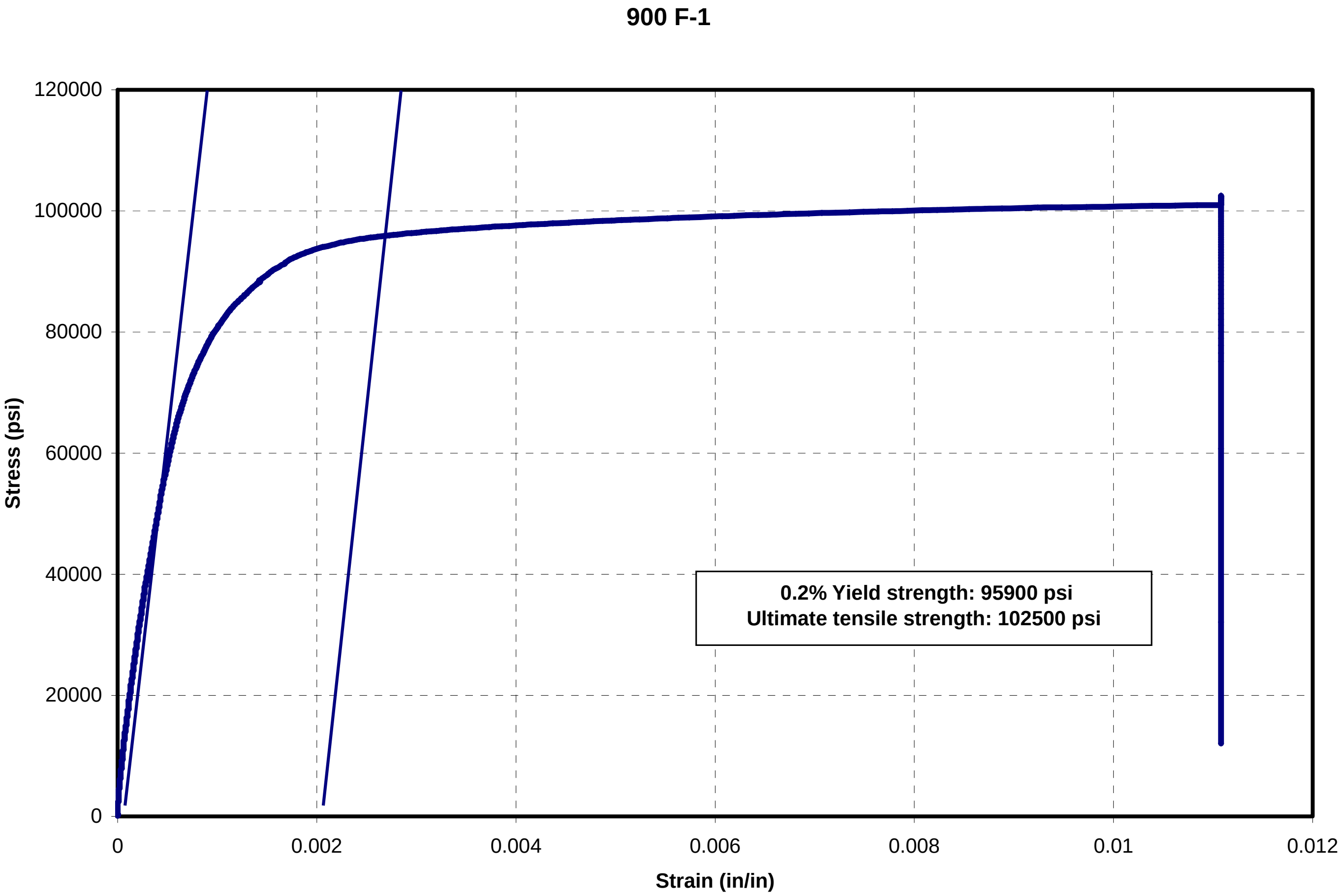
BC04-1063 **50/93**

A 1041-04



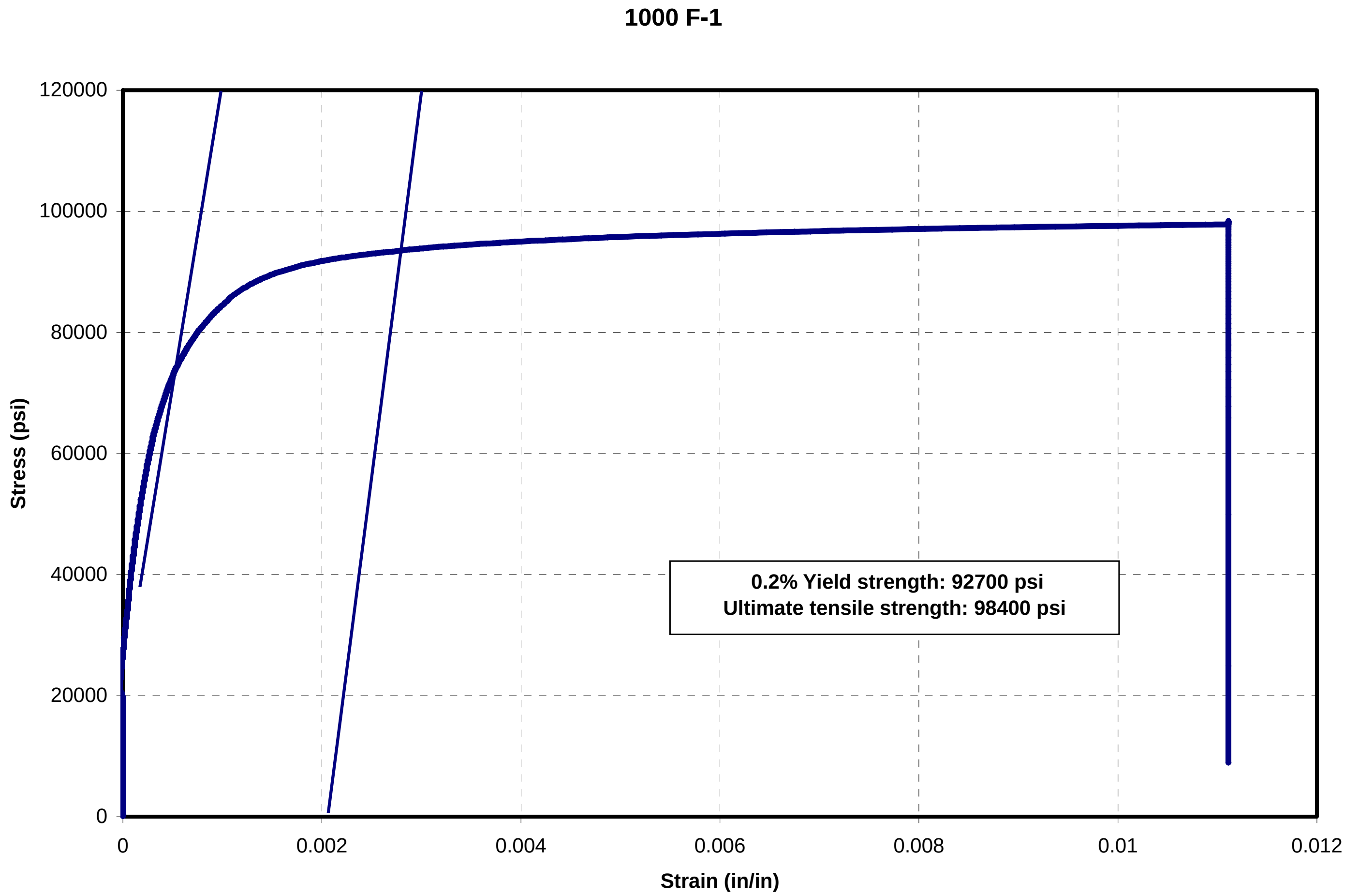
BC04-1063 **51/93**

A 1041-04



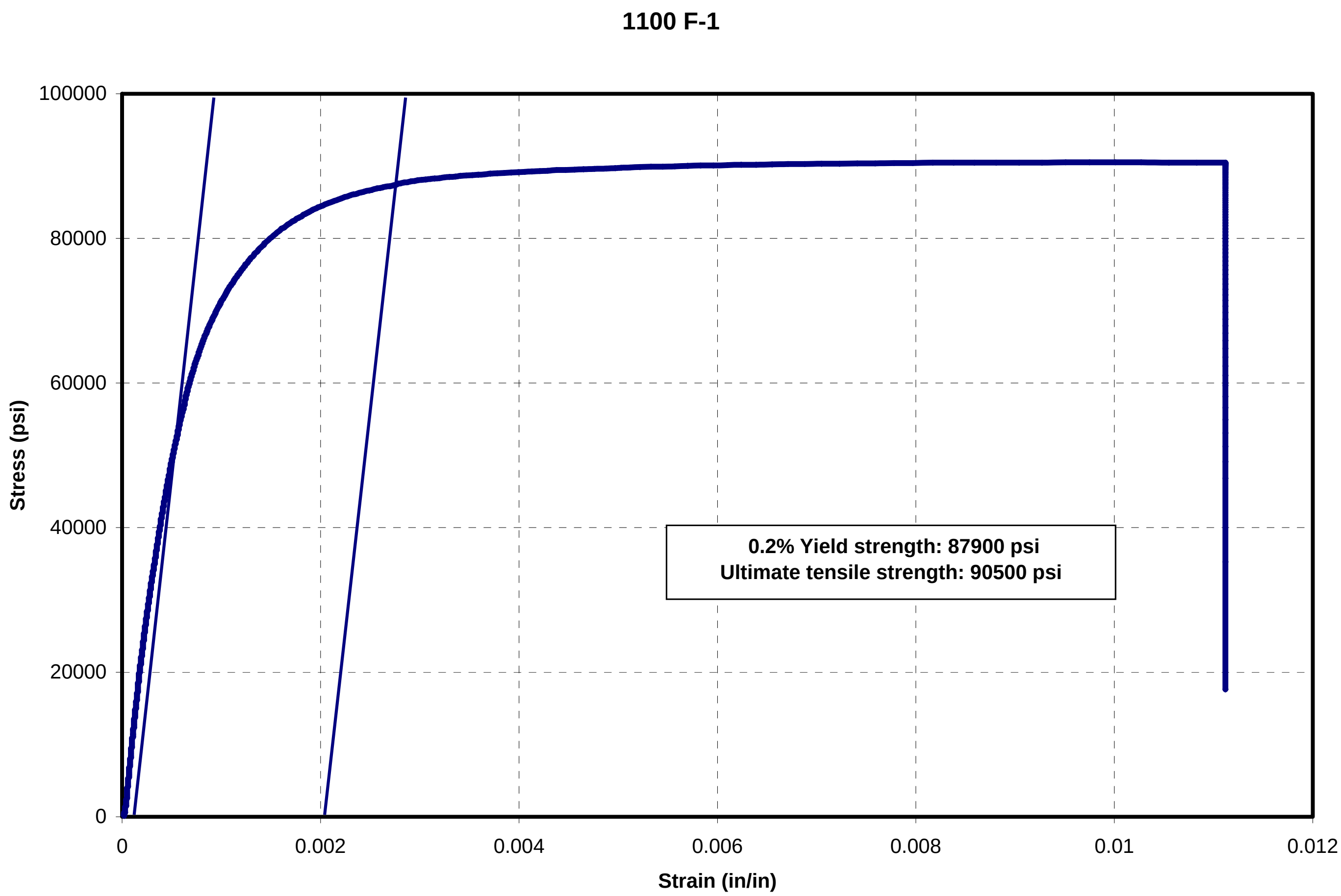
BC04-1063 **52/93**

A 1041-04



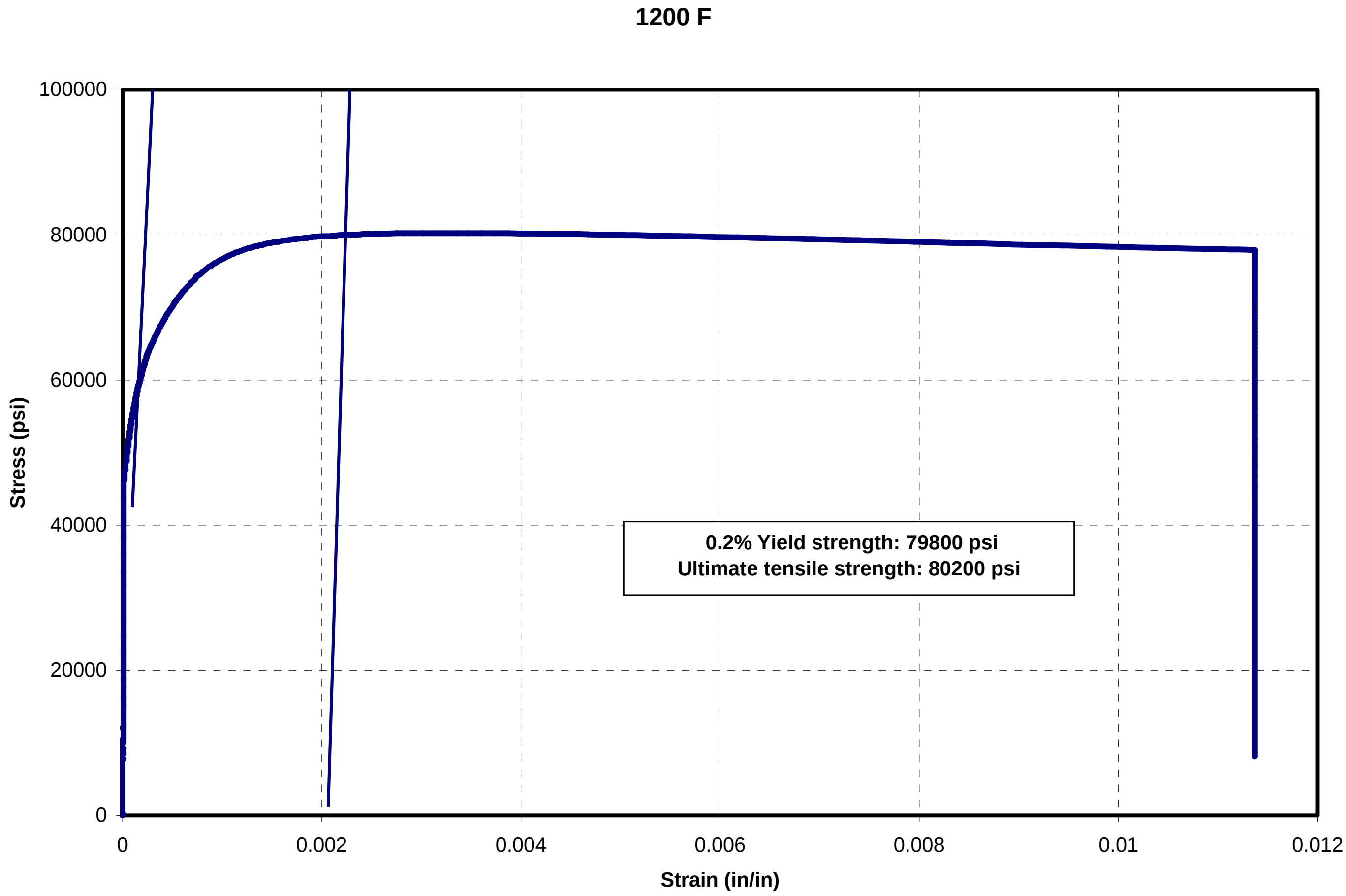
BC04-1063 **53/93**

A 1041-04



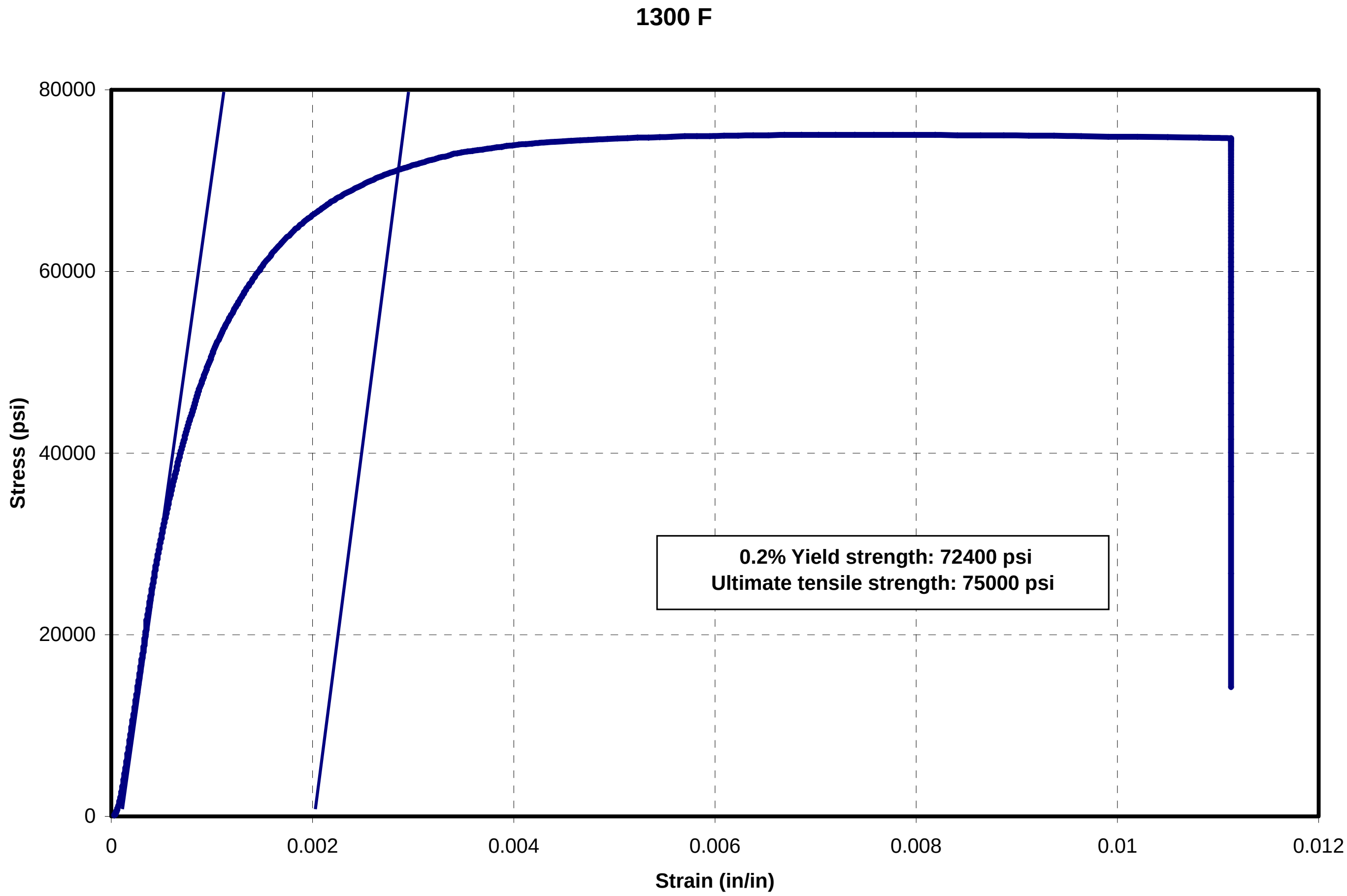
BC04-1063 **54/93**

A 1041-04



BC04-1063 **55/93**

A 1041-04



A 1041-04

Creep Data

A 1041-04

Heat No. 79741 (Commercial Heat No. 1)-1346°F Temper
Heat Treatment N/T 2012°F / 1346°F -1 Hr
Product form ***Forging***- Base metal
Specimen orientation Longitudinal

Test No.	Specimen No.	Temp° F	Stress (ksi)	Rupture time (hr)	Minimum creep rate (%/h)	Rupture elongation (%)	Reduction of area (%)
C79244	79741-C2-12	1100	32.0	493.3	0.0053	19.1	69.9
C79247	79741-C2-15	1100	22.0	1493.1	0.00215	25.3	76.7
C79242	79741-C2-10	1150	30.0	143.8	0.0218	26.1	79.8
C79245	79741-C2-13	1150	20.0	465.0	0.00916	34.6	82.9
C79248*	79741-C2-16	1150	12.0	2701.5			
C79243	79741-C2-11	1200	20.0	142.7	0.0288	26.4	84.9
C79246	79741-C2-14	1200	12.3	725.3	0.01127	33.6	88.6
C79264*	79741-C2-17	1200	9.5	2538.4			

***** Test in progress

A 1041-04

Heat No. 79741(Commercial Heat No. 1)- 1346°F Temper
Heat Treatment N/T 2012°F / 1346°F -1 Hr
Product form ***Plate***- Base metal
Specimen orientation Longitudinal

Test No.	Specimen No.	Temp° F	Stress (ksi)	Rupture time (hr)	Minimum creep rate (%/h)	Rupture elongation (%)	Reduction of area (%)
C79452	741-P-1	1000	62.0	0.6	3.5824	18.2	78.5
C79543	79741-1-2-P8	1000	55.0	7.4	0.3948	24.3	78.0
C79548	79741-1-6-P10	1000	45.0	99	0.03511	21.1	79.5
C79453	741-P-2	1100	40.0	100.7	0.02898	19.8	66.8
C79454	741-P-3	1100	26.0	958.5	0.00278	20.3	64.1
C79554*	79741-1-3-P11	1100	20.0	169.7			
C79455	741-P-4	1150	20.0	515.7	0.0079	26.9	79.7
C79553*	79741-1-1-P9	1150	16.0	196.9			
C79562*	79741-2-1-P12	1150	12.0	137.1			
C79536*	79741-1-4-P6	1200	6.0	313.3			
C79541*	79741-1-5-P7	1200	3.0	238.9			

***** Test in progress

A 1041-04

Heat No. 79742 (Commercial Heat No.2)-1346°F Temper
Heat Treatment N/T 2012°F / 1346°F -1 Hr
Product form ***Forging-*** Base metal
Specimen orientation Longitudinal

Test No.	Specimen No.	Temp° F	Stress (ksi)	Rupture time (hr)	Minimum creep rate (%/h)	Rupture elongation (%)	Reduction of area (%)
C79316	79742-C2-13	1100	32.0	719.0	0.0027	15.5	53.0
C79315	79742-C2-16	1100	22.0	1693.0	0.0011	14.4	68.7
C79312	79742-C2-11	1150	30.0	213.2	0.0101	11.8	48.9
C79320	79742-C2-14	1150	20.0	715.9	0.0057	30.4	78.7
C79338*	79742-C2-17	1150	12.0	1920.2			
C79319	79742-C2-12	1200	20.0	194.8	0.023	29.2	83.4
C79324	79742-C2-15	1200	12.3	917.9	0.0076	48.8	89.5
C79326*	79742-C2-18	1200	9.5	2041.0			

* Test in progress

A 1041-04

Heat No. 79743 (Commercial Heat No. 3) 1292°F Temper
Heat Treatment N/T 2012°F / 1292°F -1 Hr
Product form ***Forging***- Base metal
Specimen orientation Longitudinal

Test No.	Specimen No.	Temp° F	Stress (ksi)	Rupture time (hr)	Minimum creep rate (%/h)	Rupture elongation (%)	Reduction of area (%)
C78960	79743-C2-12	1100	32.0	616.7	0.00206	23.0	78.1
C78957	79743-C2-15	1100	22.0	1715.8	0.001	20.2	80.8
C78962	79743-C2-10	1150	30.0	143.5	0.012	16.9	79.0
C78959	79743-C2-13	1150	20.0	613.4	0.00295	25.7	82.5
C78955*	79743-C2-16	1150	12.0	4390.0			
C78961	79743-C2-11	1200	20.0	135.8	0.022	28.3	87.9
C78958	79743-C2-14	1200	12.3	1128.0	0.0056	30.6	88.3
C78956	79743-C2-17	1200	9.5	3098.3	0.0026	25.8	80.2

* Test in progress

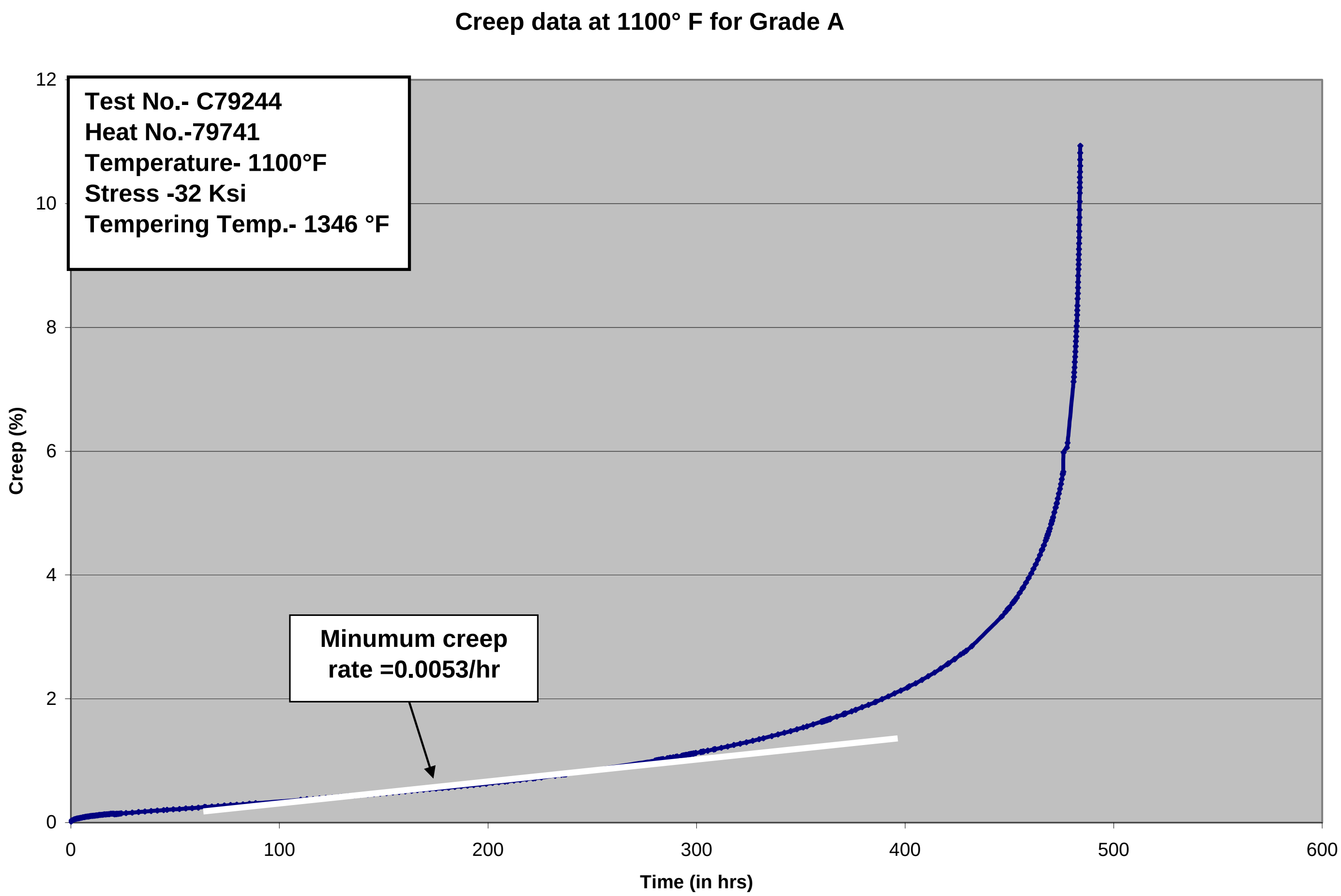
A 1041-04

Heat No. 79743 (Commercial Heat No.3)-1346°F Temper
Heat Treatment N/T 2012°F / 1346°F -1 Hr
Product form ***Forging-*** Base metal
Specimen orientation Longitudinal

Test No.	Specimen No.	Temp° F	Stress (ksi)	Rupture time (hr)	Minimum creep rate (%/h)	Rupture elongation (%)	Reduction of area (%)
C79458	79743-C3-2	900	72.0	251.7	0.0053	14.3	72.3
C79459*	79743-C3-3	900	65.0	1035.5			
C79460	79743-C3-4	1000	62.0	40.6	0.0514	17.8	74.8
C79461	79743-C3-5	1000	55.0	311.9	0.0076	17.4	72.2
C79465*	79743-C3-6	1000	49.0	1010.2			
C79466*	79743-C3-7	1000	47.0	1010.2			
C79533*	79743-C3-8	1000	40.0	334.5			
C79176	79743-C2-12	1100	32.0	1225.0	0.0013	6.1	15.9
C79183*	79743-C2-15	1100	22.0	3094.6			
C79182	79743-C2-13	1150	20.0	1414.9	0.002	14.7	44.5
C79184*	79743-C2-16	1150	12.0	3095.2			
C79175	79743-C2-11	1200	20.0	325.3	0.0117	24.7	73.1
C79162	79743-C2-14	1200	12.3	1771.7	0.004	28.8	73.6
C79185*	79743-C2-17	1200	9.5	3094.7			

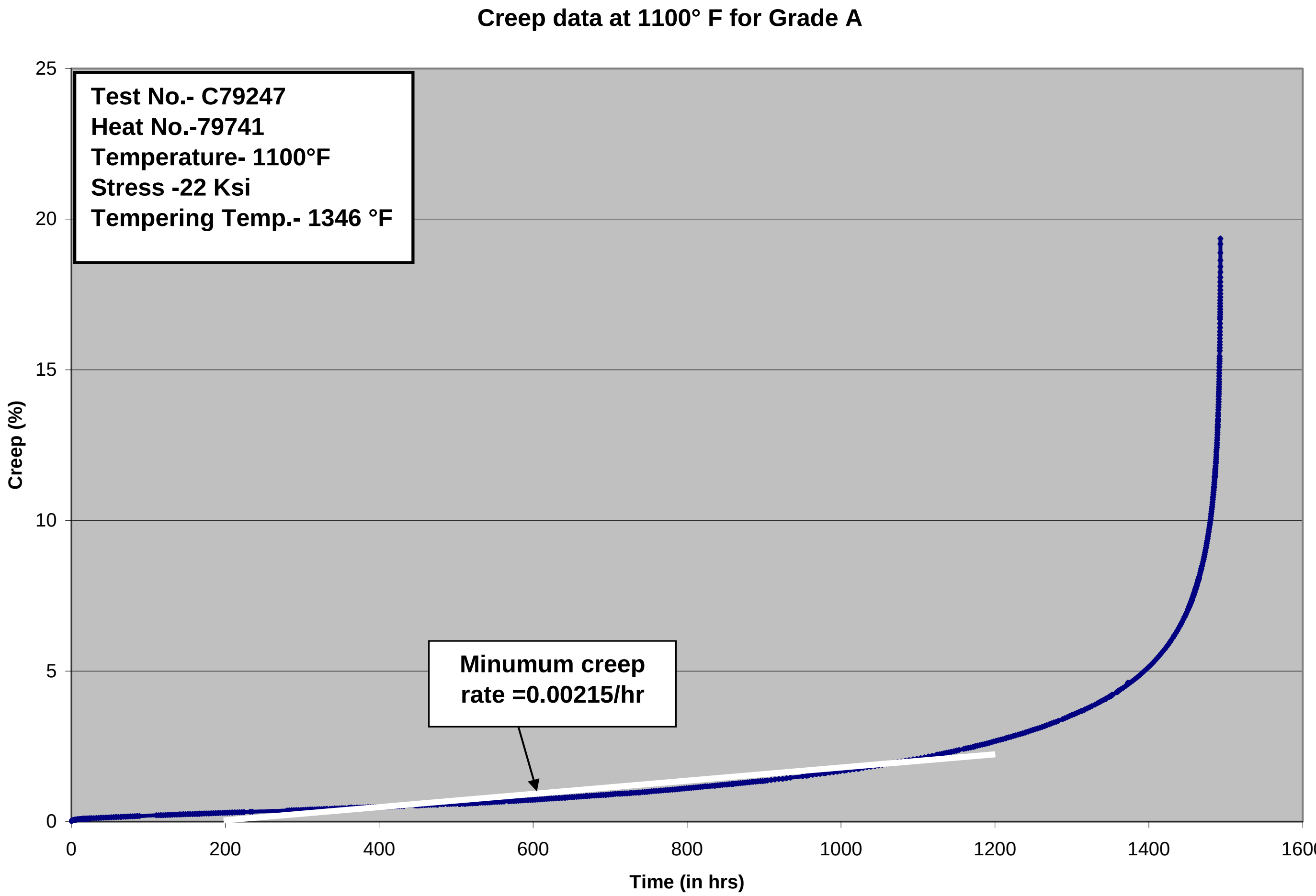
***** Test in progress

A 1041-04

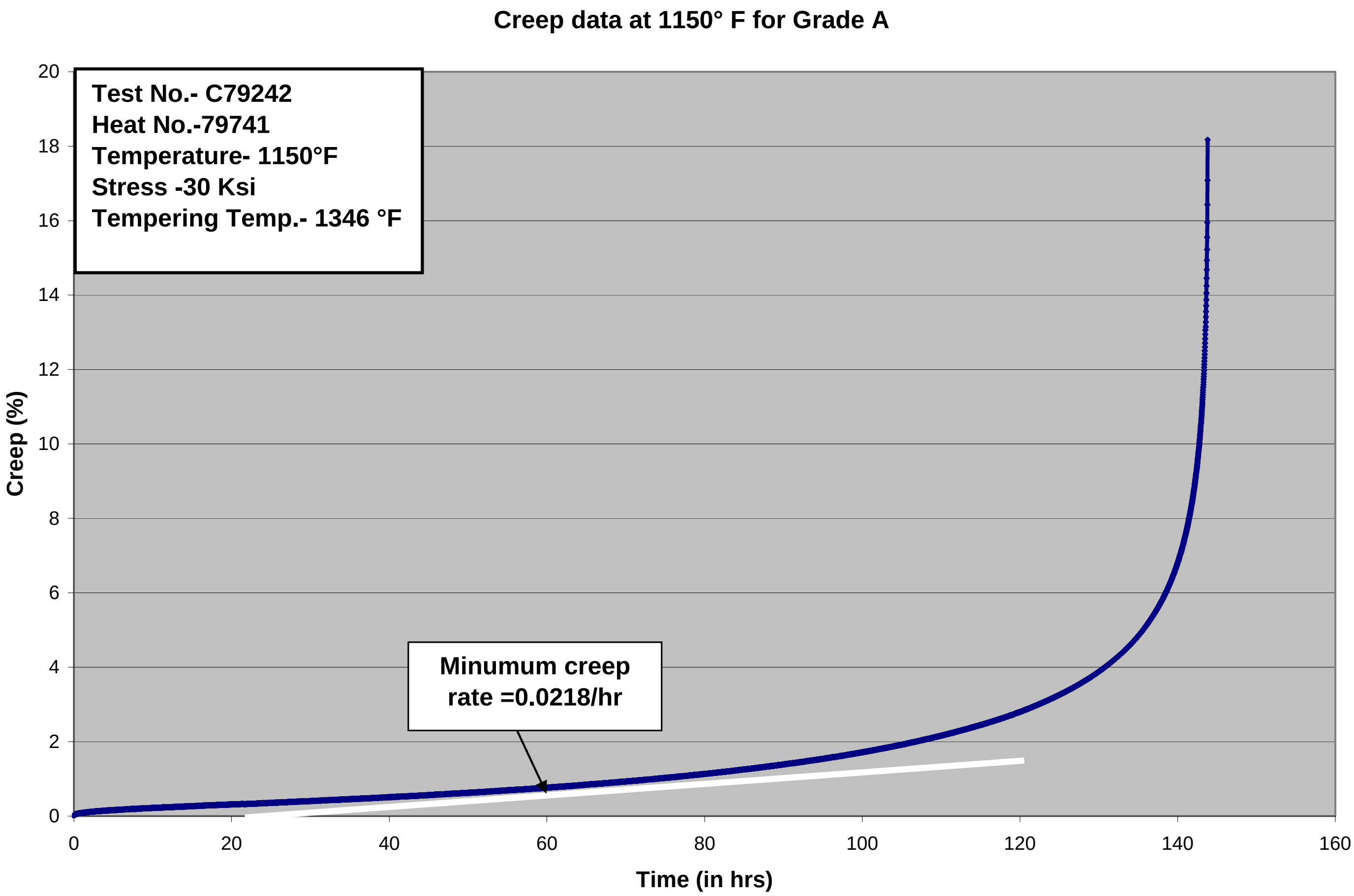

Creep data at 1100° F for Grade A
Test No.- C79244
Heat No.-79741
Temperature- 1100°F
Stress -32 Ksi
Tempering Temp.- 1346 °F
Minumum creep rate =0.0053/hr
Creep (%)
Time (in hrs)
0
2
4
6
8
10
12
0
100
200
300
400
500
600

BC04-1063 **63/93**

A 1041-04

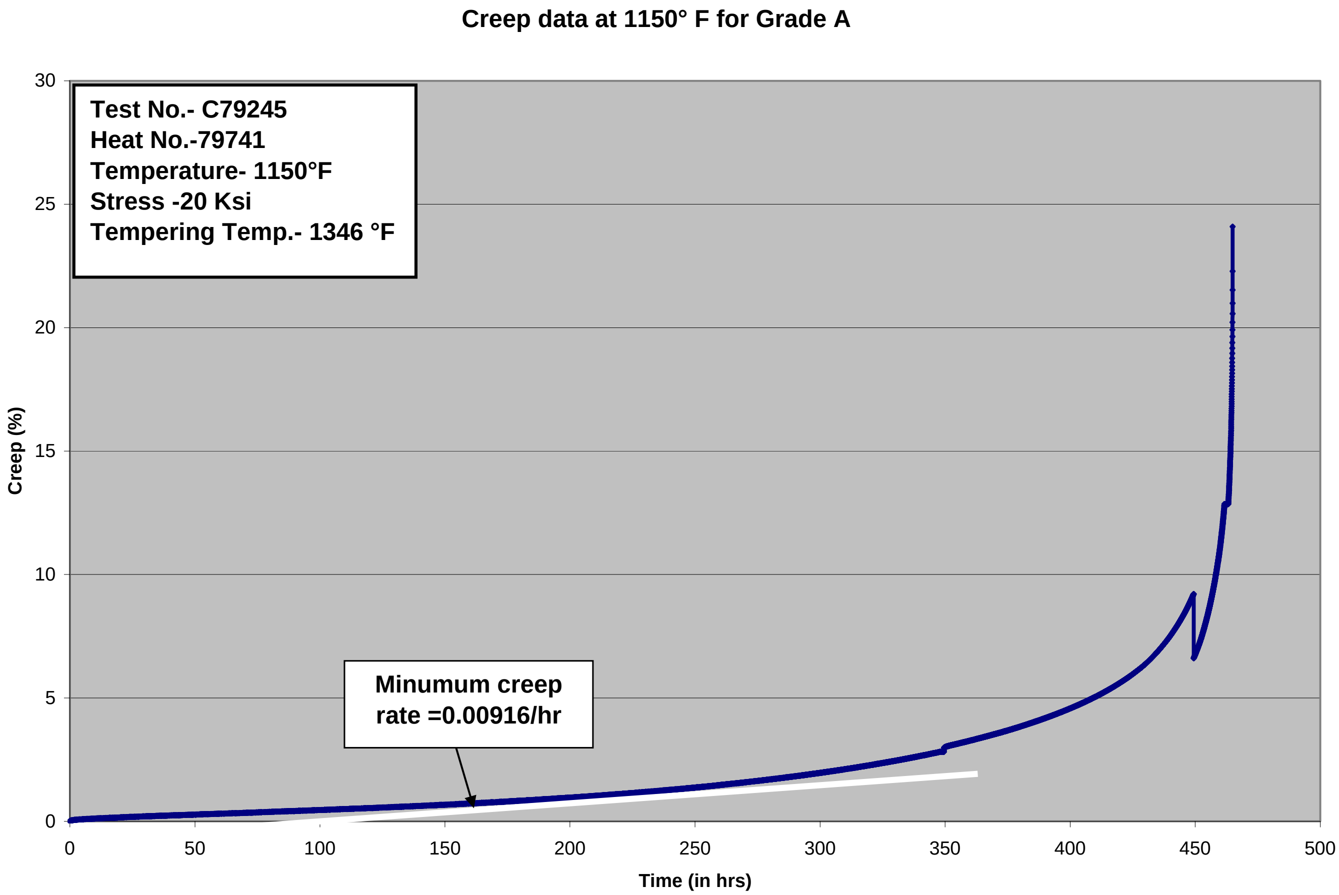


A 1041-04


Creep data at 1150° F for Grade A
Test No.- C79242
Heat No.-79741
Temperature- 1150°F
Stress -30 Ksi
Tempering Temp.- 1346 °F
Minumum creep rate =0.0218/hr
Creep (%)
0
2
4
6
8
10
12
14
16
18
20
0
20
40
60
80
100
120
140
160
Time (in hrs)

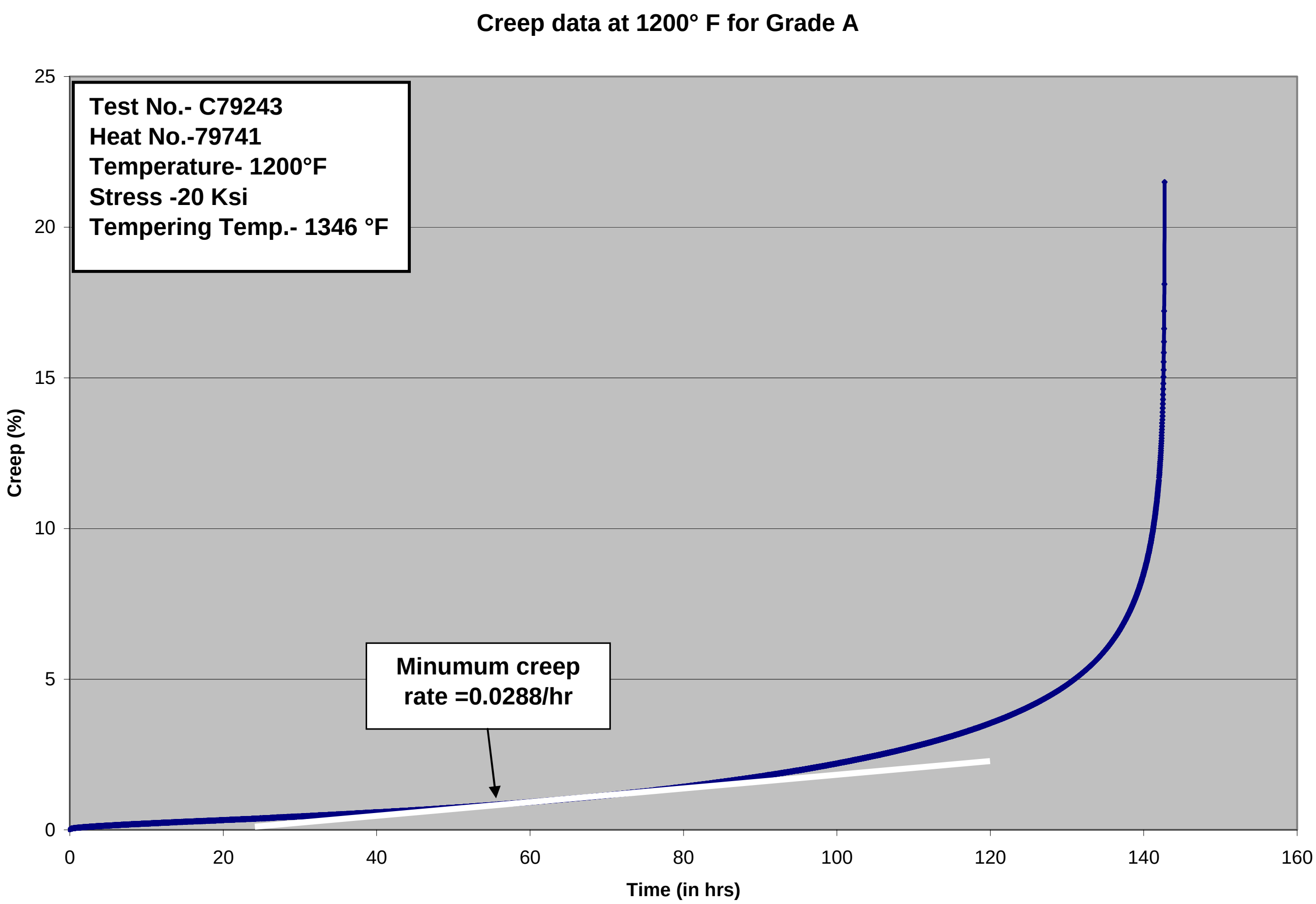
BC04-1063 **65/93**

A 1041-04



BC04-1063 **66/93**

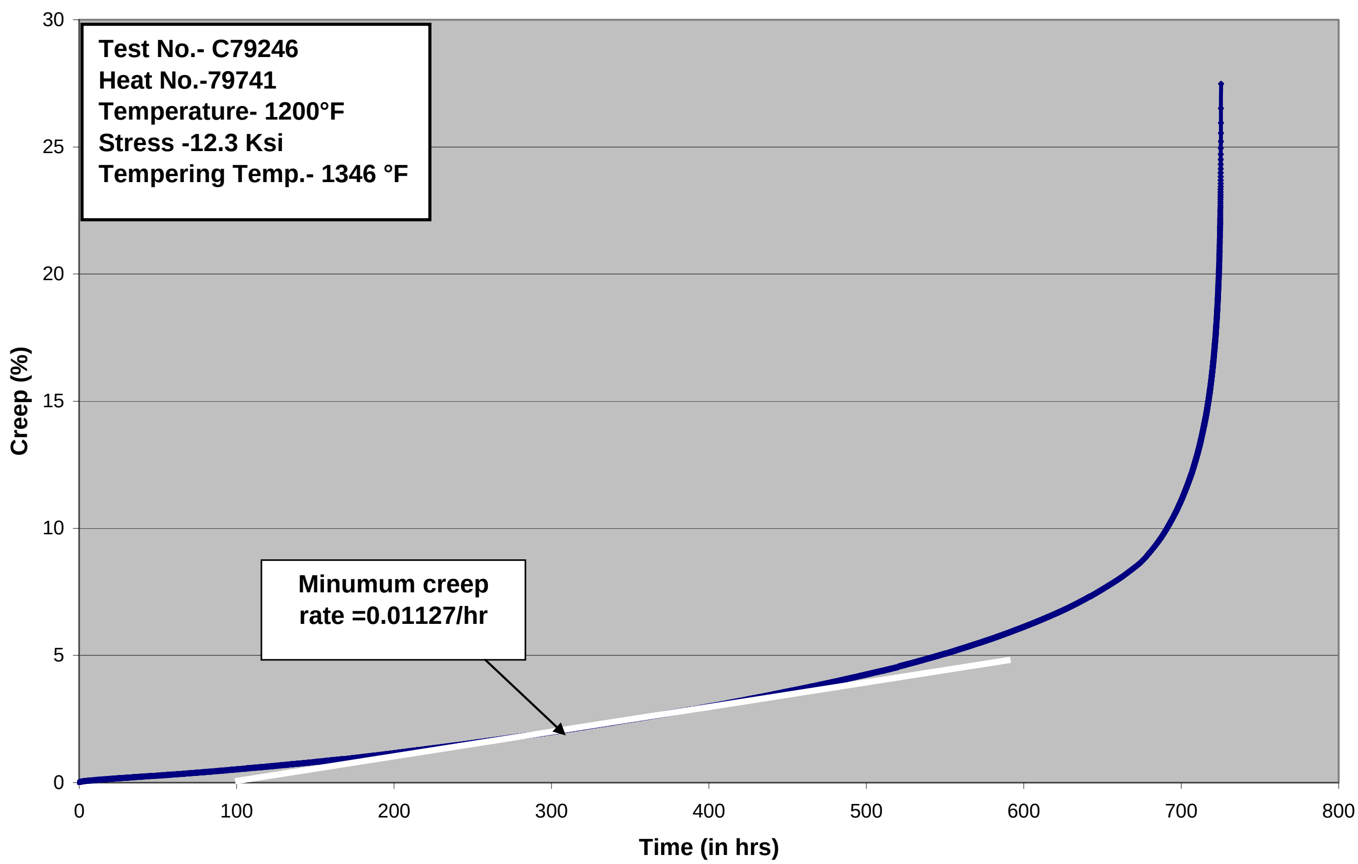
A 1041-04



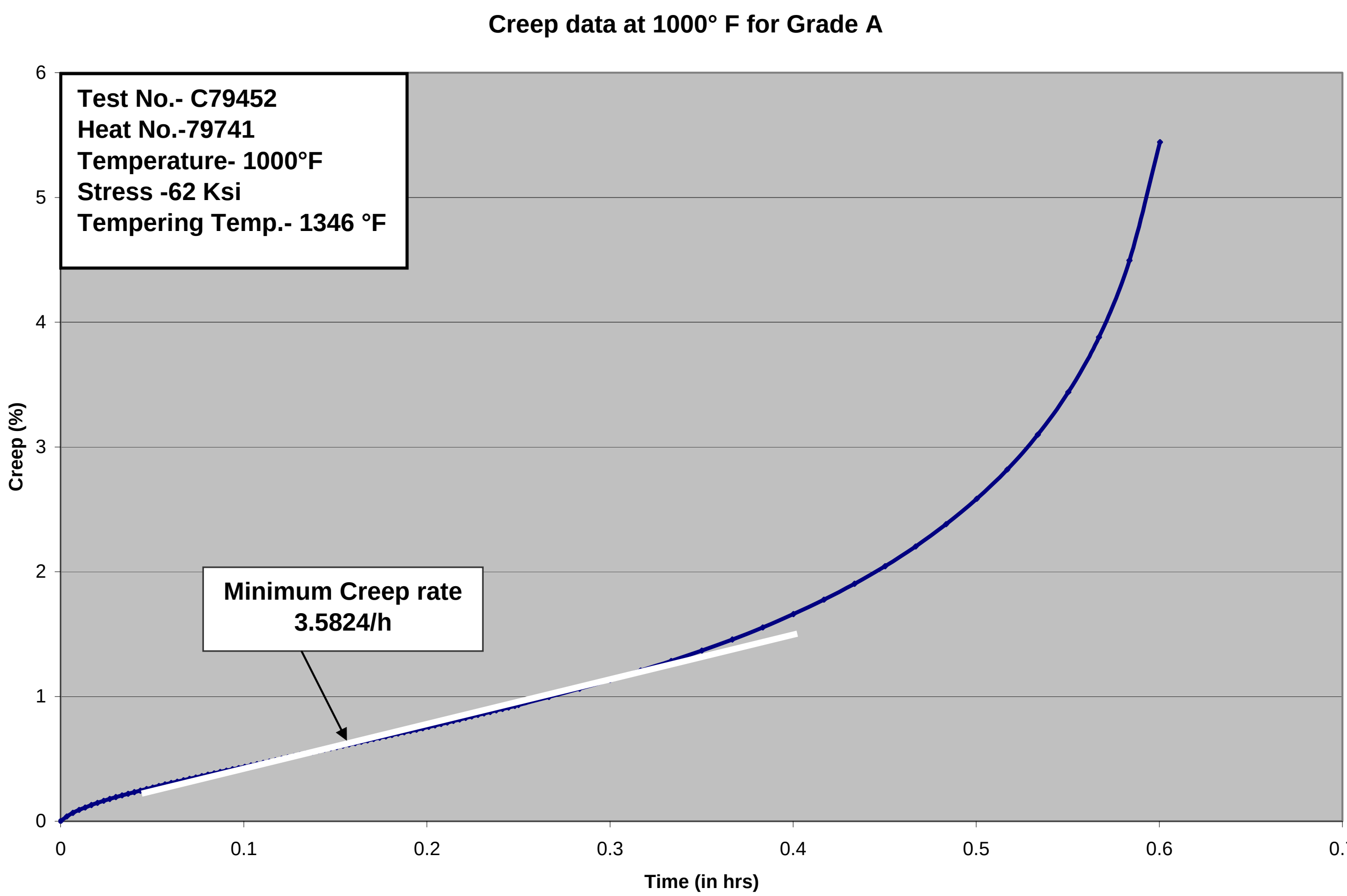
BC04-1063 **67/93**

A 1041-04

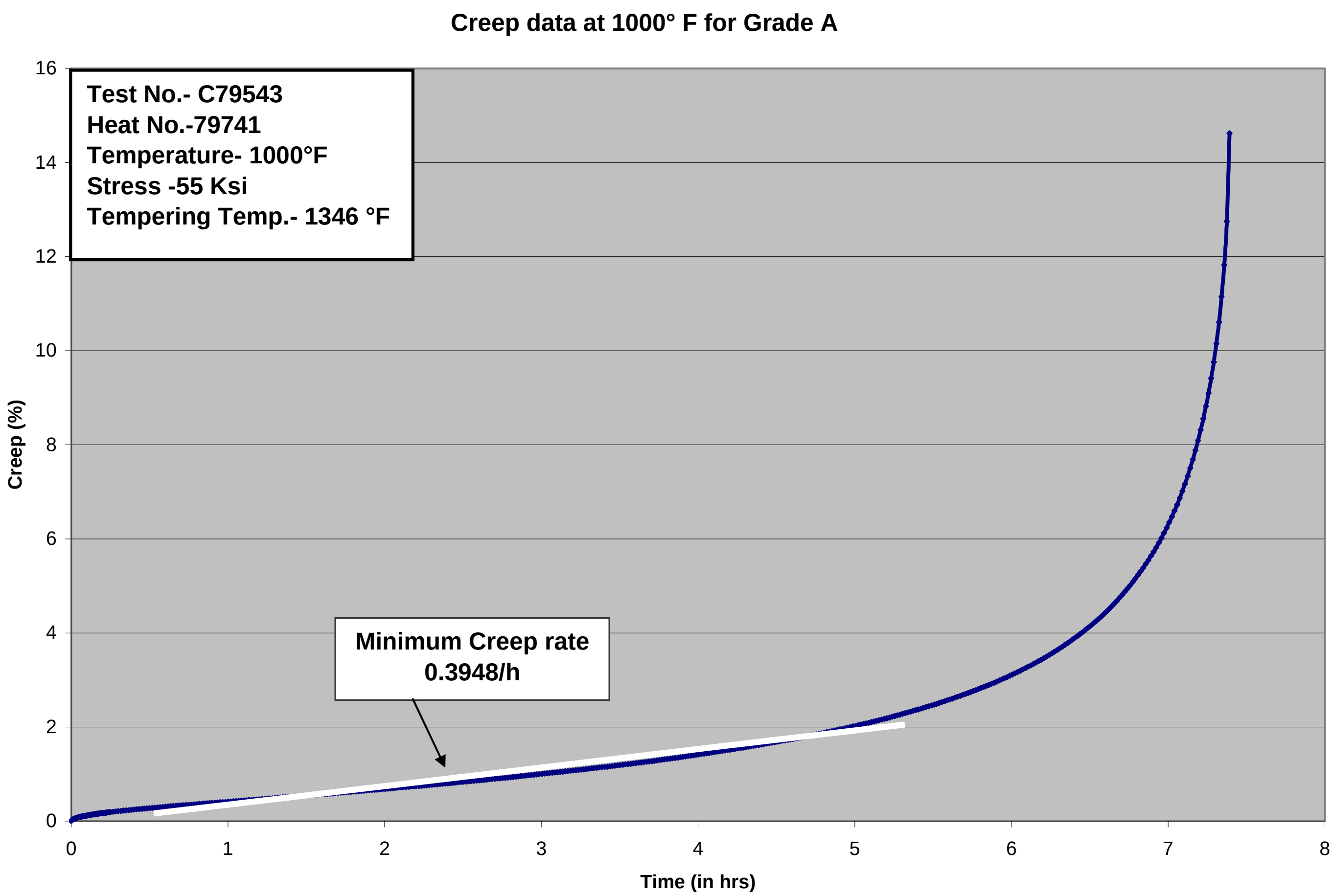
Creep data at 1200° F for Grade A



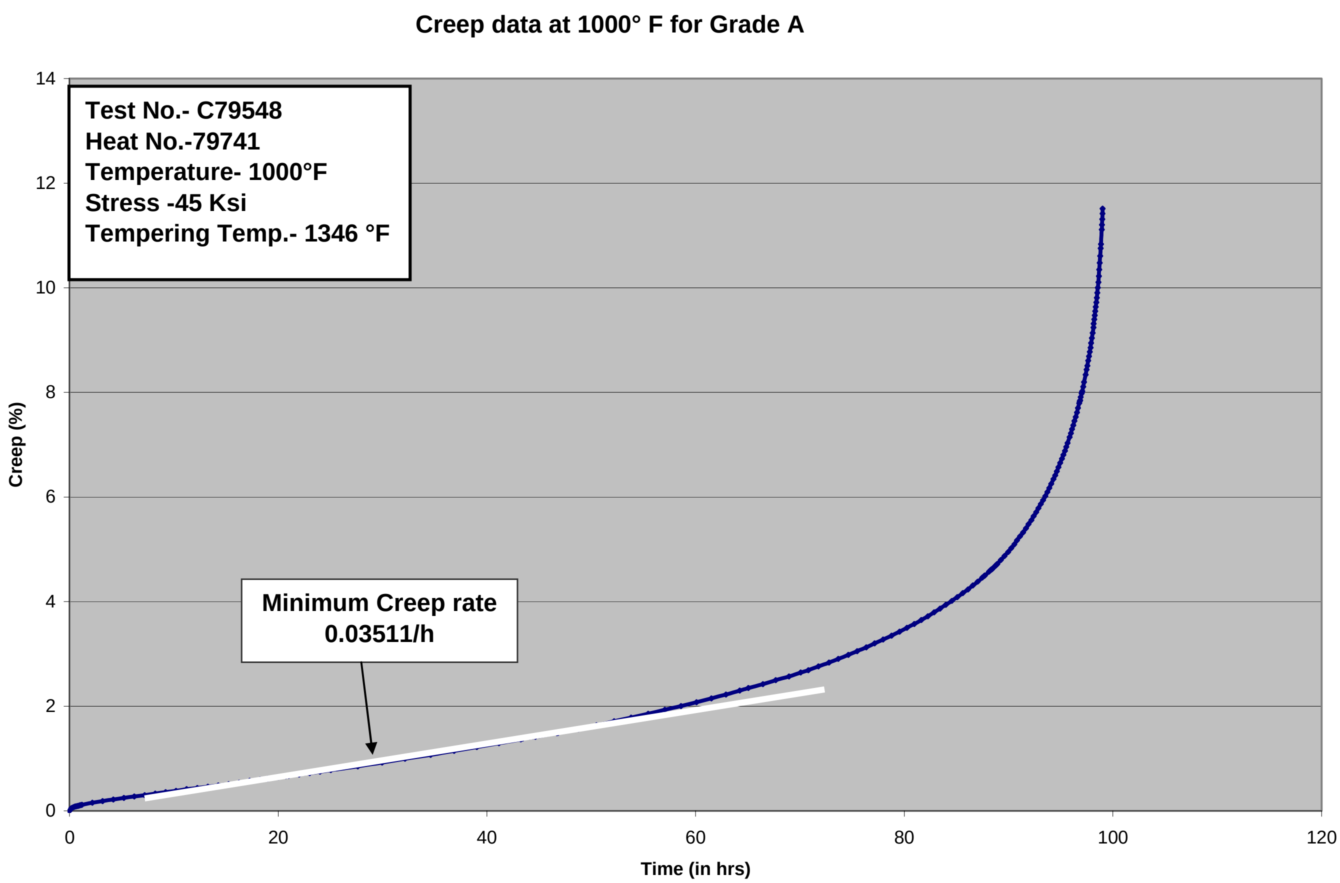
A 1041-04


Creep data at 1000° F for Grade A
Test No.- C79452
Heat No.-79741
Temperature- 1000°F
Stress -62 Ksi
Tempering Temp.- 1346 °F
Minimum Creep rate
3.5824/h
Creep (%)
0
1
2
3
4
5
6
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Time (in hrs)

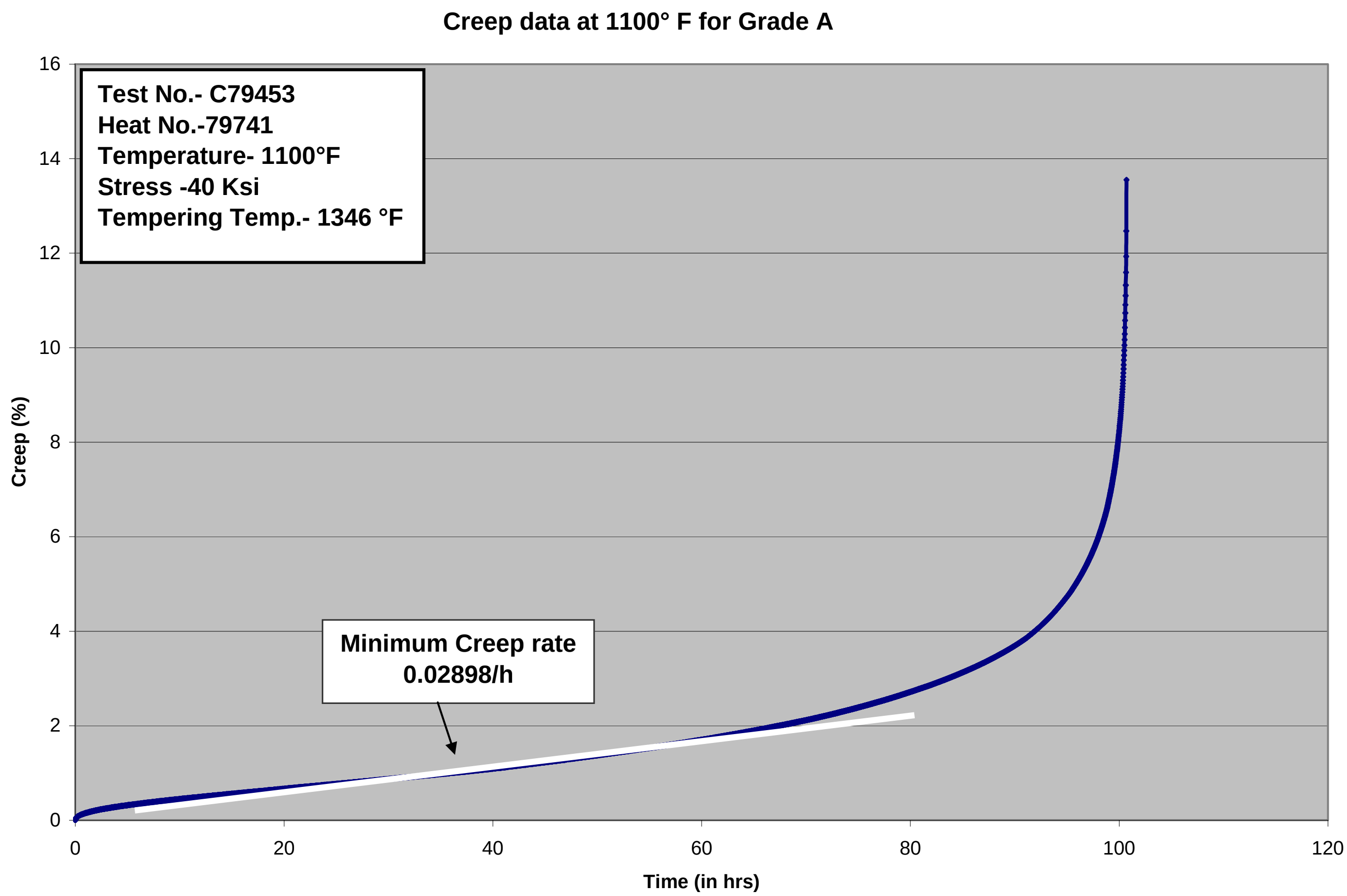
A 1041-04


Creep data at 1000° F for Grade A
Test No.- C79543
Heat No.-79741
Temperature- 1000°F
Stress -55 Ksi
Tempering Temp.- 1346 °F
Minimum Creep rate
0.3948/h
Creep (%)
Time (in hrs)
0
2
4
6
8
10
12
14
16
0
1
2
3
4
5
6
7
8

A 1041-04

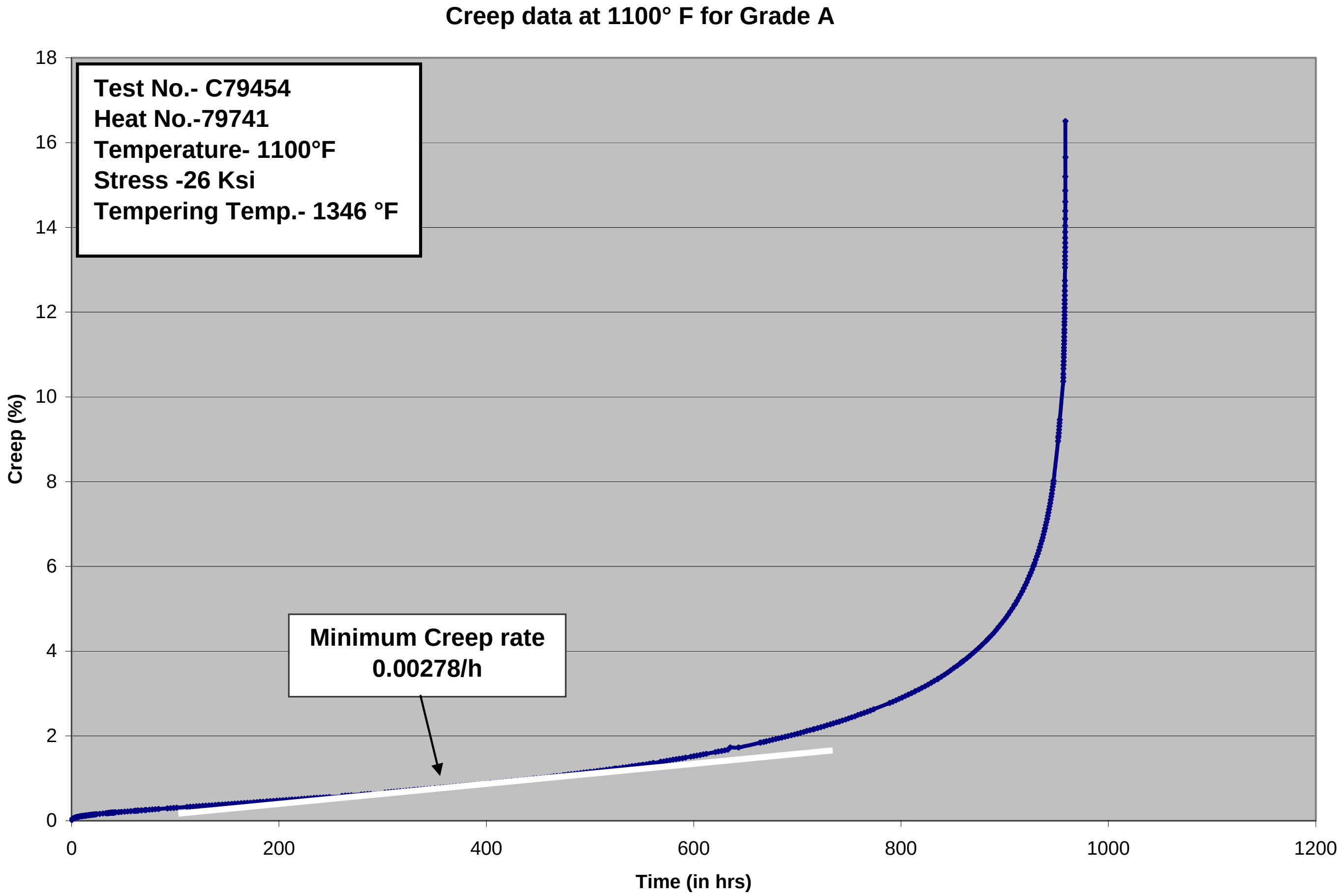

Creep data at 1000° F for Grade A
Test No.- C79548
Heat No.-79741
Temperature- 1000°F
Stress -45 Ksi
Tempering Temp.- 1346 °F
Minimum Creep rate
0.03511/h
Creep (%)
Time (in hrs)
0
2
4
6
8
10
12
14
0
20
40
60
80
100
120

A 1041-04


Creep data at 1100° F for Grade A
Test No.- C79453
Heat No.-79741
Temperature- 1100°F
Stress -40 Ksi
Tempering Temp.- 1346 °F
Minimum Creep rate
0.02898/h
Creep (%)
Time (in hrs)
0
2
4
6
8
10
12
14
16
0
20
40
60
80
100
120

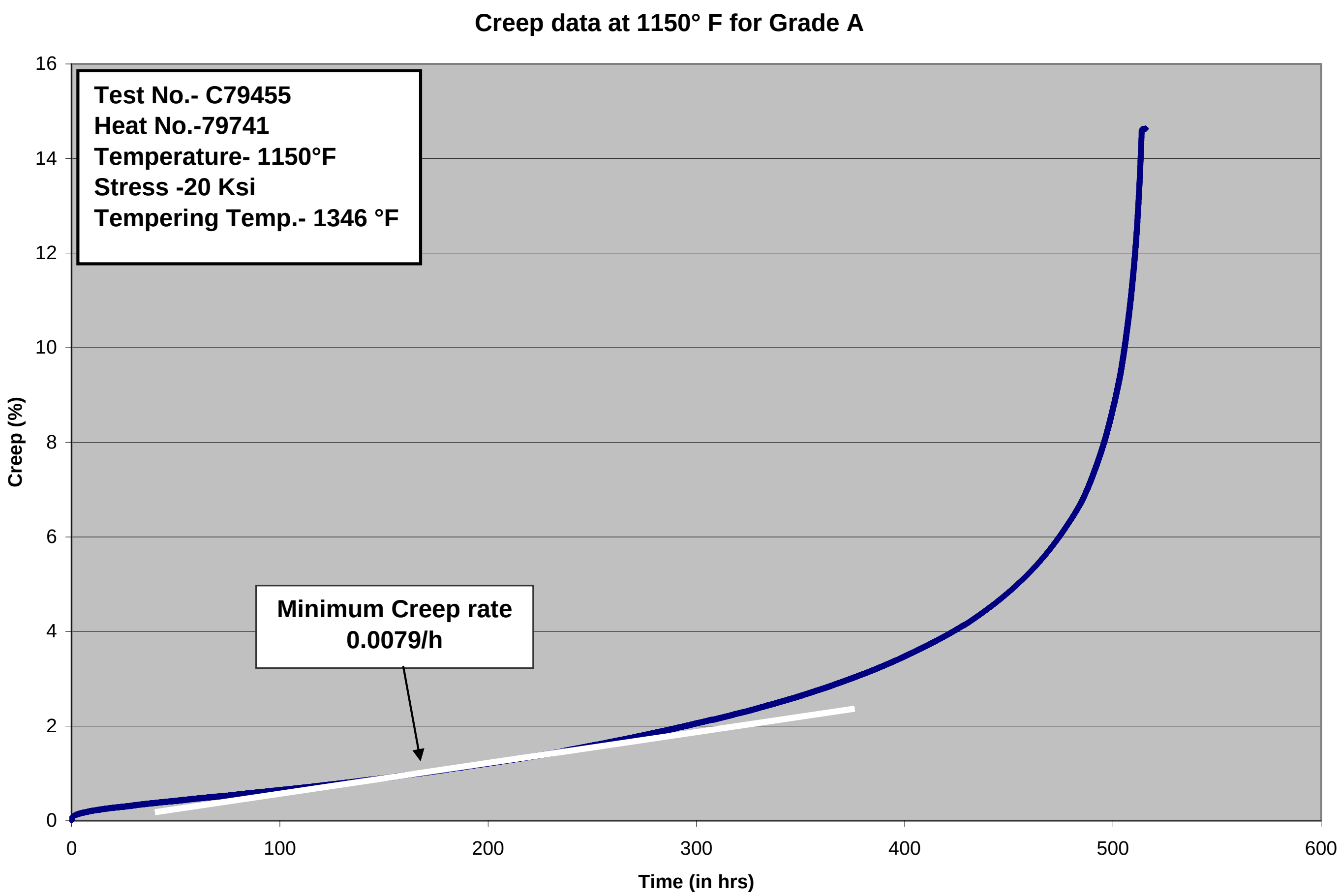
BC04-1063 **72/93**

A 1041-04



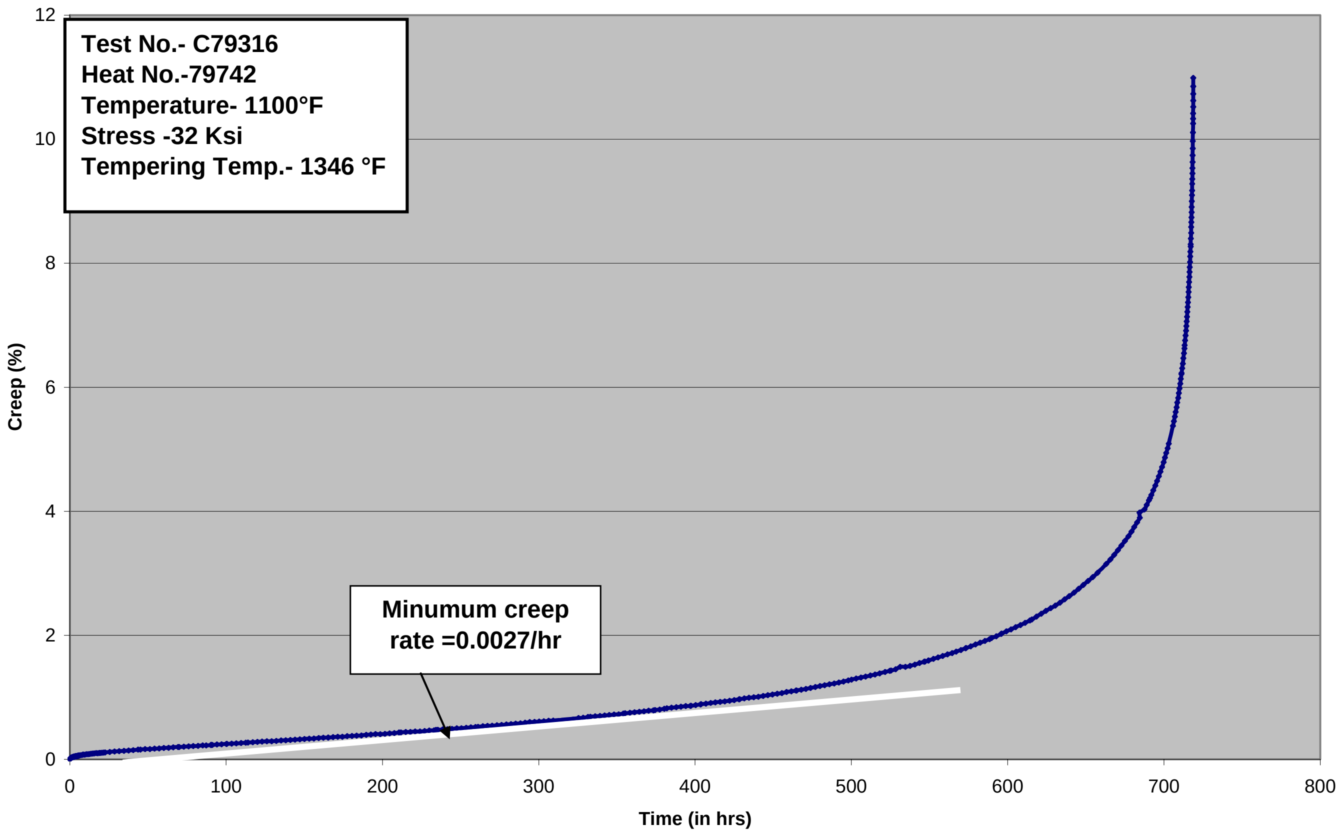
BC04-1063 **73/93**

A 1041-04



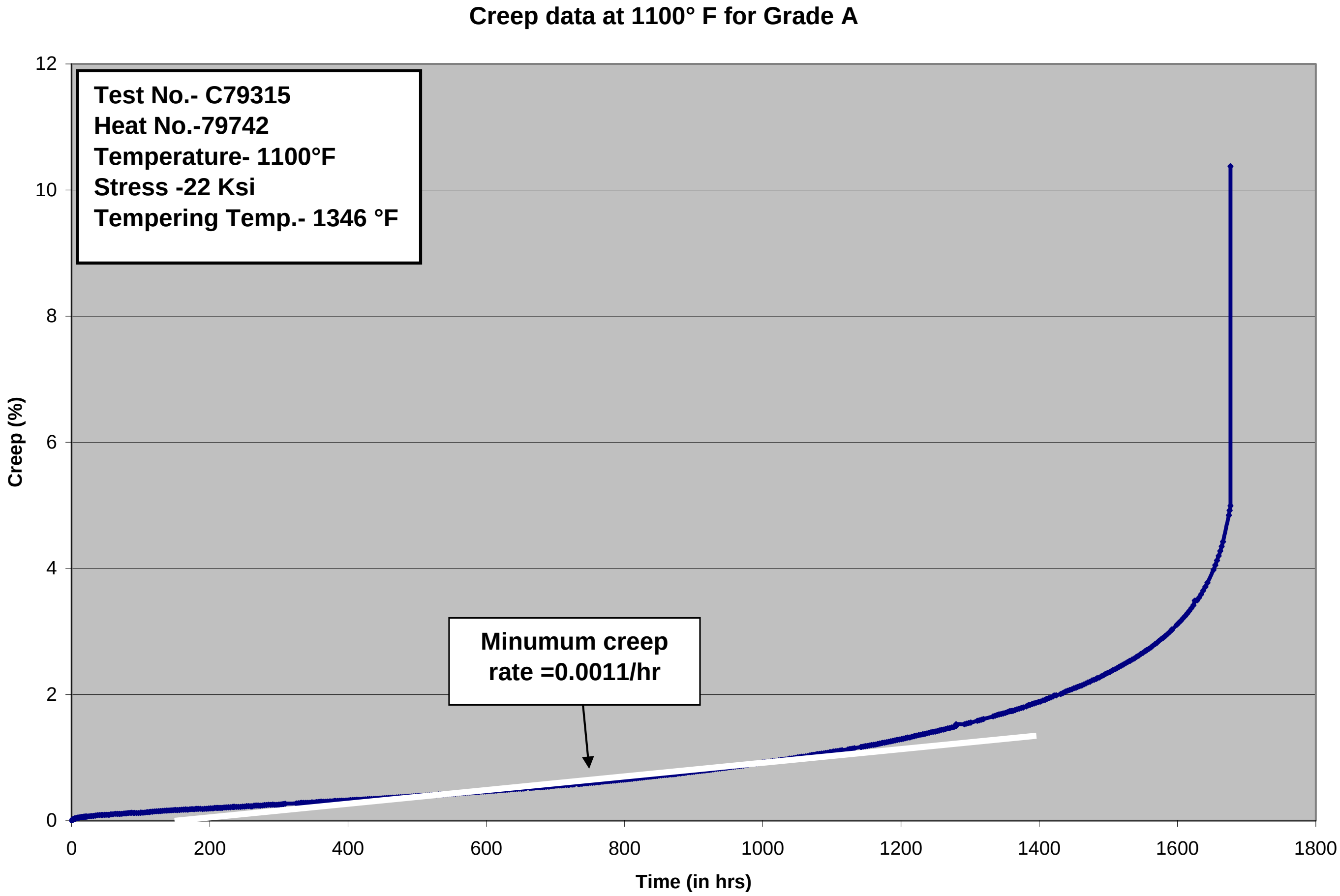
A 1041-04

Creep data at 1100° F for Grade A



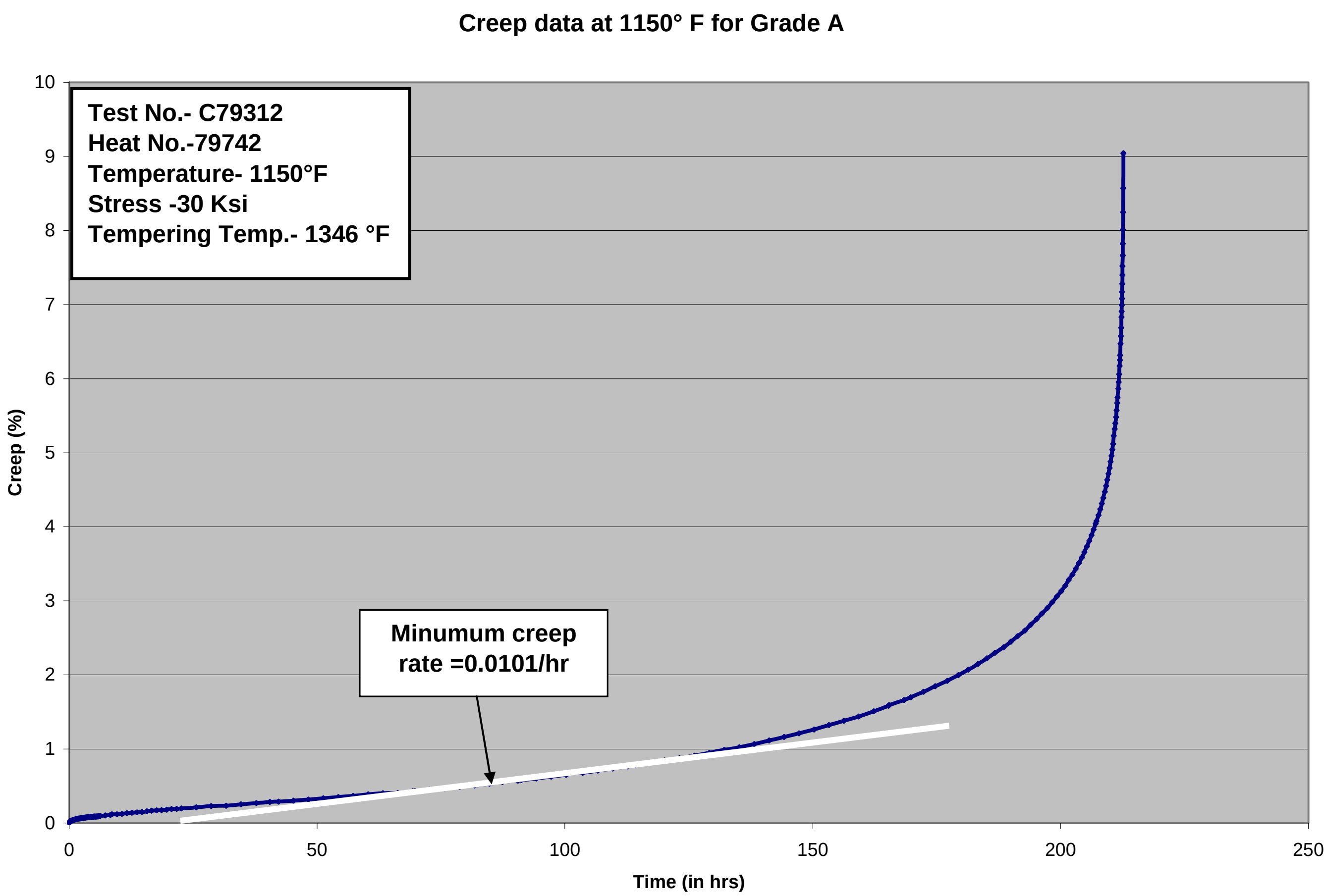
BC04-1063 **75/93**

A 1041-04



BC04-1063 **76/93**

A 1041-04



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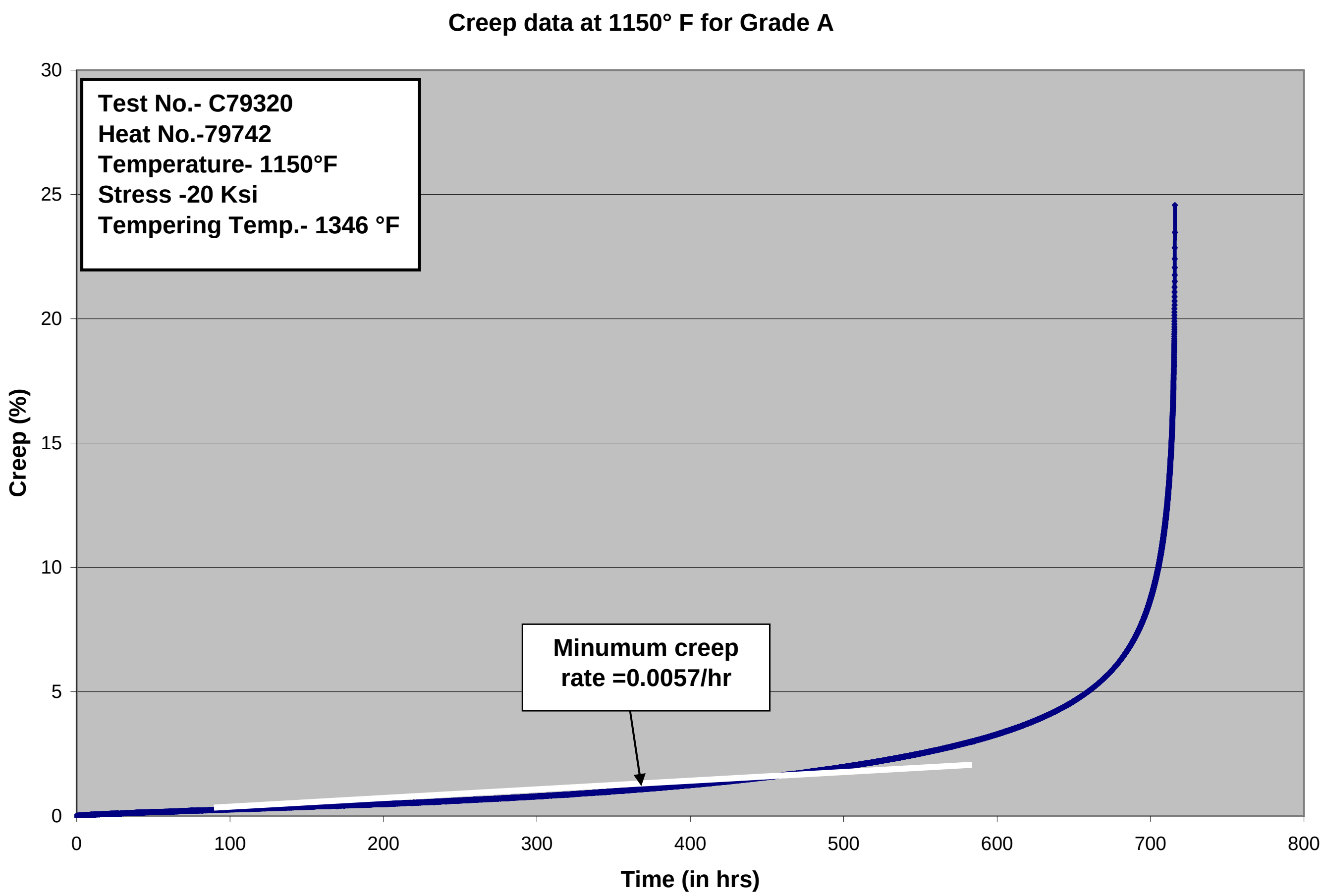
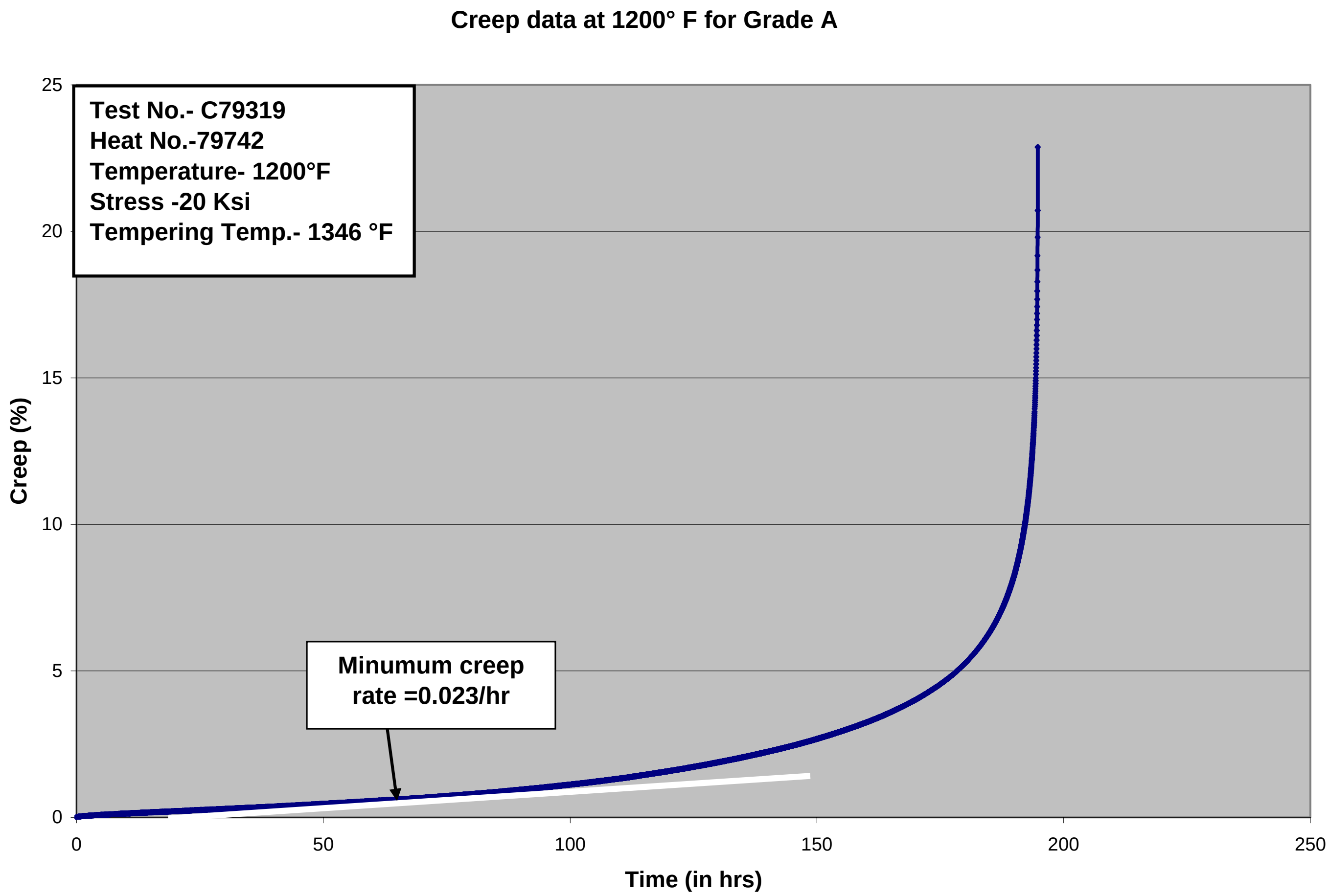

Creep data at 1150° F for Grade A
Test No.- C79320
Heat No.-79742
Temperature- 1150°F
Stress -20 Ksi
Tempering Temp.- 1346 °F
Minumum creep rate =0.0057/hr
Creep (%)
Time (in hrs)
0
5
10
15
20
25
30
0
100
200
300
400
500
600
700
800

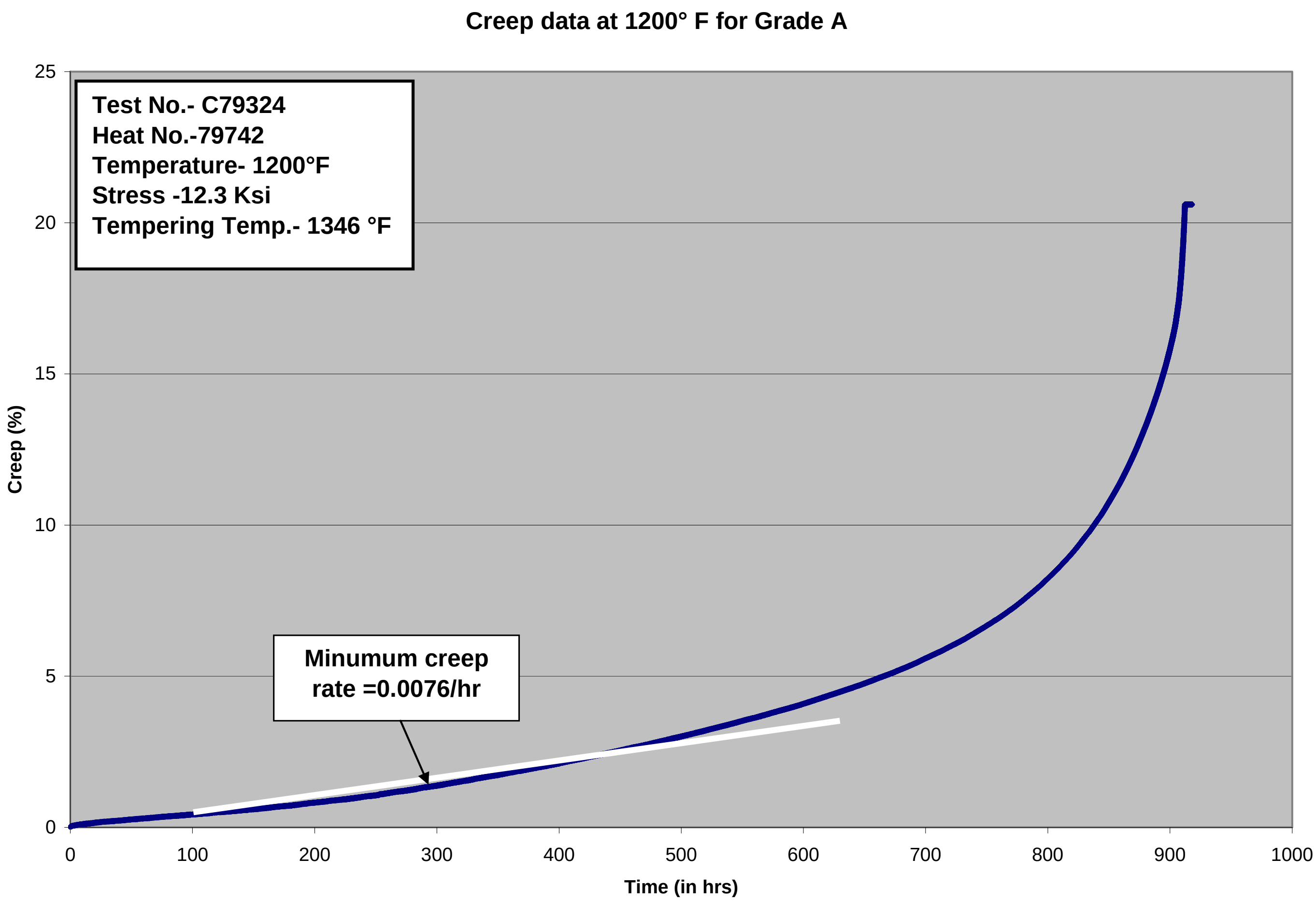
BC04-1063 **78/93**

A 1041-04



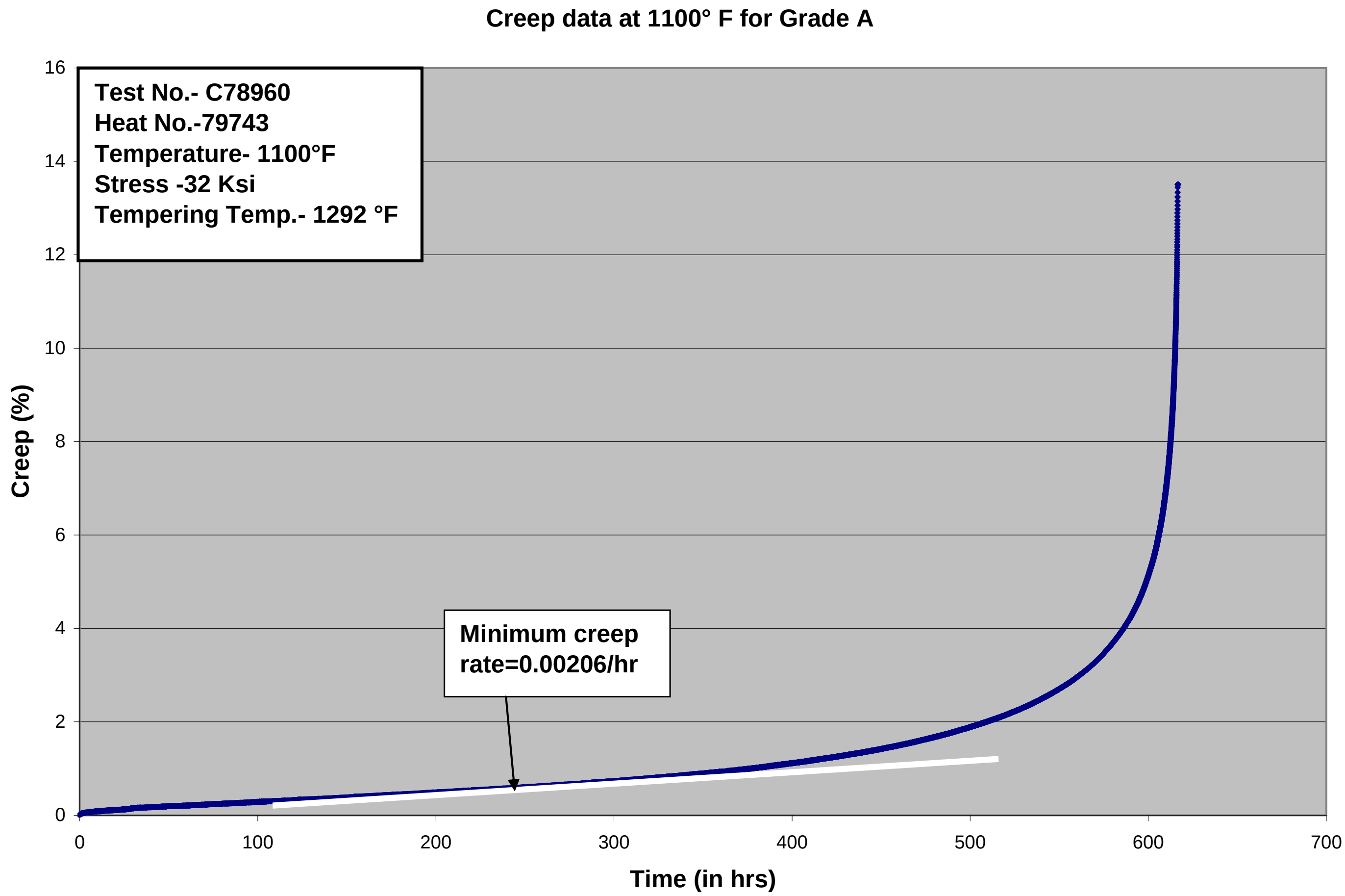
BC04-1063 **79/93**

A 1041-04



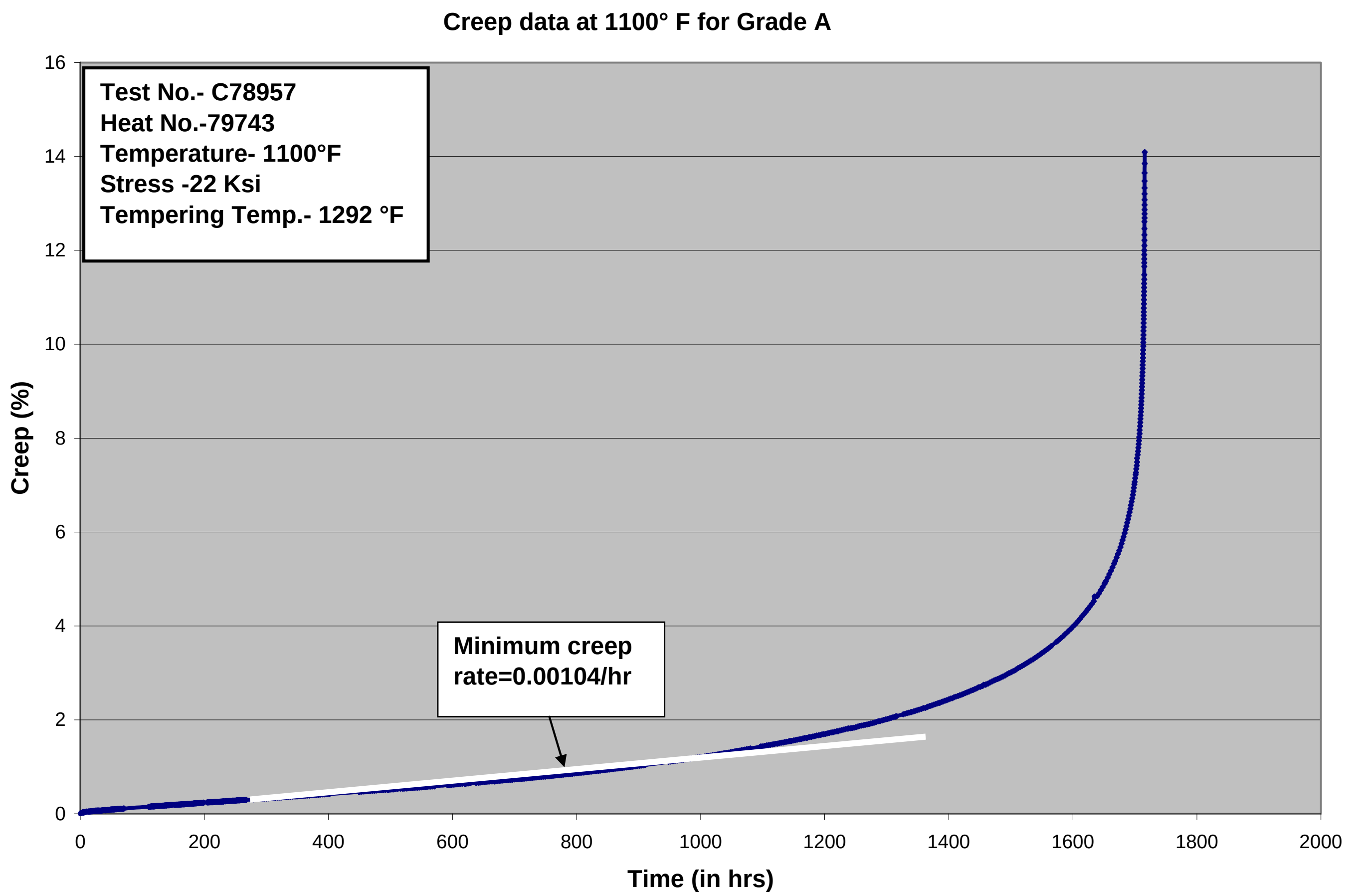
BC04-1063 **80/93**

A 1041-04



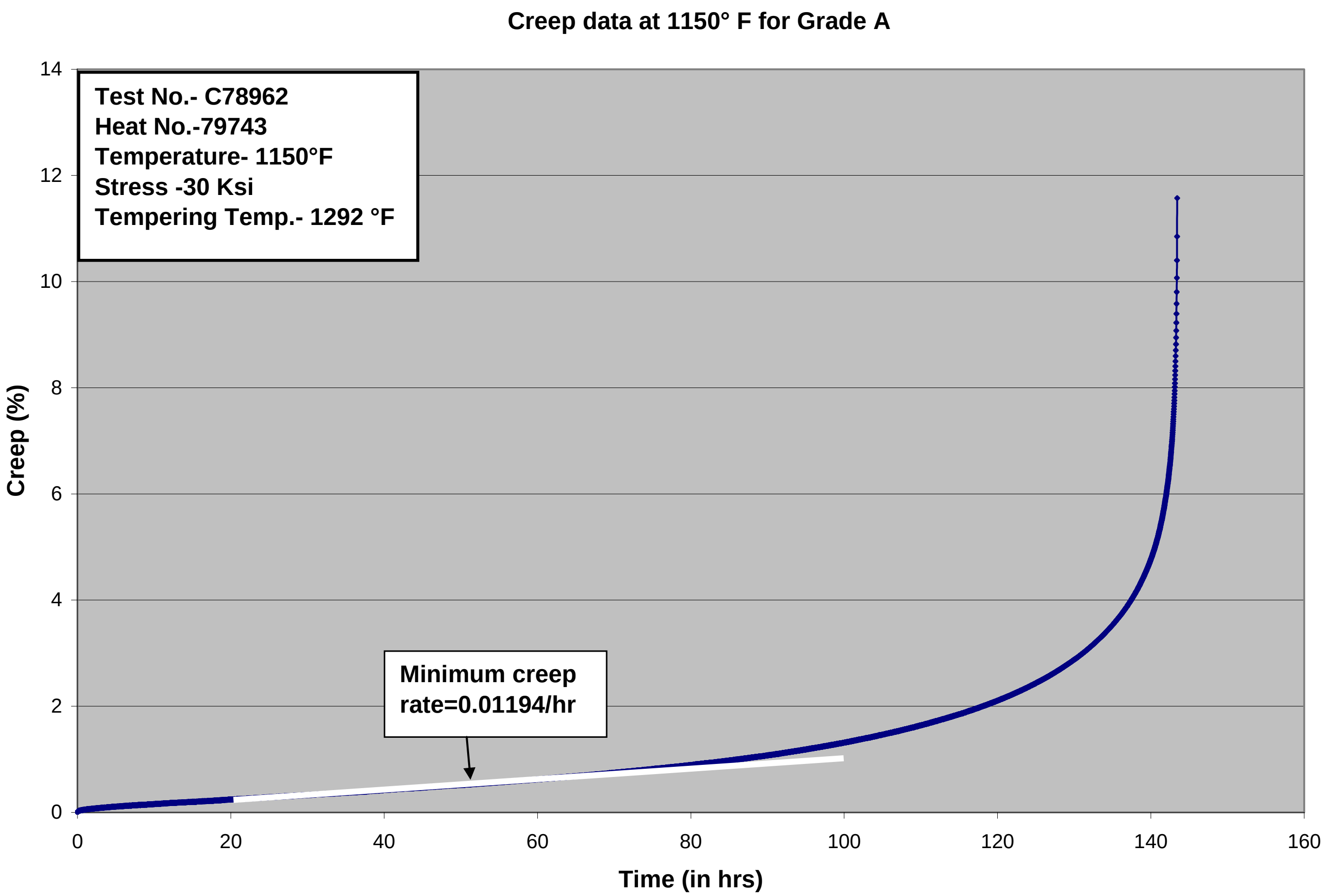
BC04-1063 **81/93**

A 1041-04



BC04-1063 **82/93**

A 1041-04



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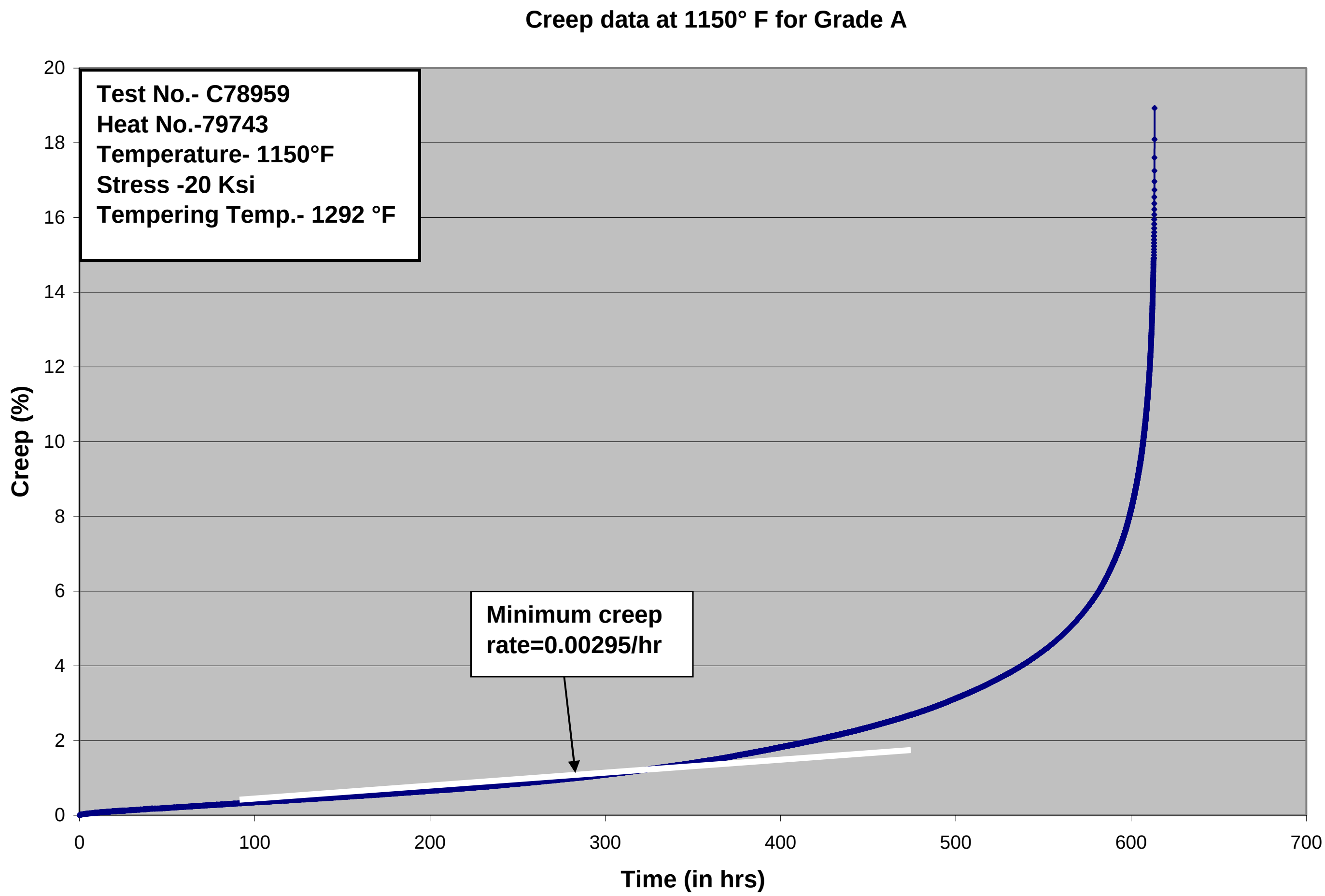
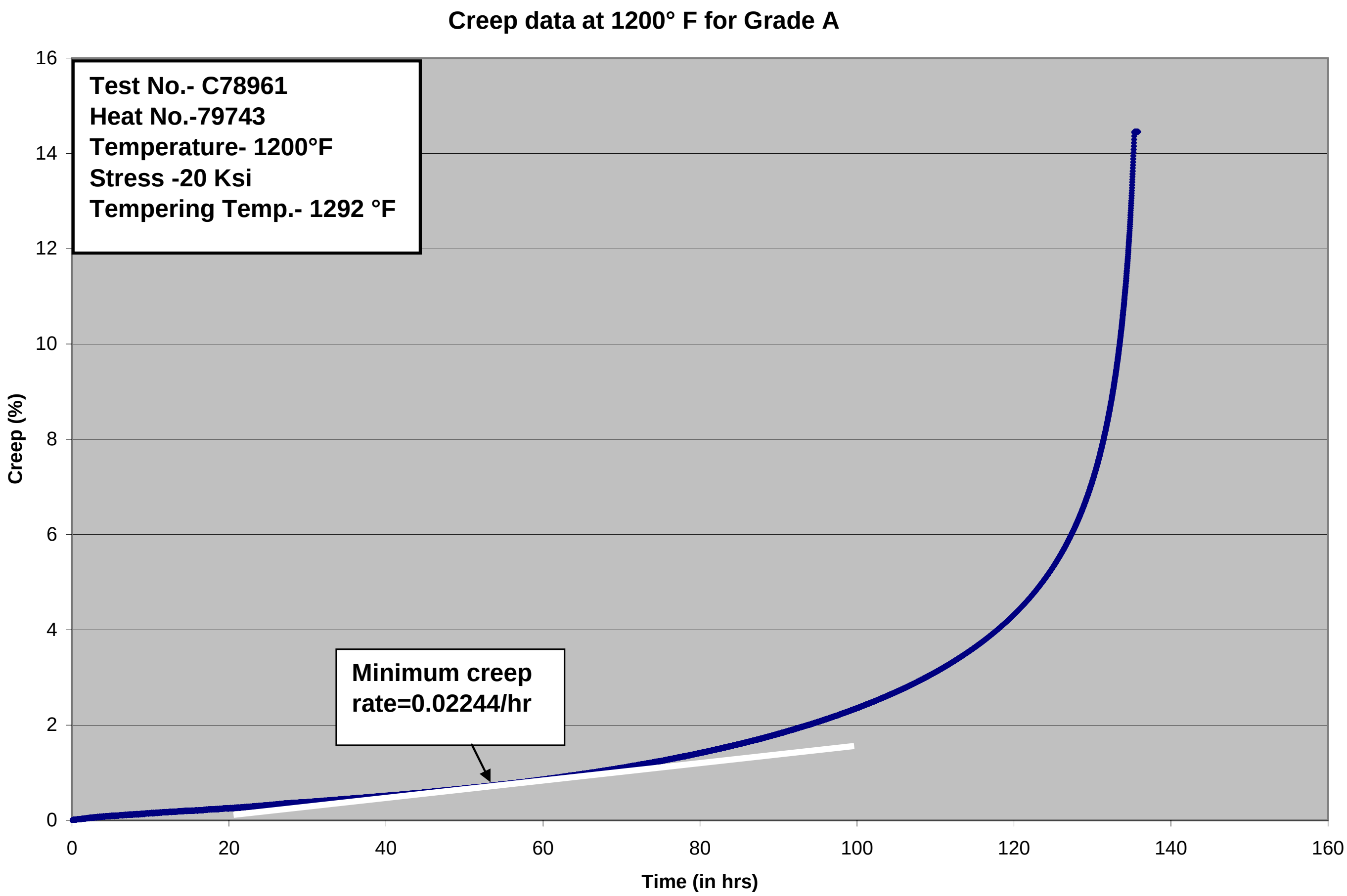

Creep data at 1150° F for Grade A
Test No.- C78959
Heat No.-79743
Temperature- 1150°F
Stress -20 Ksi
Tempering Temp.- 1292 °F
Minimum creep rate=0.00295/hr
Creep (%)
Time (in hrs)
0
2
4
6
8
10
12
14
16
18
20
0
100
200
300
400
500
600
700

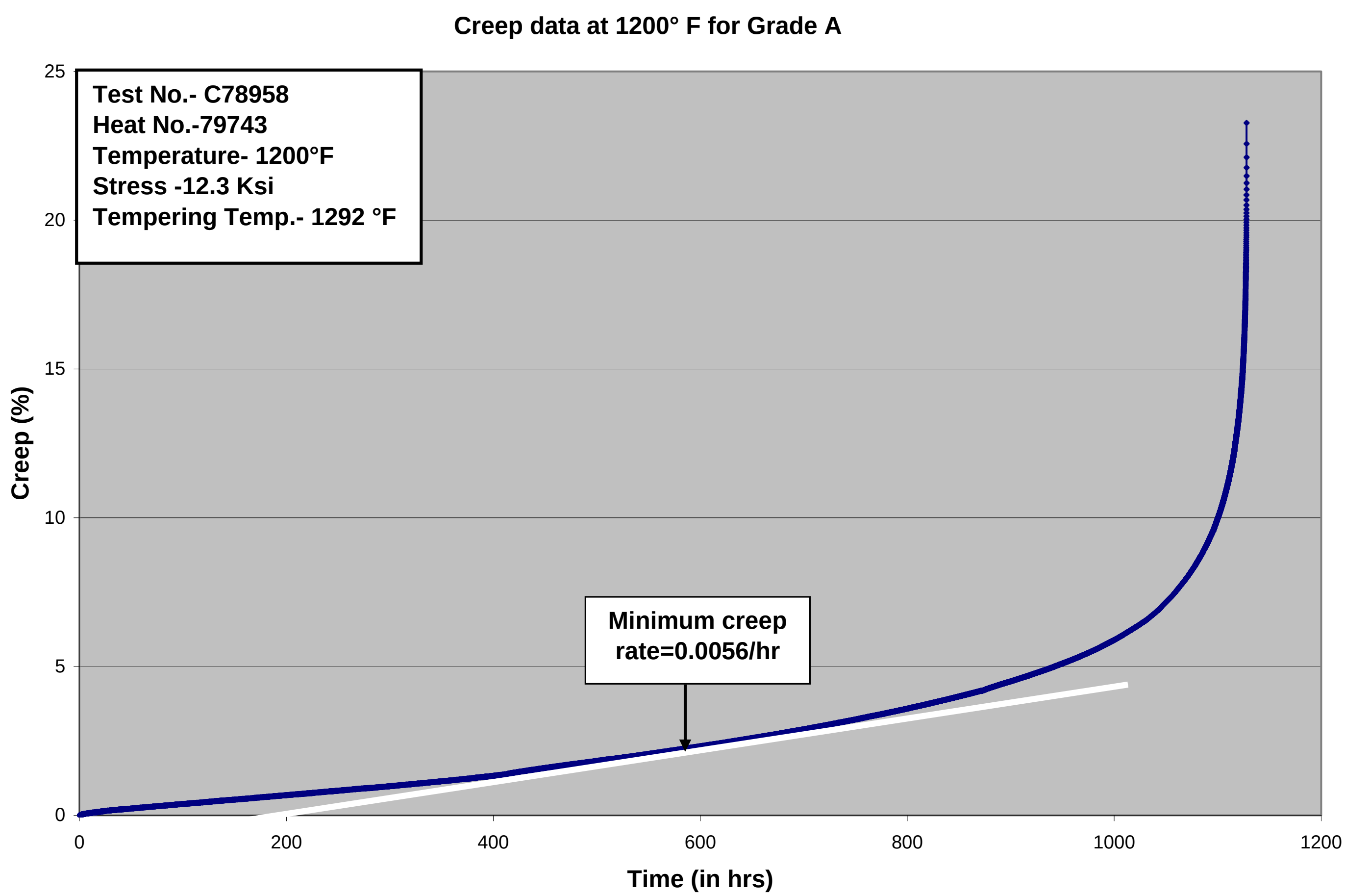
BC04-1063 **84/93**

A 1041-04



BC04-1063 **85/93**

A 1041-04



BC04-1063 **86/93**

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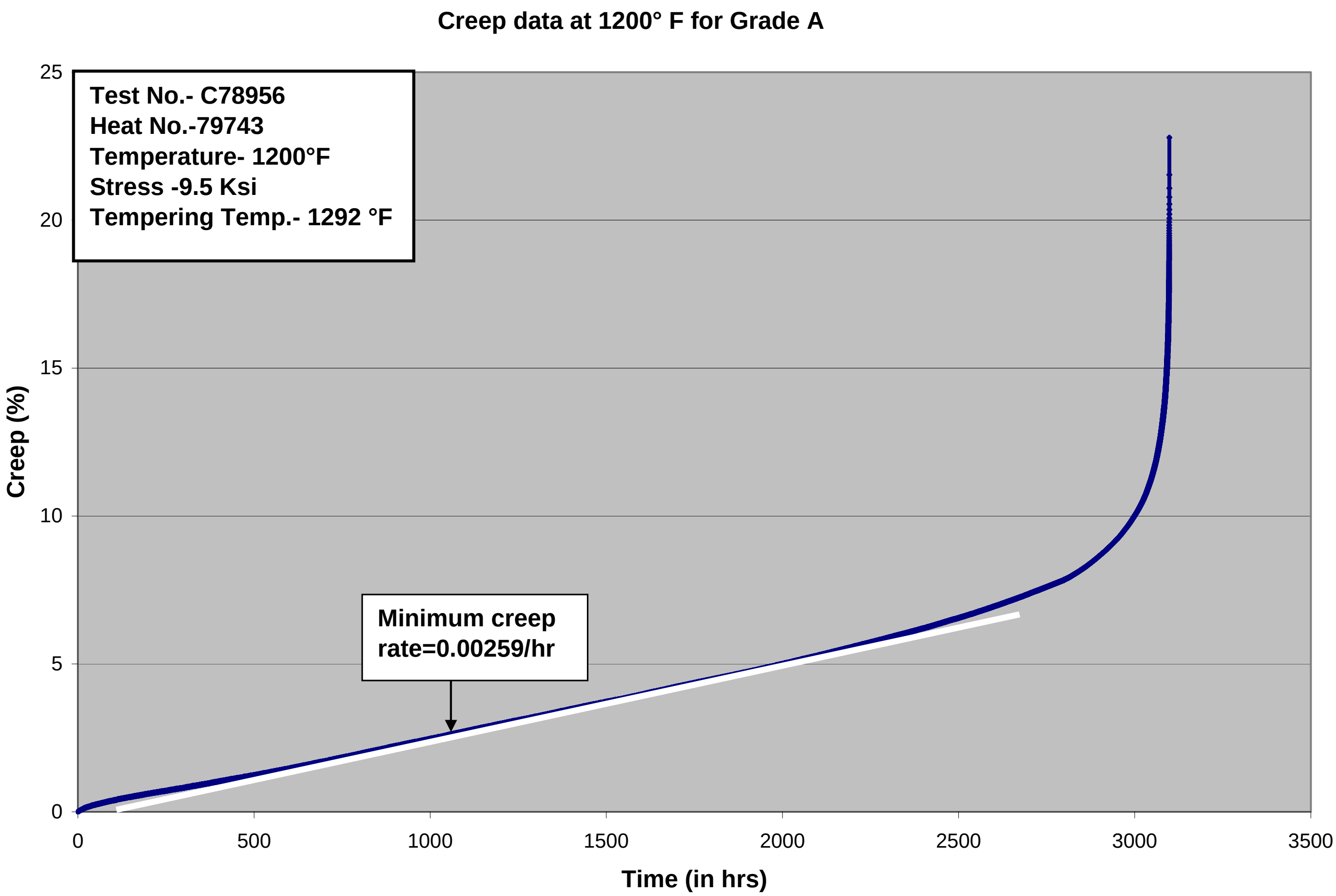
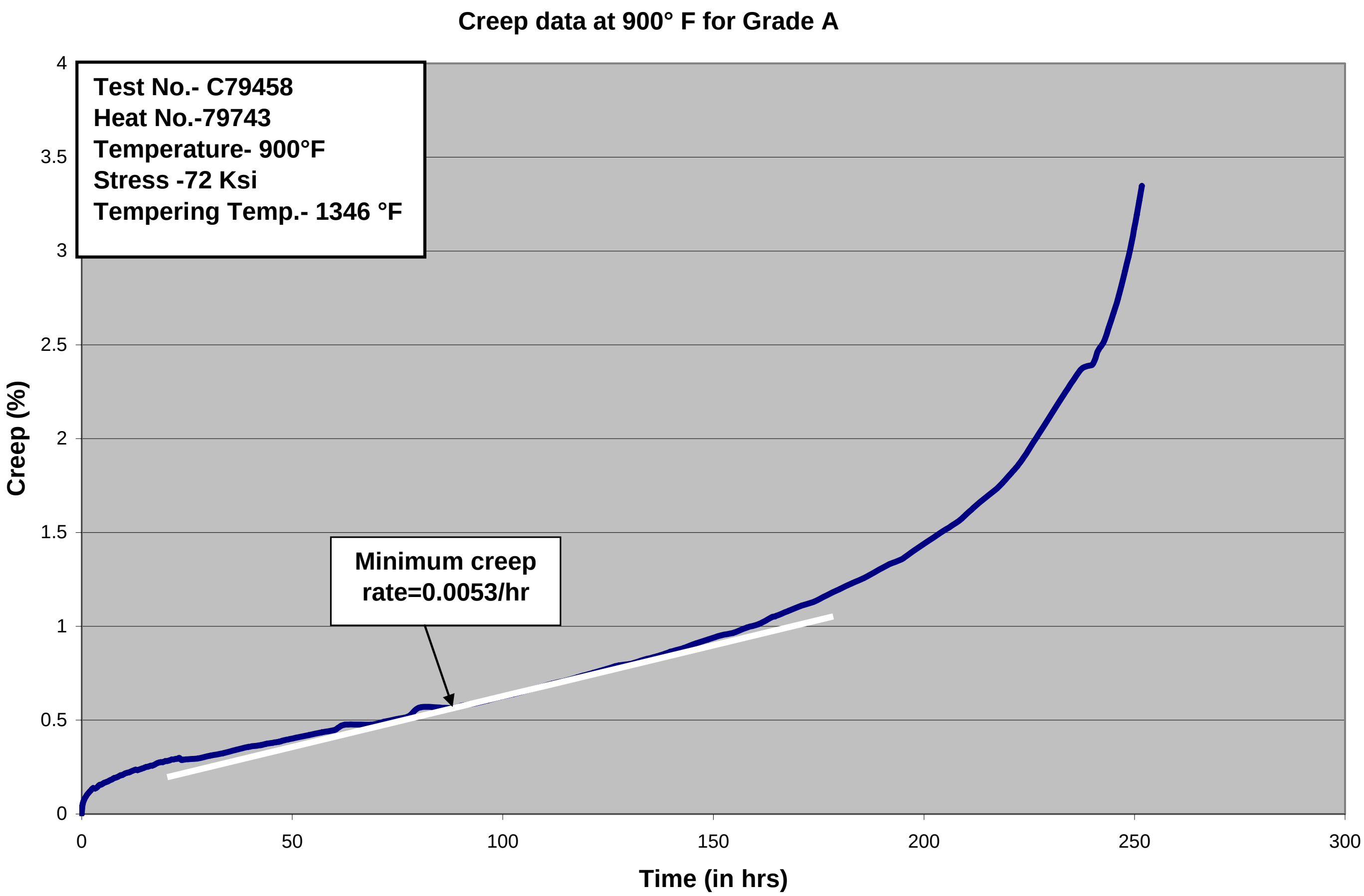


BC04-1063 **87/93**

A 1041-04



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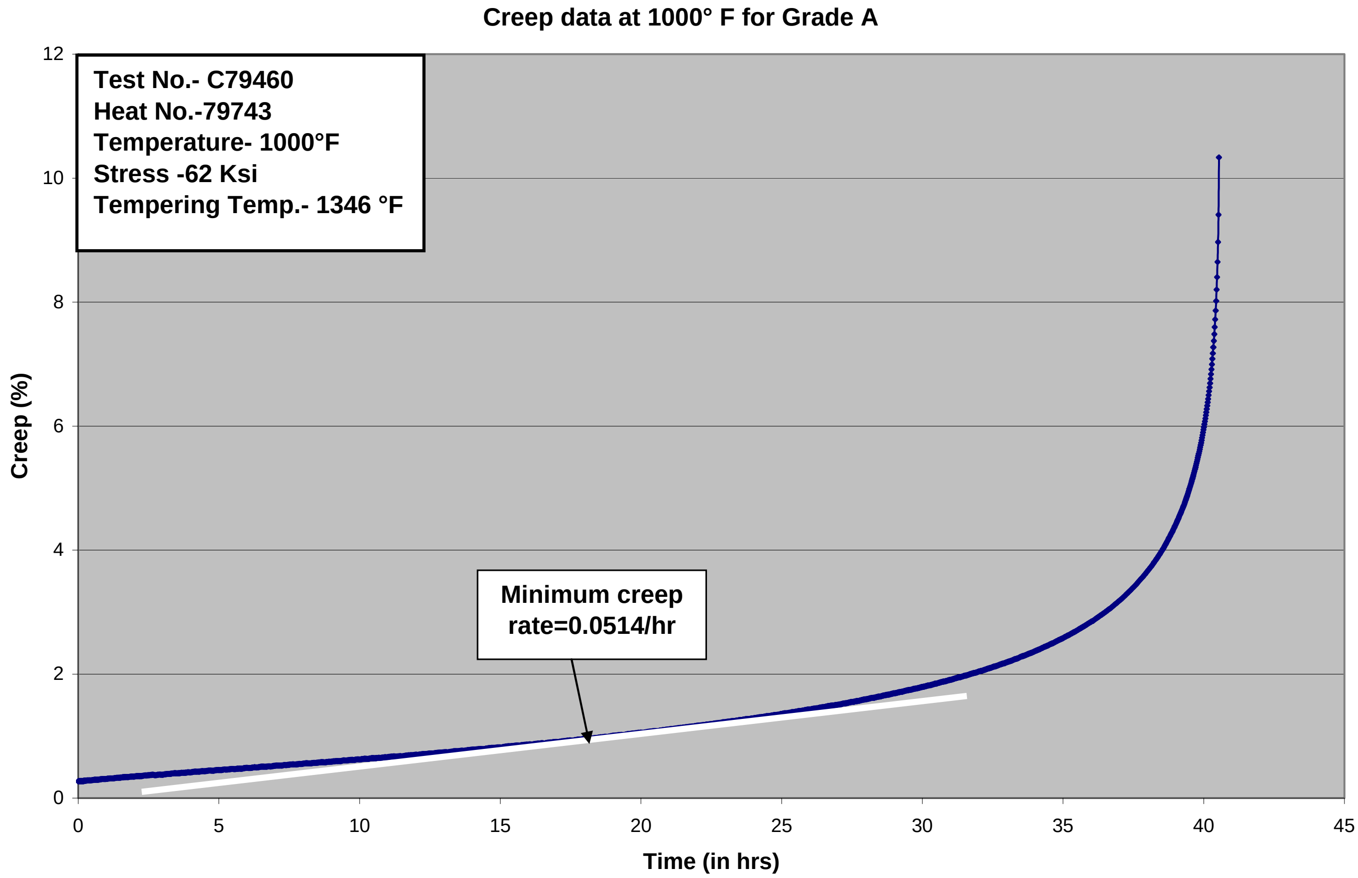
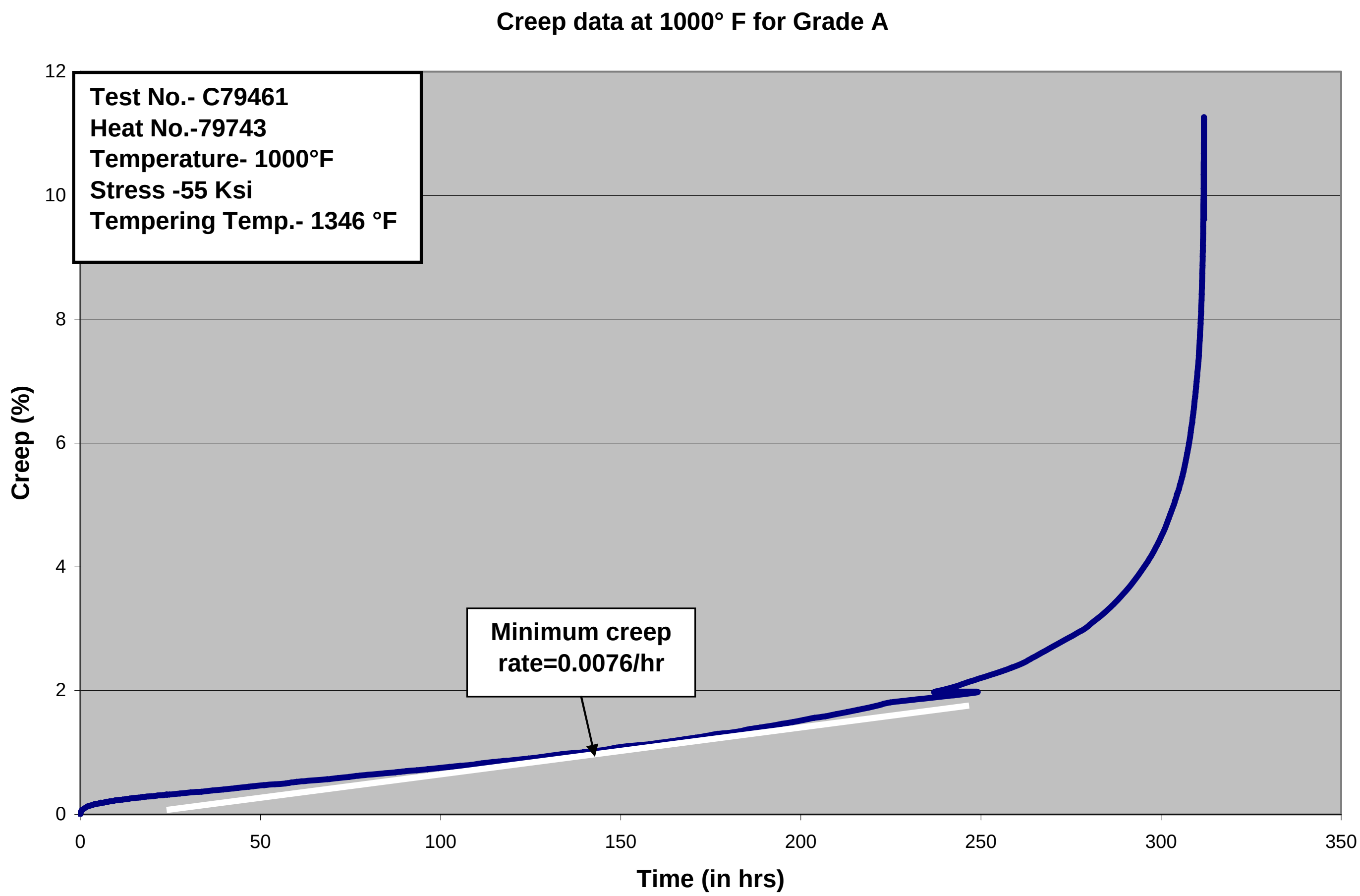

Creep data at 1000° F for Grade A
Test No.- C79460
Heat No.-79743
Temperature- 1000°F
Stress -62 Ksi
Tempering Temp.- 1346 °F
Minimum creep rate=0.0514/hr
Creep (%)
Time (in hrs)
0
2
4
6
8
10
12
0
5
10
15
20
25
30
35
40
45

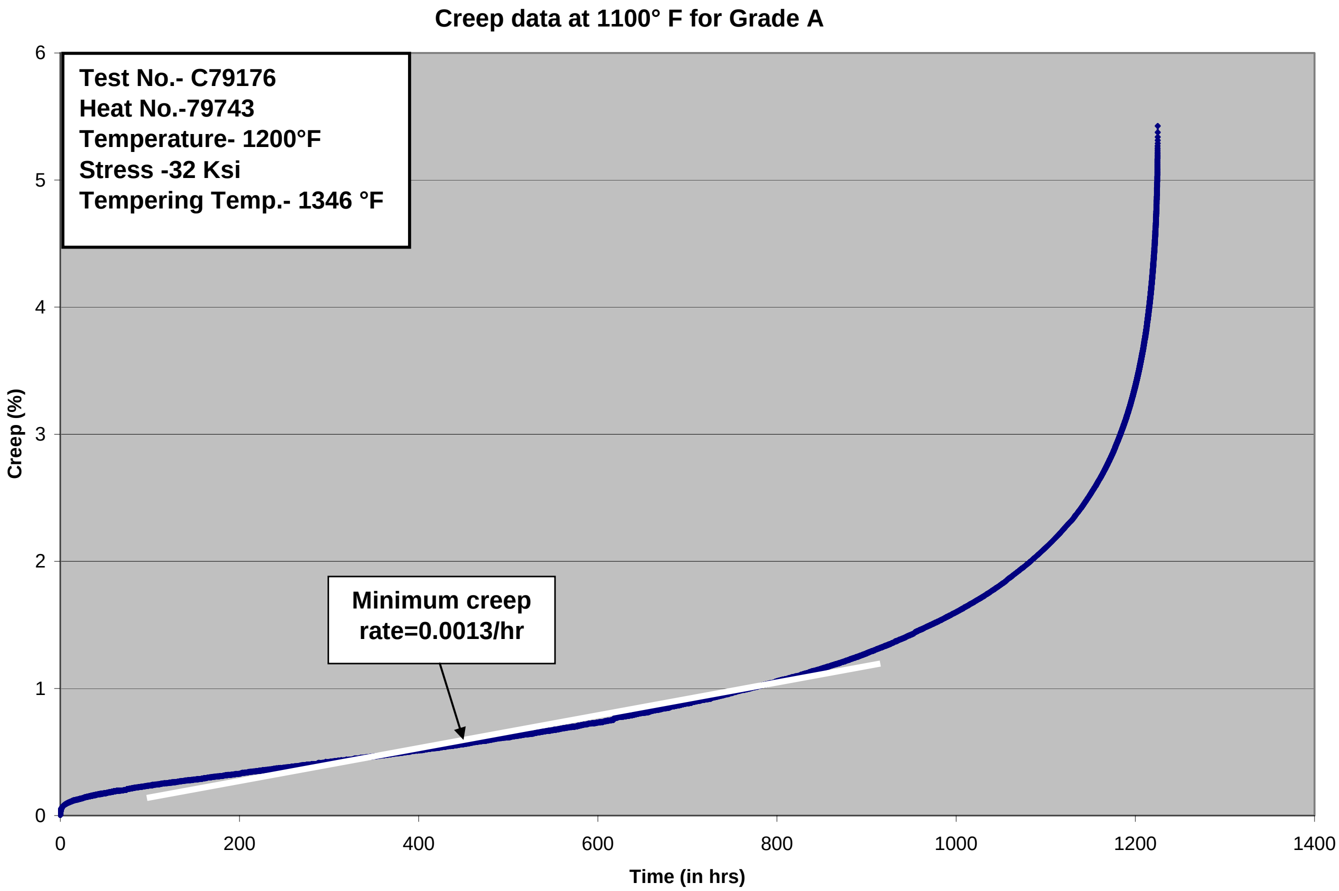
BC04-1063 **89/93**

A 1041-04

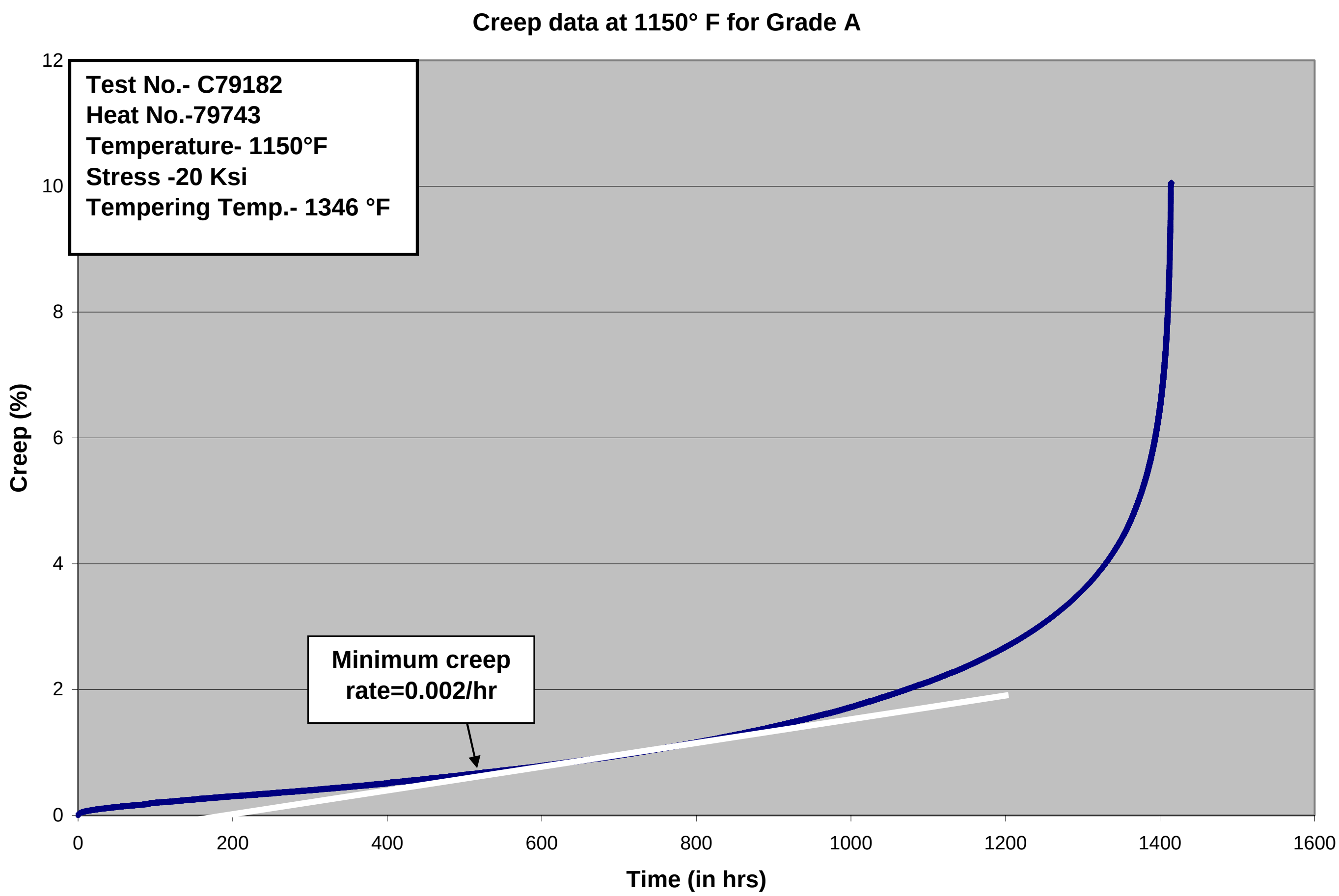


BC04-1063 **90/93**

A 1041-04

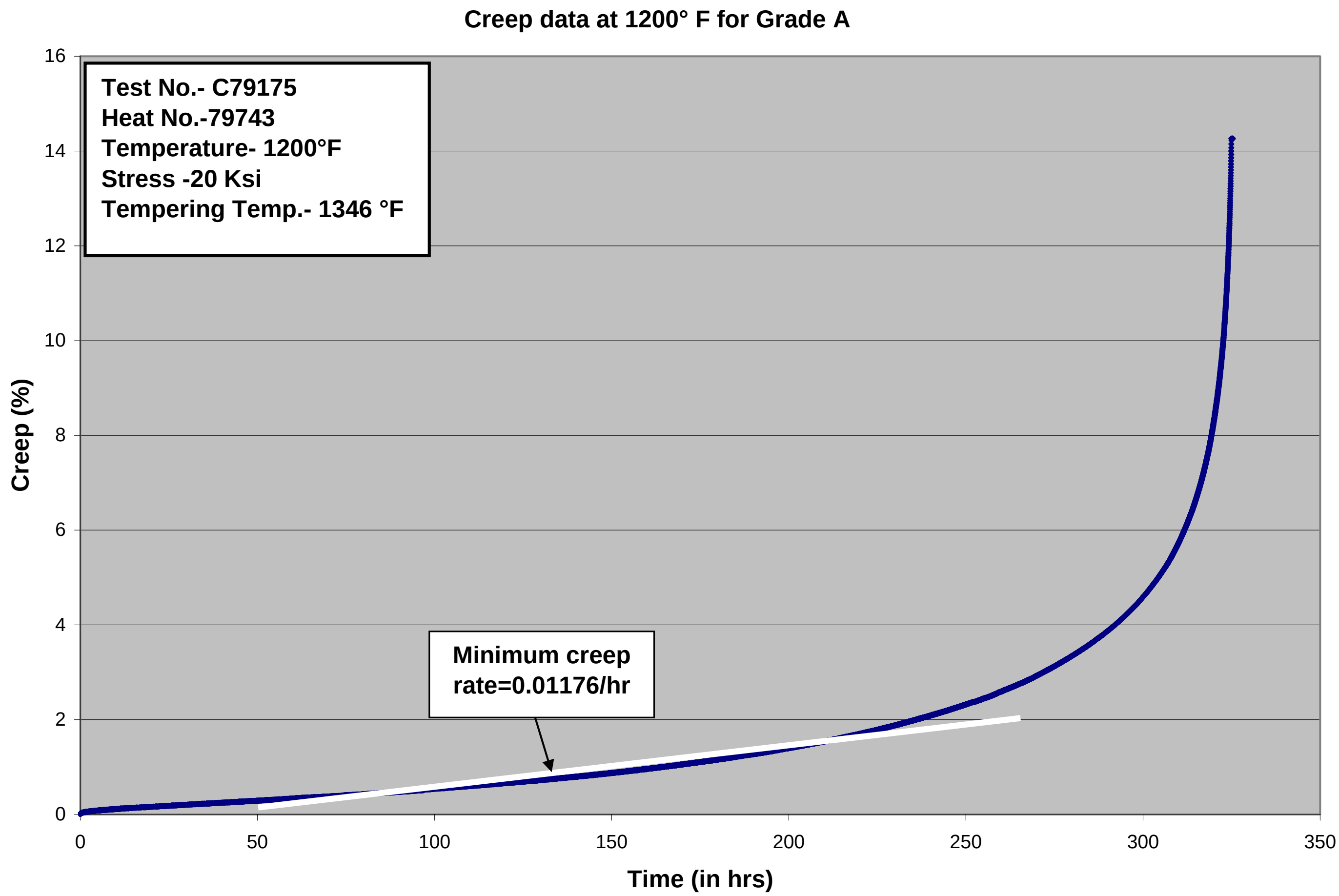


A 1041-04


Creep data at 1150° F for Grade A
Test No.- C79182
Heat No.-79743
Temperature- 1150°F
Stress -20 Ksi
Tempering Temp.- 1346 °F
Minimum creep rate=0.002/hr
Creep (%)
Time (in hrs)
0
2
4
6
8
10
12
0
200
400
600
800
1000
1200
1400
1600

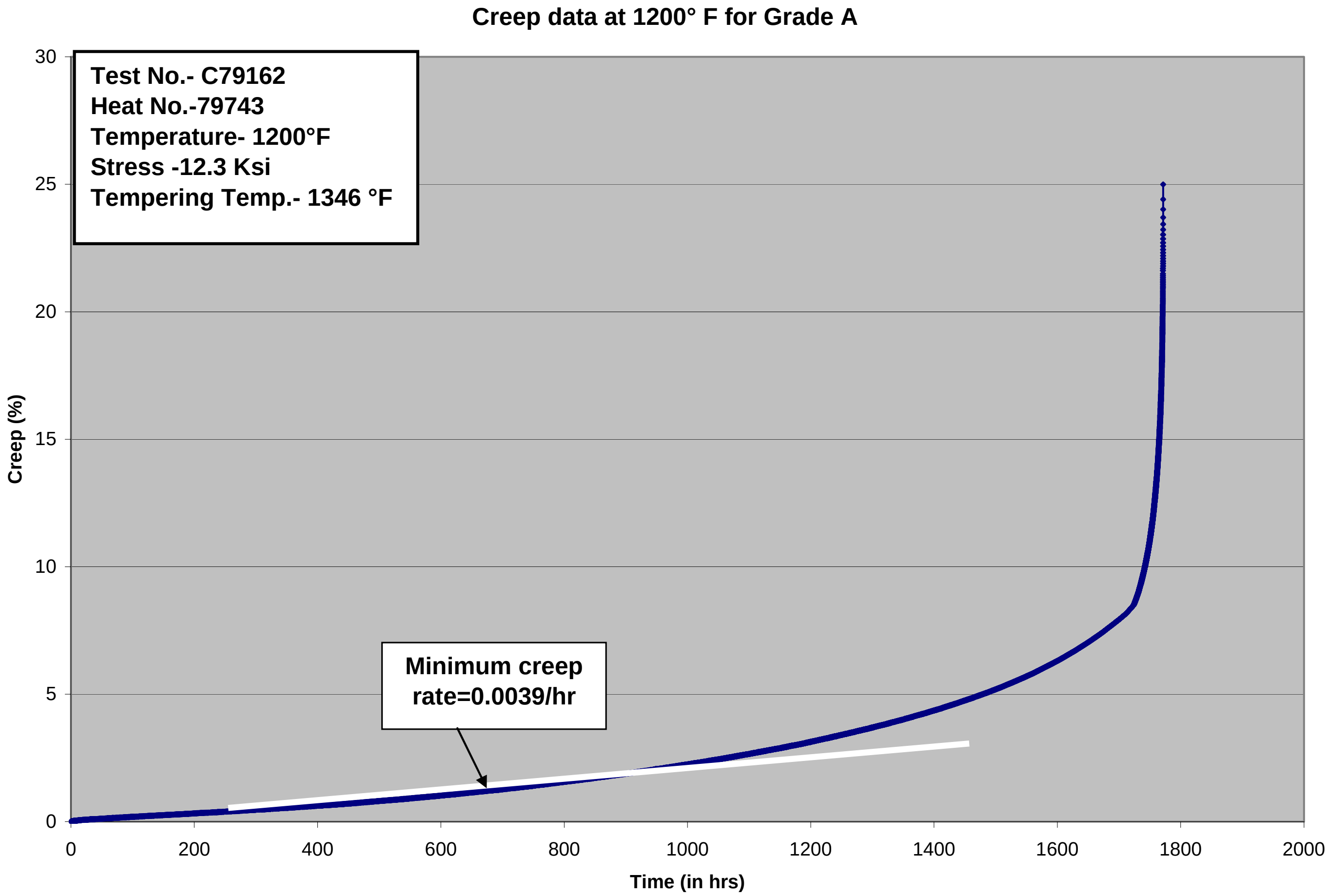
BC04-1063 **92/93**

A 1041-04



BC04-1063 **93/93**

A 1041-04



Appendix B

Publications

1. High-Strength Fe-3Cr-W(Mo) Steel for Petrochemical Applications
2. Mechanical Properties of New Grades of Fe-3Cr-W Alloys

HIGH-STRENGTH Fe-3Cr-W(Mo) STEEL FOR PETROCHEMICAL APPLICATIONS

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ABSTRACT

This paper describes the development of a new class of high strength Fe-3Cr-W(Mo) ferritic steel. The new steel has two grades A and B. The Grade A is a base Fe-3Cr-W(Mo) composition that is strengthened by optimum additions of C and V. The Grade B also contains 0.10 wt % Ta for additional high-temperature creep strength. Both alloys are air hardenable and are recommended for use in the normalized and tempered condition. The best combination of strength and toughness properties is obtained when both grades are austenitized at 2012^{o}F and tempered at 1345^{o}F. Both grades were commercially melted in 50-ton heats by electric furnace melting. The round and slab ingots from the 50-ton heats were forged into billets and rolled into plates by using processing conditions similar to those used for Fe-2.25Cr-1Mo steels. This paper has presented the Charpy impact, tensile, and creep data available to date on both Grades A and B. Tensile and creep data on Grades A and B are compared with the data on the commercially used grades T22, T23, T24, and the modified Fe-9Cr-1Mo Grade 91.

INTRODUCTION

Ferritic steels [1] such as 2.25Cr-1Mo, commonly known as Grade 22, is used for petrochemical applications such as catalytic crackers and coke drums. Being very large units, they use plates and forgings of Grade 22 ranging in thickness from 3 to 10 in. Fabrication of such large units require specialty equipment for forming the component shape from plates and forgings and long periods of time and large quantity of materials for welding. The postweld heat treatment (PWHT) of such units also requires very large furnaces and long times. Some of the units are so large that they can only be shipped as components and assembled in the field. Thus, there are significant incentives in developing higher strength grades of Fe-2.25Cr steels. This paper describes an effort that was funded by the Department of Energy to develop a new class of high-strength versions of ferritic steels in the United States. The paper presents the project status after 30 months of a 36-month project. This represents first the effort in the United States in developing the higher strength ferritic steels since the last government-funded effort during 1978 through 1982 that developed the high-strength version of Fe-9Cr-1Mo steel, Grade 91 [refs. 2,3].

ALLOY DEVELOPMENT

This project focused on developing a Fe-3Cr-W(Mo) alloy [4] with nominal W addition of 1.5 wt % and Mo of 0.75 wt %. The alloy is further modified by an addition of 0.25 wt % V. The alloy is also optimized for its C, Si, and Mn contents. The base Fe-3Cr-W(Mo) alloy is known as Grade A. A second grade of the same base composition with 0.10 wt % Ta addition is known as Grade B which has significantly higher creep strength than Grade A. This project is focusing on taking both grades for commercialization.

HEAT TREATMENTS

The alloy is recommended for use in normalized and tempered conditions. The nominal normalizing and tempering temperatures for Grades A and B are 1100 and 730°C, respectively. Holding time is a function of section thickness. Alloys were tested after both 700 and 730°C tempering treatments.

COMMERCIAL MELTING AND PROCESSING OF ALLOYS

Both Grades A and B were electric furnace melted into 50-ton heats followed by vacuum degassing at Ellwood Quality Steel. The 50-ton heats were cast into 27-in.-diam ingots and 12-in.-thick slabs. One each of the 27-in.-diam ingots from each grade was also remelted by electroslag remelting (ESR) and vacuum-arc remelting (VAR) and cast into 30-in.-diam ingots.

The 27- and 30-in.-diam ingots were hot-forged into 12-in.-diam rounds and rounded corner square billets. Both Grades A and B were forged in a manner similar to Grade 22. The rounded-corner forged billets were further hot-rolled into 3.75-in.-diam bar and 1-in.-thick plate. The hot-rolled bar will be used for producing seamless tubing at Plymouth Tube. The 12-in.-thick slabs were hot-rolled at ISG Plate – Coatesville into 1.5- and 3-in.-thick plates.

CHEMICAL ANALYSIS

The chemical analysis of the 50-ton electric furnace heats is shown in Table 1. This table includes the AIM chemistry, and as noted there were no problems encountered in meeting the target. Table 2 compares the chemical analysis of forgings from Grades A and B of the electric furnace, ESR, and VAR heats. This paper will compare the properties of Grades A and B with commercially used T22 and T91 and recent high-strength alloys, T23 and T24. Chemical analysis of these alloys is compared in Table 3.

Table 1: Chemical analysis of 50-ton heats of Grades A and B melted in electric furnace followed by vacuum degassing

Element	Weight percent							
	Grade A, Heat L7974				Grade B, Heat L8644			
	27-in. Round			12-in. Slab	27-in. Round			12-in. Slab
	AIM	Vendor	Check	Vendor	AIM	Vendor	Check	Vendor
Carbon	0.10	0.11	0.099	0.11	0.10	0.11	0.11	0.11
Manganese	0.35	0.36	0.34	0.36	0.35	0.36	0.35	0.36
Phosphorus	0.01[a]	0.007	0.009	0.007	0.01[a]	0.008	0.009	0.008
Sulfur	0.01[a]	0.002	0.003	0.002	0.01[a]	0.002	0.002	0.002
Silicon	0.2	0.21	0.21	0.21	0.2	0.2	0.2	0.2
Nickel	0.02[a]	0.15	0.15	0.15	0.02[a]	0.12	0.12	0.12
Chromium	3.00	2.99	2.97	2.99	3.00	3.01	3.02	3.01
Molybdenum	0.75	0.76	0.73	0.76	0.75	0.74	0.73	0.74
Vanadium	0.25	0.249	0.22	0.249	0.25	0.236	0.21	0.236
Columbium	----	----	0.002	----	----	----	0.002	----
Titanium	----	----	0.003	----	----	----	0.004	----
Cobalt	----	----	0.014	----	----	----	0.016	----
Copper	----	0.11	0.11	0.11	----	0.17	0.17	0.17
Aluminum	----	0.013	0.008	0.013	----	0.011	0.006	0.011
Boron	0.01[a]	0.0002	<0.001	0.0002	0.01[a]	0.0001	<0.001	0.0001
Tungsten	1.5	1.55	1.68	1.55	1.5	1.48	1.62	1.48
Arsenic	----	----	0.005	----	----	----	0.006	----
Tin	----	----	0.008	----	----	----	0.009	----
Zirconium	----	----	<0.001	----	----	----	<0.001	----
Nitrogen	----	----	0.009	----	----	----	0.011	----
Oxygen	----	----	0.004	----	----	----	0.001	----
Hydrogen	----	1.6[b]	----	2.2[b]	----	1.3[b]	----	2.3[b]
Tantalum	----	----	----	----	0.10	0.107	0.1	0.107

[a]Maximum
[b]Parts per million

RESULTS AND DISCUSSION

The commercial heats of Grades A and B are being tested for their Charpy-impact, tensile, and creep properties. Each of these properties is presented below.

CHARPY IMPACT

The Charpy-impact tests were conducted on the rounded-corner 6-in.-square forged billets in both longitudinal and transverse orientations. All data reported here are for preferred tempering temperature of 1345°F. The Charpy-impact energy and lateral expansions for Grades A and B in the electric-furnace-melted condition are shown in Figs. 1 and 2. These data show that both alloys have very similar impact properties. The longitudinal values are better than transverse properties. The 40 ft-lb transition temperature for longitudinal orientation is between -30 to -40°F for the two grades. For transverse orientation, the 40 ft-lb transition temperature is between 0 and +15°F. The 20-mil (0.02-in.) lateral expansion temperature varies from 0 to -60°F. It is -60°F for Grade A in the longitudinal orientation.

Table 2: Change in chemical analysis of electric-furnace-melted 50-ton Heats of Grades A and B after electronslag-remelting and vacuum-arc-remelting processes

Element	Heat (wt %)					
	Grade A			Grade B		
	Electric 79741	ESR[a] 79742	VAR[b] 79743	Electric 86441	ESR[a] 86442	VAR[b] 86443
C	0.099	0.11	0.11	0.11	0.11	0.11
Mn	0.34	0.33	0.25	0.35	0.33	0.22
P	0.009	0.008	0.008	0.009	0.009	0.009
S	0.003	0.001	0.001	0.002	0.001	0.001
Si	0.21	0.15	0.21	0.2	0.15	0.2
Ni	0.15	0.15	0.21	0.12	0.12	0.12
Cr	2.97	2.95	2.97	3.02	3.03	3.03
Mo	0.73	0.74	0.74	0.73	0.72	0.72
V	0.22	0.22	0.22	0.21	0.21	0.21
Cb	0.002	0.001	0.002	0.002	0.002	0.002
Ti	0.003	0.003	0.003	0.004	0.003	0.003
Co	0.014	0.013	0.013	0.016	0.016	0.016
Cu	0.11	0.11	0.11	0.17	0.17	0.15
Al	0.008	0.005	0.008	0.006	0.016	0.016
B	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
W	1.68	1.67	1.68	1.62	1.61	1.61
As	0.005	0.007	0.007	0.006	0.008	0.007
Sn	0.008	0.008	0.008	0.009	0.01	0.01
Zr	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
N	0.009	0.013	0.004	0.011	0.012	0.004
O	0.004	0.001	<0.001	0.001	0.001	<0.001
Ta	----	<0.001	<0.01	0.1	0.08	0.1

[a]ESR = electroslag remelting.
[b]VAR = vacuum-arc remelting.

Table 3:Chemical analysis of commercial alloys used for property comparison with Grades A and B of this investigation

Element	Alloy (wt %)			
	Commercial / Near Commercial			
	T22[a]	T23[a,c]	T24[a,d]	T91[a,e]
C	0.15 max	0.04-0.10	0.05-0.10	0.08-0.12
Si	0.25-1.00	0.50 max	0.15-0.45	0.20-0.50
Mn	0.30-0.60	0.10-0.60	0.30-0.70	0.30-0.60
P	0.030 max	0.030 max	0.020 max	0.020 max
S	0.030 max	0.010 max	0.010 max	0.010 max
Cr	1.9-2.6	1.9-2.6	2.2-2.6	8.0-9.5
Mo	0.87-1.13	0.05-0.30	0.90-1.10	0.85-1.05
N	*b*	0.030 max	0.12 max	0.030-0.070
W	*b*	1.45-1.75	*b*	*b*
V	*b*	0.20-0.30	0.20-0.30	0.18-0.25
Nb	*b*	0.02-0.08	*b*	0.06-0.10
Ta	*b*	*b*	*b*	*b*
B	*b*	0.0005-0.0060	0.0015-0.0070	*b*
Ti	*b*	*b*	0.05-0.10	*b*
Ni	*b*	*b*	*b*	0.40 max
Al	*b*	0.030 max	0.020 max	0.040 max
Fe	*f*	*f*	*f*	*f*

[a]ASTM A213.
[b]Not specified.
[c]Code Case 2199.
[d]Code Case draft.
[e]Code approved.
[f]Balance.

The Charpy properties for Grade B in the electric-furnace-melted and VAR conditions are compared in Fig. 3 and 4. These plots show that VAR results in a significant improvement in Charpy-impact properties of Grade B alloy. For example, the 40 ft-lb transition temperature is lowered by nearly 40°F both in the longitudinal and transverse orientations. Similar lowering in temperature is noted for 20-mil (0.020-in.) lateral expansion values.

Tensile tests were conducted on 0.505-in. specimens in. longitudinal orientation at temperatures from room temperature to 1300°F. All tests were at a strain rate of $1 \times 10^{-3}s^{-1}$, and the same strain rate was maintained throughout the tests. Tensile properties for electric-furnace-melted Grades A and B are plotted as a function of temperature in Figs. 5 and 6. Data for alloys T22, T23 and T24 are also included for comparison. This figure shows only a small difference in the properties of Grades A and B. However, the yield and ultimate tensile strength properties are nearly 25 to 30 ksi higher than the highest strength alloy, T23. This improvement is considered very significant, especially at test temperature of 1200°F. The total elongation and reduction of area values for both Grades A and B are similar to the commercial alloys.

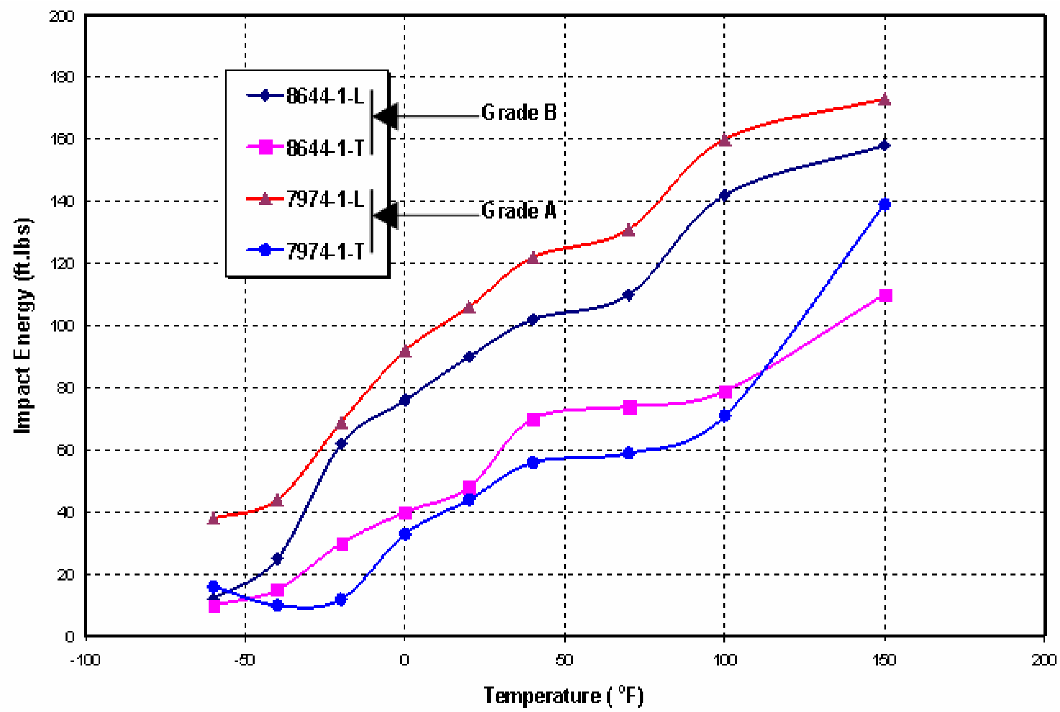


Figure 1: Comparison of Charpy-impact energy values for electric-furnace-melted and forged billets of 50-ton heats of Grades A and B of Fe-3Cr-W(Mo) alloys. Data for both longitudinal and transverse orientations are included.

A comparison of tensile properties of Grade B in electric-furnace-melted and VAR conditions are shown in Figs. 7 and 8. This figure shows that VAR reduces the strength properties somewhat. Even with the reduction in properties, Grade B is nearly 15 to 20 ksi stronger than alloy T23. The chemical analysis in Table 2 shows that VAR reduces the nitrogen content from 0.012 to 0.004 wt %. It is believed that this reduction in nitrogen content is responsible for reducing strength properties and improvement in impact properties, as noted in Figs. 3 and 4.

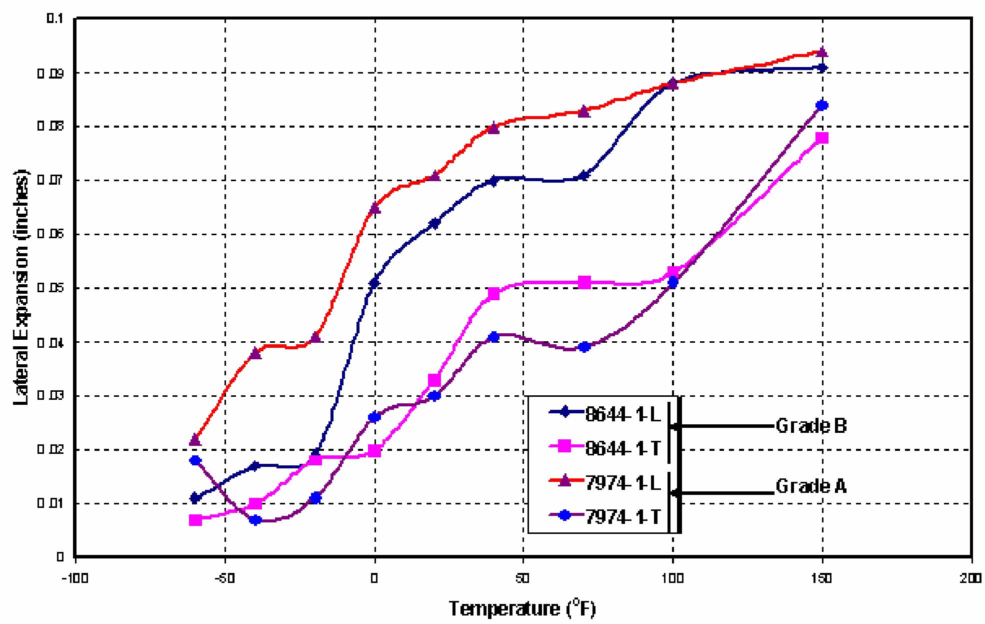


Figure 2: Comparison of lateral expansion of Charpy-impact-tested specimens of electric-furnace-melted and forged billets of 50-ton heats of Grades A and B of Fe-3Cr-W(Mo) alloys. Data for both longitudinal and transverse orientations are included.

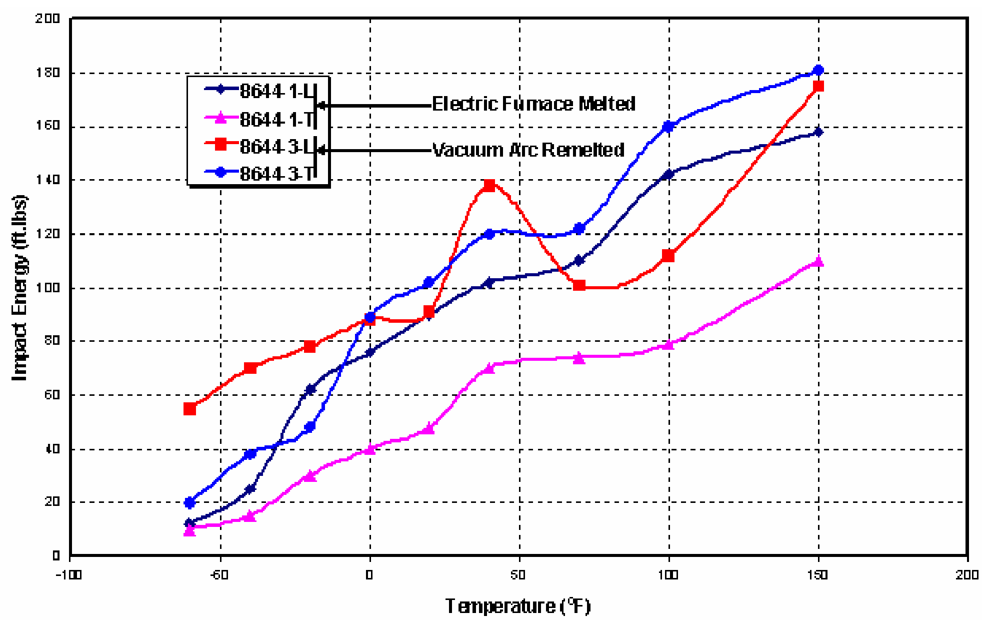


Figure 3: Comparison of Charpy-impact energy values for forged billets of 50-ton heats of Grade B melted by electric furnace and vacuum-arc remelting. Data for both longitudinal and transverse orientations are included.

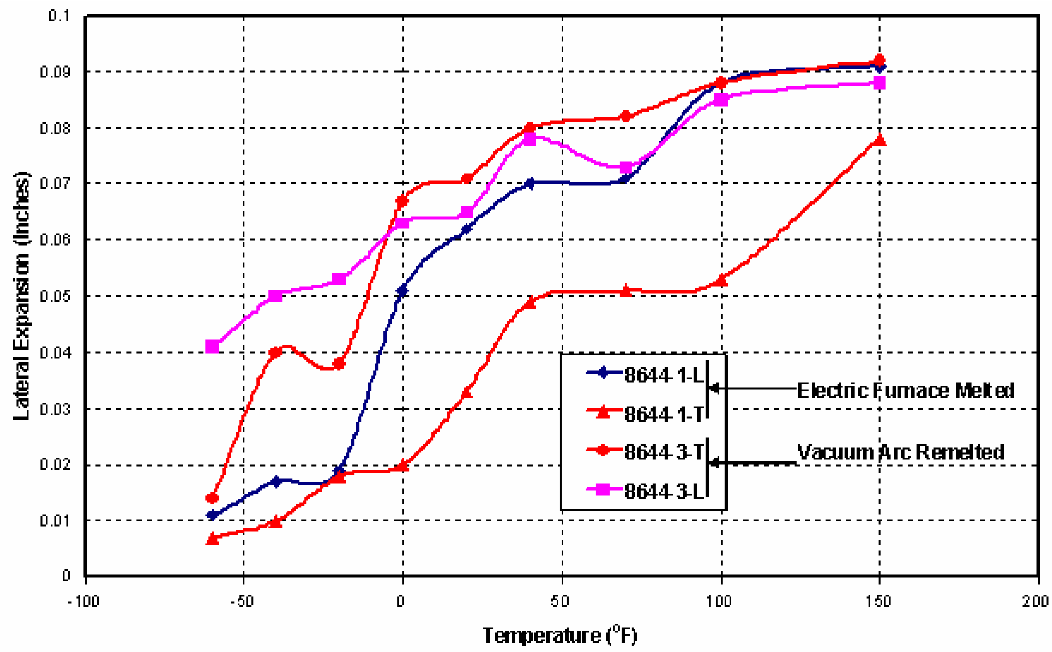
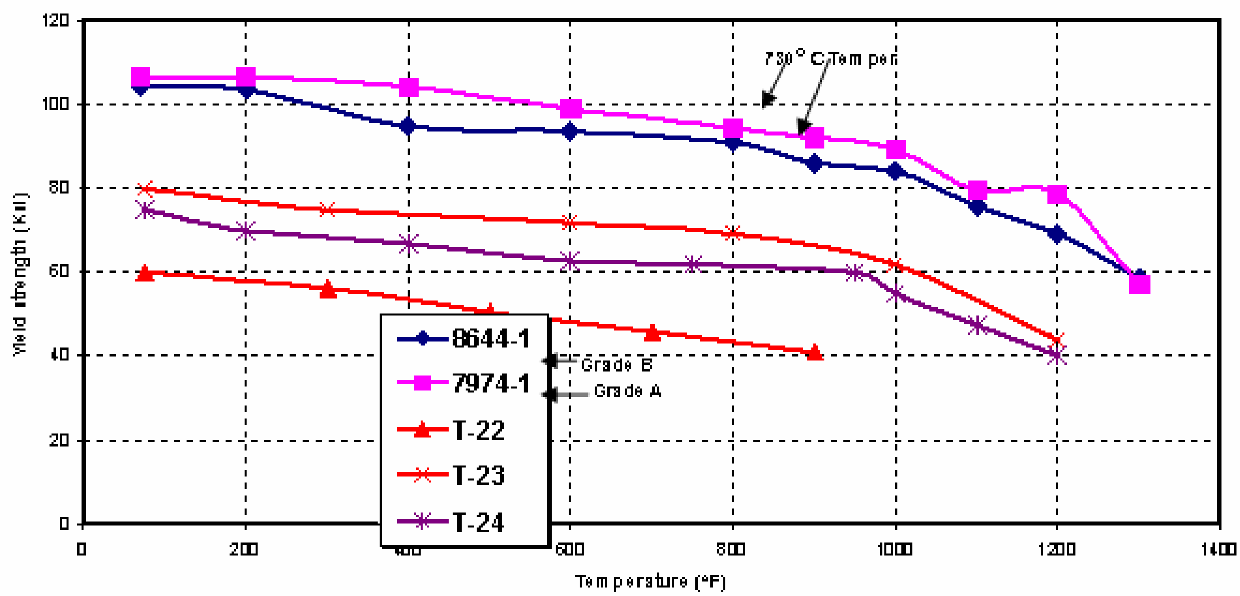
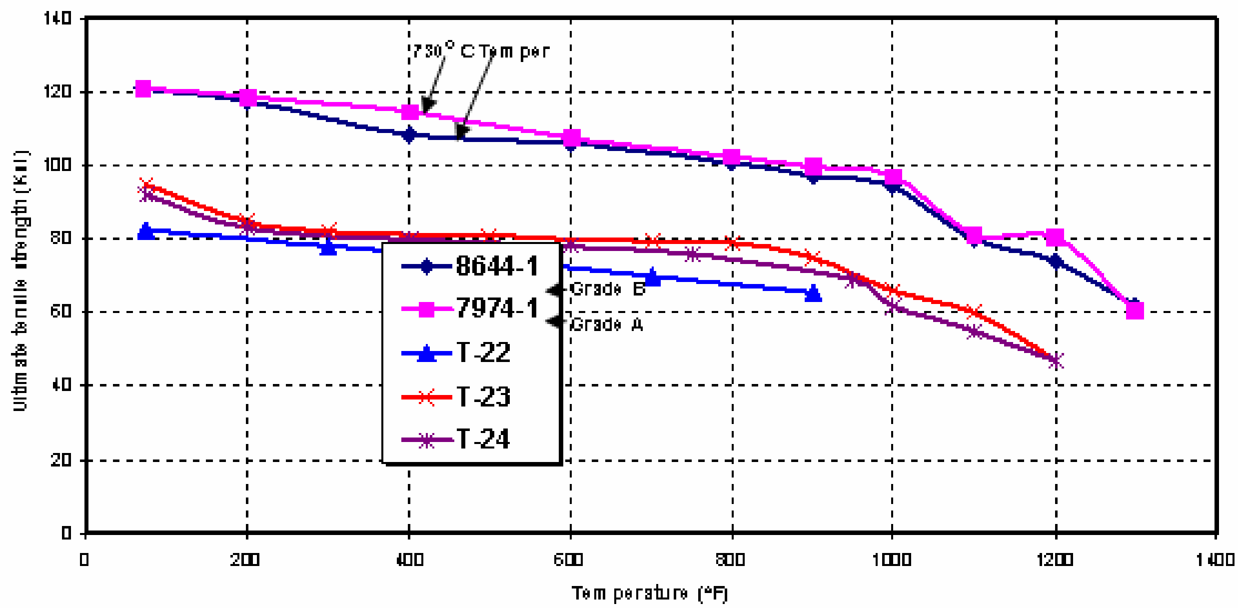


Figure 4: Comparison of lateral expansion of Charpy-impact-tested specimens for forged billets of 50-ton heats of Grade B melted by electric furnace and vacuum-arc remelting. Data for both longitudinal and transverse orientations are included.

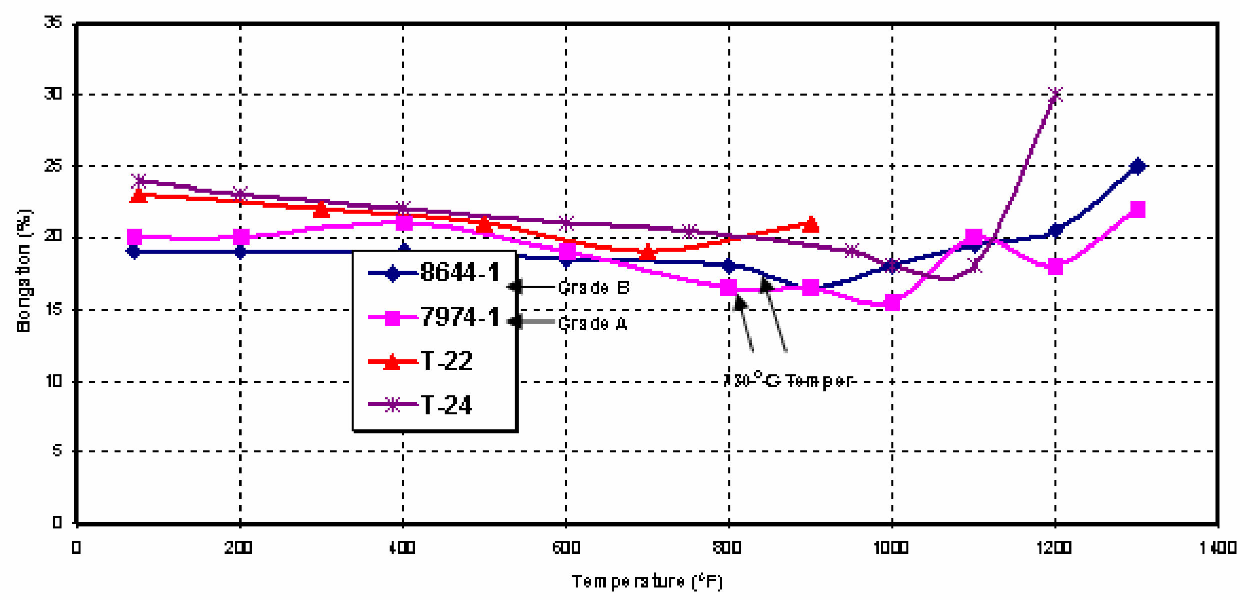


(a)

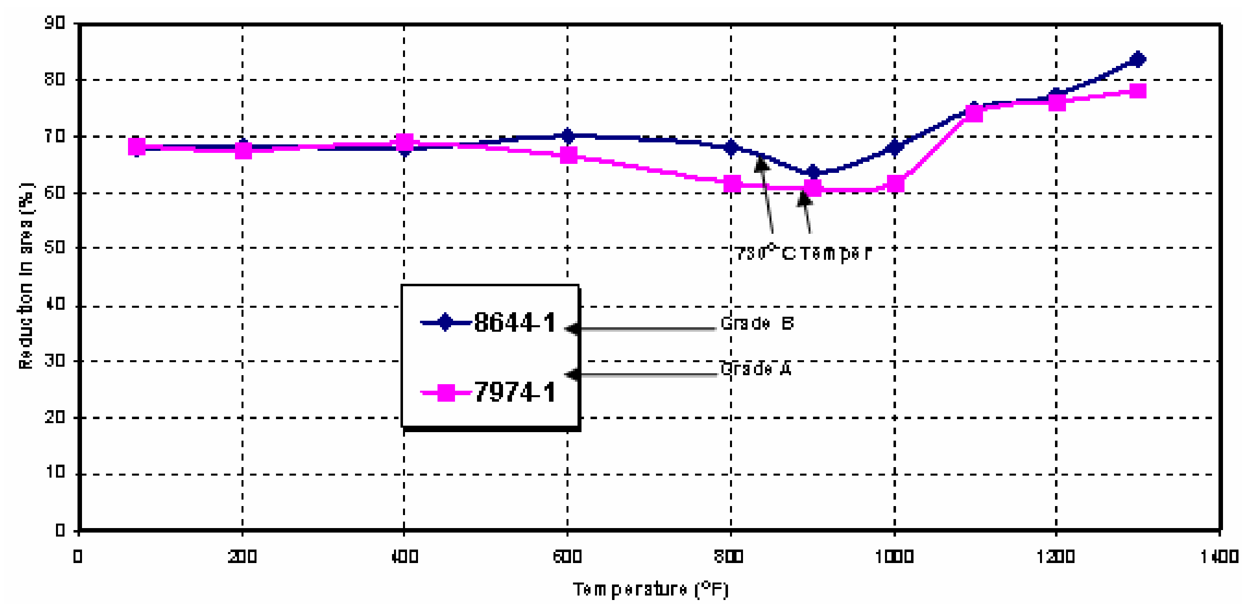


(b)

Figure 5: Comparison of tensile properties for electric-furnace-melted and forged billets of 50-ton heats of Grades A and B of Fe-3Cr-W)Mo) alloys. Data for commercial alloys T22, T23, and T24 are also included for comparison: (a) yield strength and (b) ultimate tensile strength.

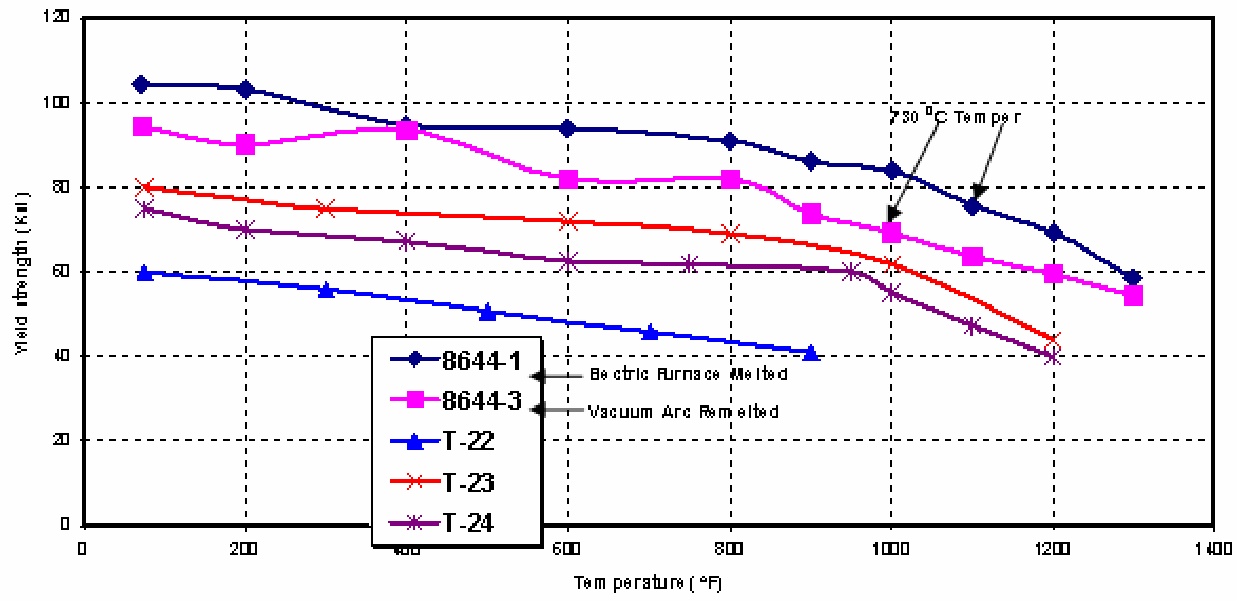


(a)

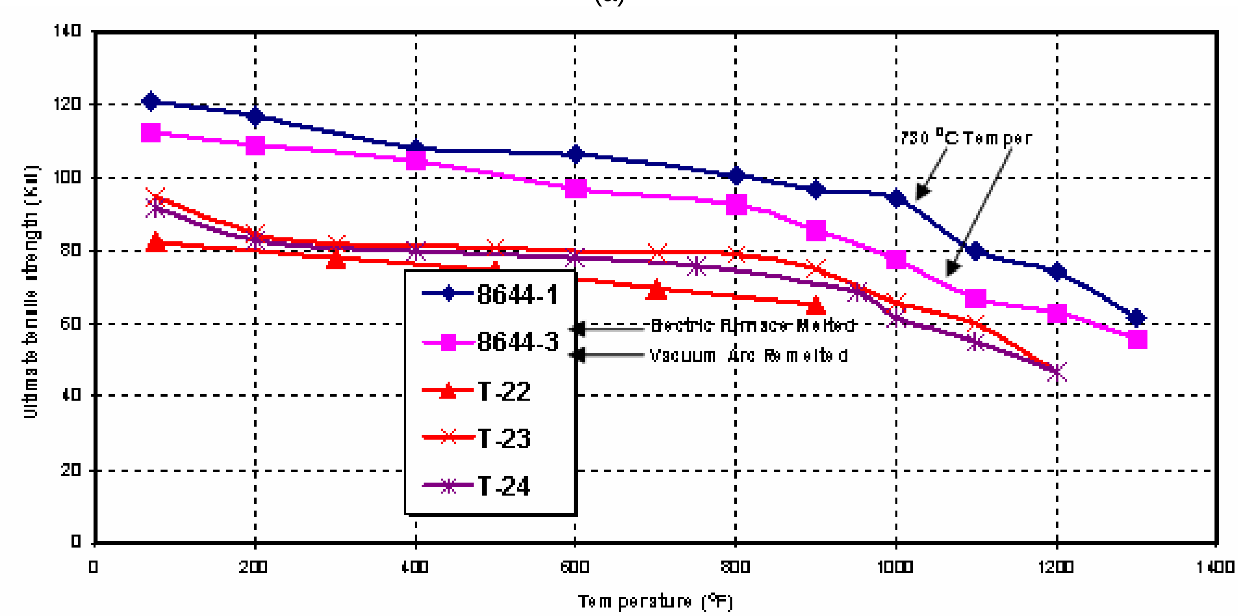


b)

Figure 6: Comparison of tensile properties for electric-furnace-melted and forged billets of 50-ton heats of Grades A and B of Fe-3Cr-W)Mo) alloys. Data for commercial alloys T22, T23, and T24 are also included for comparison: (a) total elongation and (b) reduction of area.

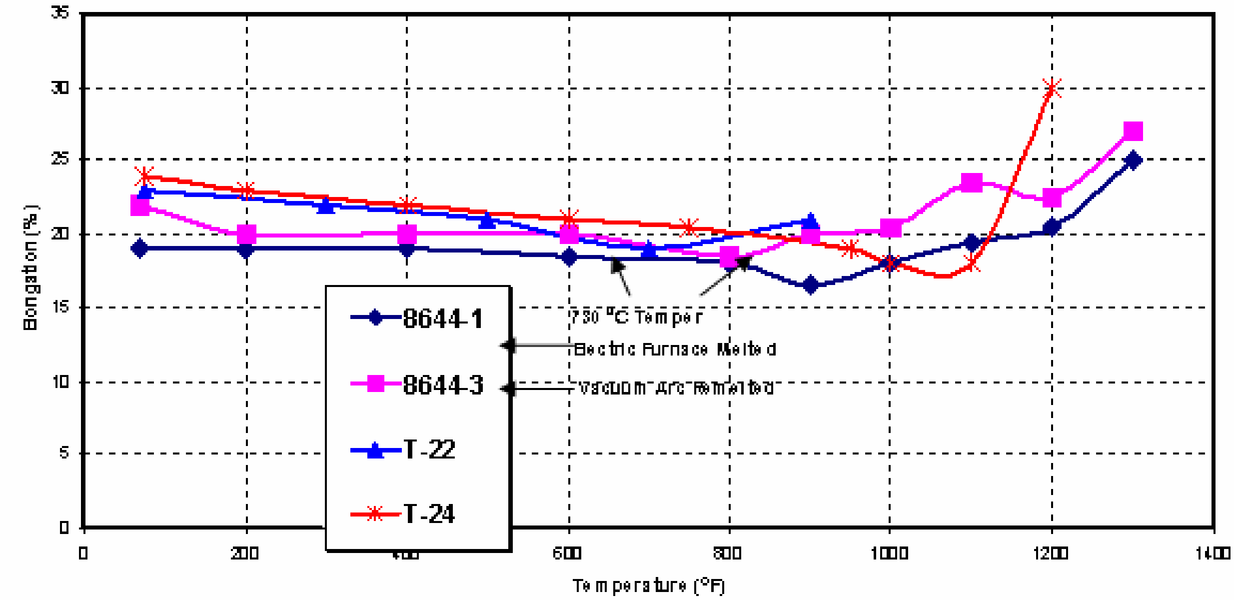


(a)

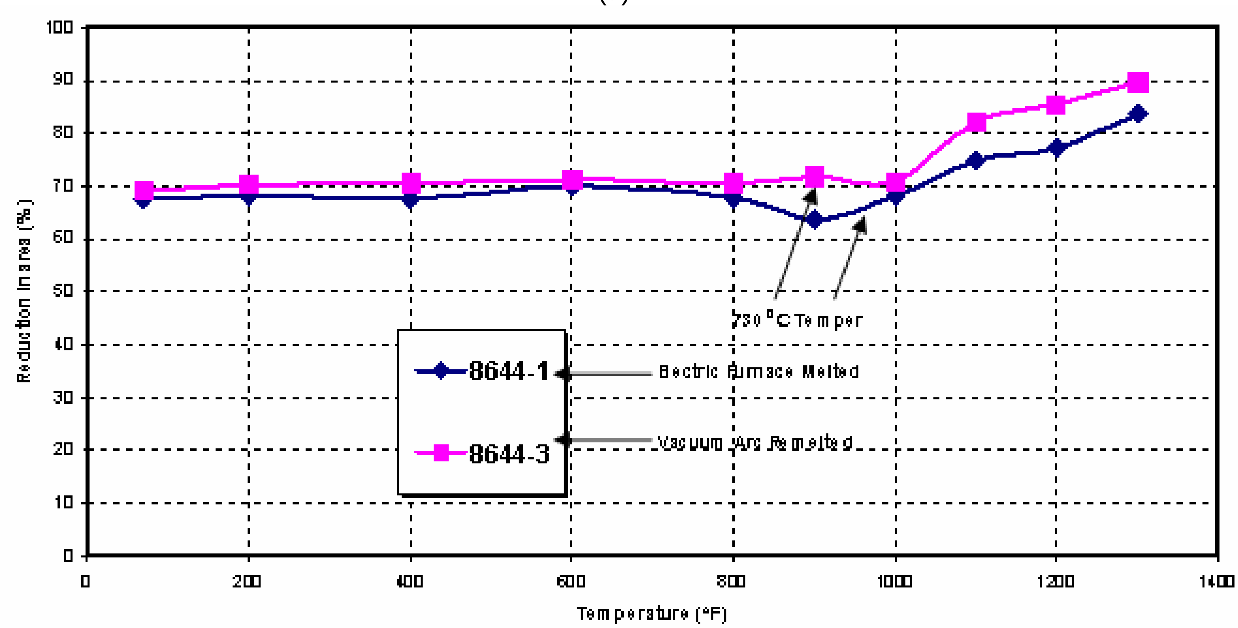


(b)

Figure 7: Comparison of tensile properties for forged billets of 50-ton heats of Grade B melted by electric furnace and vacuum-arc remelting. Data for commercial alloys T22, T23, and T24 are also included for comparision: (a) yield strength and (b) ultimate tensile strength.



(a)



(b)

Figure 8: Comparison of tensile properties for forged billets of 50-ton heats of Grade B melted by electric furnace and vacuum-arc remelting. Data for commercial alloys T22, T23, and T24 are also included for comparision: (a) total elongation and (b) reduction of area.

The creep tests are in progress on both Grades A and B after tempering at 700 and 730°C. Data available to date is only for tempering temperature of 700°C. Creep tests are being conducted in the temperature range of 900 to 1300°F and at stresses to yield 100-, 1000-, and 10,000-h rupture lives. The stress-to-rupture values for Grade A are plotted as a function of Larsen-Miller parameter (LMP) in

Fig. 9. Eight creep test points on the 50-ton heat are included in this figure. Four of the eight tests have ruptured, and the other four are in progress, as indicated by the arrows next to the data points. All tests for Grade A are on specimens in the longitudinal orientation. The LMP line, based on data for experimental heats, is included for comparison. This figure shows that the predicted LMP line describes well the rupture behavior of the 50-ton heat of Grade A. It is expected that the tests in progress will continue to support the same trend for long-term data.

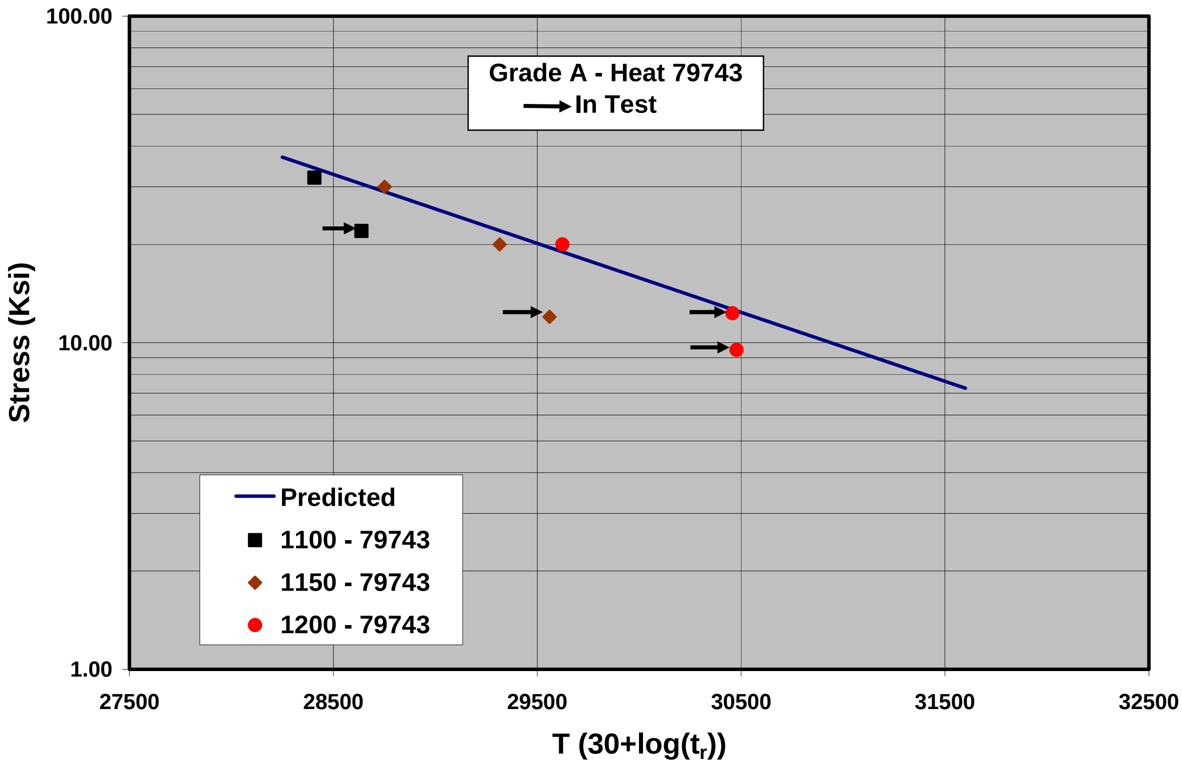


Figure 9: Plot of stress-to-rupture versus Larsen-Miller parameter (LMP) for forged billets of a 50-ton heat of Grade A. The predicted LMP, based on experimental heats, is included for comparison.

The creep-rupture data for 50-ton heats of Grade B are plotted in Fig. 10. This plot also includes the LMP based on experimental heats. A total of five tests have ruptured for one heat (86441) and two tests for the second heat (86442). Data for heat 86441 are on specimens in transverse orientation and for heat 86442 are on longitudinal orientation. Data in Fig. 10 show that the LMP predicts the creep-rupture behavior of longitudinal specimens of 50-ton heat (heat 86442) of Grade B well. However, the limited data on the transverse specimens of Grade B of heat 86441 appear to be slightly lower in strength. Since experimental data were only developed for the longitudinal orientation, the data in Fig. 10 suggest that transverse orientation is slightly weaker than the longitudinal orientation for the forged billet used for these test data.

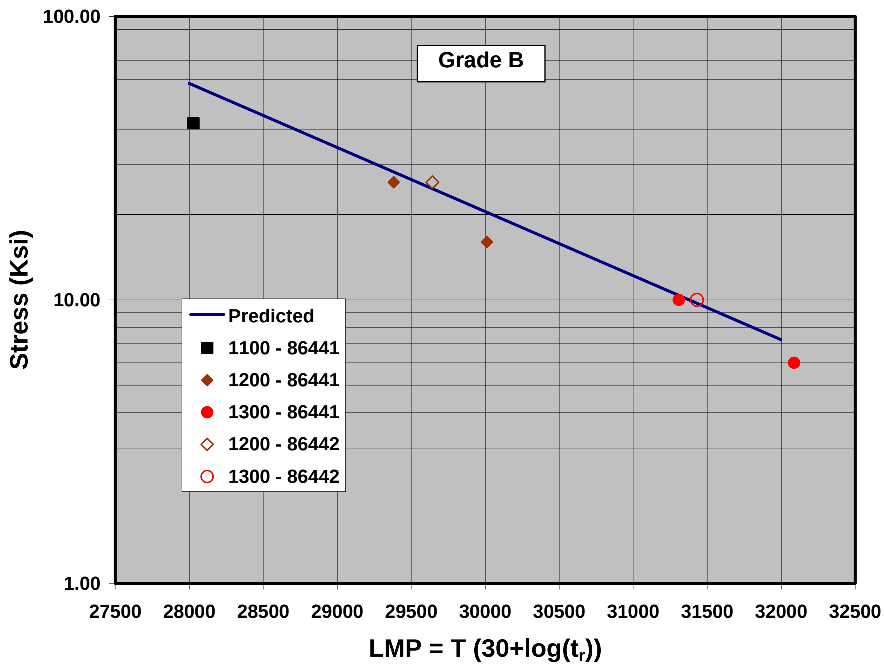


Figure 10: Plot of stress-to-rupture versus Larsen-Miller parameter (LMP) for forged billets of two 50-ton heats of Grade B. The predicted LMP, based on experimental heats, is included for comparison.

The predicted values of stress to rupture versus LMP for Grades A and B are compared with the average LMP for commercial grades T22, T23, T24, and T91 in Figs. 11 and 12. The plot in Fig. 11 shows that Grade A is stronger than T23 and T91 to approximately 1100°F. At higher temperatures, creep-rupture strength of Grade A is similar to that of T23. The plot in Fig. 12 shows that Grade B is stronger than T23 for the entire test temperature range used in the LMP for this plot. Grade B is also stronger than T91 for LMP that corresponds to a temperature of approximately 1150°F. The lower strength of Grade B at temperatures higher than 1150°F is potentially related to its poor oxidation because of its 3Cr as opposed to 9Cr in T91.

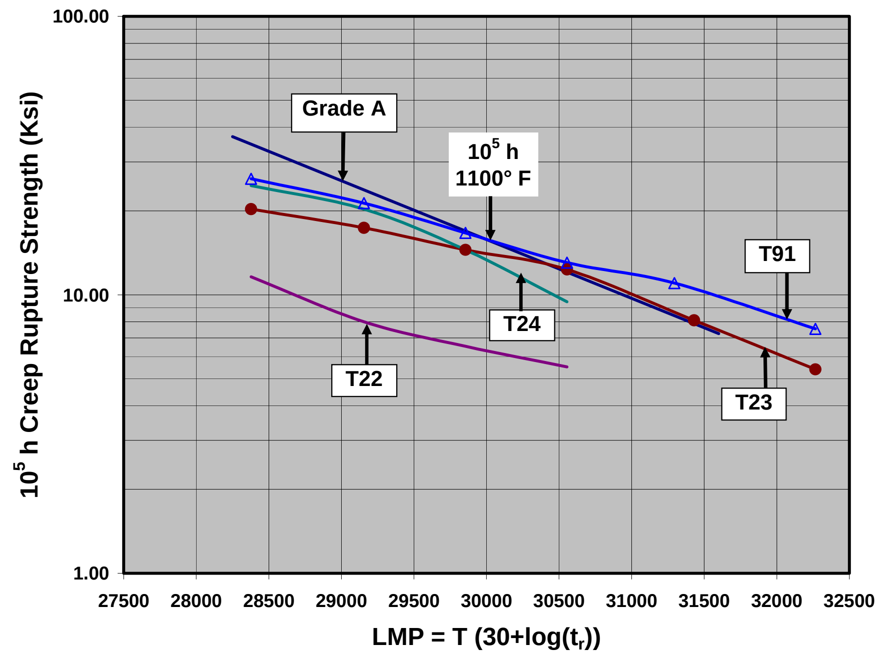


Figure 11: Comparison of stress-to-rupture versus Larsen-Miller parameter of Grade A with commercial alloys T22, T23, T24, and T91.

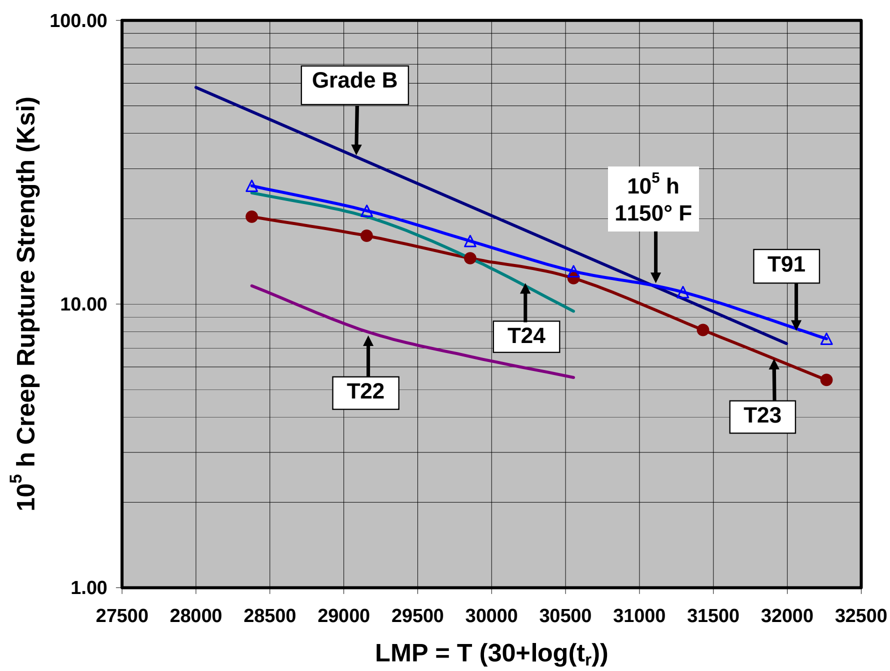


Figure 12: Comparison of stress-to-rupture versus Larsen-Miller parameter of Grade B with commercial alloys T22, T23, T24, and T91.

WELDING

Initial welding trials on the experimental heats of Grades A and B have shown that both grades are weldable by conventional gas-tungsten-arc and submerged arc processes. The welding trials for the 50-ton heats are currently underway.

SUMMARY AND CONCLUSIONS

This paper describes the development of a new class of high-strength Fe-3Cr-W(Mo) ferritic steel. The new steel has two grades, A and B. Grade A is a base Fe-3Cr-W(Mo) composition that is strengthened by optimum additions of C and V. Grade B also contains 0.10 wt % Ta for additional high-temperature creep strength. Both alloys are air hardenble and are recommended for use in the normalized and tempered condition. The best combination of strength and toughness properties are obtained when both grades are austenitized at 2012°F and tempered at 1345°F. Both grades were commercially melted in 50-ton heats by electric furnace melting. The round and slab ingots from the 50-ton heats were forged into billets and rolled into plates by using processing conditions similar to those used for Fe-2.25Cr-1Mo steels.

This paper has presented the Charpy impact, tensile, and creep data available to date on both Grades A and B. Tensile and creep data on Grades A and B are compared with the data on the commercially used grades T22, T23, T24, and the modified Fe-9Cr-1Mo Grade 91. The following conclusions are possible from this work:

1. The 40 ft-lb transition temperature for longitudinal orientation is between -30 to -40°F for both Grades A and B melted by electric furnace. For transverse orientation, the 40 ft-lb transition temperature is between 0 and +15°F. The 20-mil (0.02-in.) lateral expansion temperature varies from 0 to -60°F. It is -60°F for Grade A in the longitudinal orientation.
2. The vacuum arc remelting (VAR) of electric-furnace-melted heats showed a significant improvement in Charpy-impact properties of Grade B alloy. For example, the 40 ft-lb transition temperature was lowered by nearly 40°F for both the longitudinal and transverse orientations. Similar lowering in temperature was noted for 20-mil (0.020-in.) lateral expansion values.
3. Tensile properties of both Grades A and B for longitudinal specimens were very similar. The yield and ultimate tensile strength values of both Grades A and B are nearly 25 to 30 ksi higher than the highest strength alloy, T23. This improvement is considered very significant, especially at test temperature of 1200°F.
4. The VAR that resulted in significant improvement in Charpy-impact properties results in lowering the yield and tensile strengths. However, these values are still 15 to 20 ksi higher than Grade T23.
5. The creep-rupture-strength values for 50-ton heats of both Grades A and B in both longitudinal and transverse orientations match the predicted values based on the experimental size heats.

6. The predicted values of 10^5h stress-to-rupture versus LMP for Grades A and B were compared with the average LMP for commercial grades T22, T23, T24, and T91. These comparisons showed that Grade A is stronger than T23 and T91 to approximately 1100°F. At higher temperatures, creep-rupture strength of Grade A is similar to that of T23. However, Grade B is stronger than T23 for the entire test temperature range and is also stronger than T91 for temperature of approximately 1150°F.
7. Preliminary data have shown that both Grades A and B are weldable by commonly used methods such as submerged arc and gas tungsten arc.

ACKNOWLEDGMENT

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MECHANICAL PROPERTIES OF NEW GRADES OF FE-3CR-W ALLOYS

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ABSTRACT

This paper describes the development of two new grades of Fe-3Cr-3W(Mo) alloys at the Oak Ridge National Laboratory. The two grades are designated as A and B. The higher strength Grade B differs from Grade A in that it contains 0.10 wt % Ta. Both grades, when tested in normalized and tempered conditions, show a good combination of tensile strength and Charpy impact properties. Tensile properties of both A and B are over 150 MPa (20 ksi) higher than the highest strength commercial alloy T23. Grade B has higher creep-rupture strength than the T23 steel for the entire temperature range from 540 to 650°C. Grade B also exceeds creep-rupture strength of modified 9Cr-1Mo alloy (Grade 91) up to 615°C. Grade A exceeds the creep-rupture strength of T23 steel up to 600°C and match its values at the higher temperatures. Both grades have been scaled up to 50-ton-size commercial heats and processed into forgings and hot-rolled plates and bars.

INTRODUCTION

Ferritic steels such as Fe-2.25Cr-1Mo and Fe-9Cr-1Mo are used extensively in the chemical and power generation industry. These alloys are highly desirable because of their low coefficient of thermal expansion, high thermal conductivity, and good resistance to stress corrosion cracking in chloride environments. Extensive literature is devoted to improving the strength properties of these steels. The most recent advances for Fe-2.25 to 3Cr steels are Grades T23 and T24 (Arndt et al. 2000[a]). This paper presents the advances made at the Oak Ridge National Laboratory (ORNL) in the development of Fe-3Cr steels, which exceed the tensile and creep properties of T23 and T24.

Alloy Development

The basis for the new advances in alloy design is given elsewhere (Klueh et al. 1995, Klueh et al. 1997). Basically, there are two classes of alloys: first one uses Fe-3Cr-3W as the base alloy and the second one uses Fe-3Cr-3(W+Mo). Part of W in these alloys is replaced by Mo, using atomic equivalence. Within each class there are two grades, A and B. Grade B is the higher creep strength grade and contains 0.10 wt % Ta. The basic characteristics of the alloys are: (1) air hardenable, (2) good hardenability, (3) good impact properties, (4) higher tensile properties than competitive alloys, and (5) creep properties that exceed the current higher strength alloy T23 and the Fe-9Cr-1Mo alloy, Grade T91. The alloys were developed based on heats weighing 500 g (1 lb) that were initially melted using nonconsumable-arc melting and casting into water-cooled copper molds. Alloys with acceptable microstructure, impact, and strength properties were vacuum-induction melted (VIM) in 7.5-kg (15-lb) heats. The next incremental steps were 150- and 500-kg (300- and 1000-lb) heats, which were both done at commercial vendors. Based on data for these heats, both Grades A and B of Class 2 (Fe-3Cr-3(W+Mo) alloys were melted in 50-ton heats at Ellwood Quality Steel (EQS), New Castle, PA. The heats were melted by an electric-arc furnace, vacuum degassed, and cast into three round ingots and two slab ingots for each heat. The two round ingots from each grade were remelted by electroslag remelting (ESR) and vacuum-arc remelting (VAR) processes and recast in round ingots.

The round ingots from the electric furnace, ESR, and VAR heats were hot-forged to 305-mm (12-in.) rounds and 152-mm (6-in.) round corner square billets at Ellwood City Forge, Ellwood City, PA. The slab ingots were hot-rolled to plate product at ISG, Coatsville, PA. Part of the 152-mm (6-in.), round corner forgings were hot-rolled to 95-mm (3.75-in.) round bars for processing into seamless tubing at Plymouth Tube Co., Winamac, IN. The actual processing of bars into tubes has not yet taken place. However, no problems have been encountered in the production of hot-rolled plate, forgings, or bars from either Grades A or B.

Alloy Compositions

The chemical composition of 50-ton heats of electric-furnace-melted heats of Grades A and B are shown in Table 1. Target compositions are included for comparison. This table shows that all elements of the 50-ton heats that were melted met all elements of the aim chemistry.

Table 1: Vendor and check analysis of two 50-ton heats of Fe-3Cr-W alloy

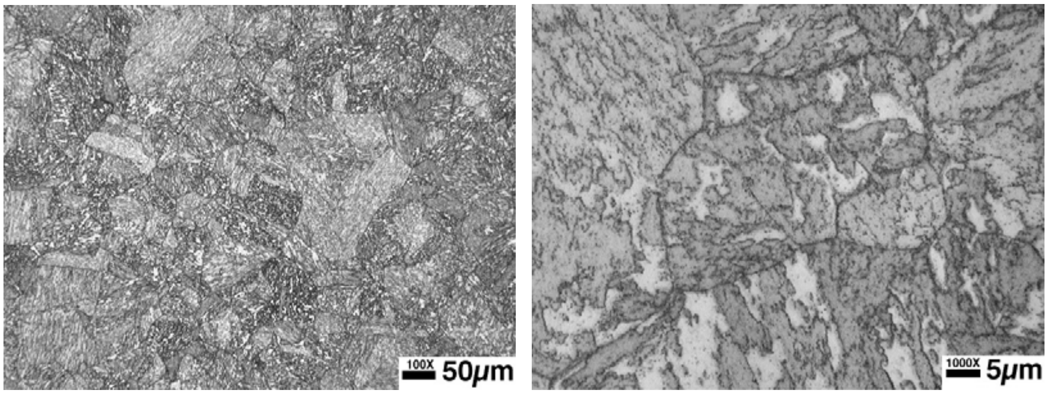
Element	Weight percent							
	Grade A, Heat L7974				Grade B, Heat L8644			
	27-in. Round			12-in. Slab	27-in. Round			12-in. Slab
	AIM	Vendor	Check	Vendor	AIM	Vendor	Check	Vendor
Carbon	0.10	0.11	0.099	0.11	0.10	0.11	0.11	0.11
Manganese	0.35	0.36	0.34	0.36	0.35	0.36	0.35	0.36
Phosphorus	0.01[a]	0.007	0.009	0.007	0.01[a]	0.008	0.009	0.008
Sulfur	0.01[a]	0.002	0.003	0.002	0.01[a]	0.002	0.002	0.002
Silicon	0.2	0.21	0.21	0.21	0.2	0.2	0.2	0.2
Nickel	0.02[a]	0.15	0.15	0.15	0.02[a]	0.12	0.12	0.12
Chromium	3.00	2.99	2.97	2.99	3.00	3.01	3.02	3.01
Molybdenum	0.75	0.76	0.73	0.76	0.75	0.74	0.73	0.74
Vanadium	0.25	0.249	0.22	0.249	0.25	0.236	0.21	0.236
Columbium	----	----	0.002	----	----	----	0.002	----
Titanium	----	----	0.003	----	----	----	0.004	----
Cobalt	----	----	0.014	----	----	----	0.016	----
Copper	----	0.11	0.11	0.11	----	0.17	0.17	0.17
Aluminum	----	0.013	0.008	0.013	----	0.011	0.006	0.011
Boron	0.01[a]	0.0002	<0.001	0.0002	0.01[a]	0.0001	<0.001	0.0001
Tungsten	1.5	1.55	1.68	1.55	1.5	1.48	1.62	1.48
Arsenic	----	----	0.005	----	----	----	0.006	----
Tin	----	----	0.008	----	----	----	0.009	----
Zirconium	----	----	<0.001	----	----	----	<0.001	----
Nitrogen	----	----	0.009	----	----	----	0.011	----
Oxygen	----	----	0.004	----	----	----	0.001	----
Hydrogen	----	1.6[b]	----	2.2[b]	----	1.3[b]	----	2.3[b]
Tantalum	----	----	----	----	0.10	0.107	0.1	0.107

[a]Maximum
[b]Parts per million

Heat-Treatment and Testing Details

The 152-mm (6-in.) long sections were cut from each of the rounded corner, 152-mm (6-in.) square forged bars. Each cut section was austenitized at 1100°C for 1.5 h and air-cooled to room temperature (RT). One each of the normalized blocks was tempered at 700 and 730°C for 1.5 h and cut to yield two 25-mm (1-in.) thick sections from one side of the block and two 0.625-mm (5/8-in.) thick sections on the second side of the block. The 25-mm (1-in.) thick sections were used for machining 12.8-mm (0.505-in.) specimens for tensile testing. The 0.625-mm (5/8-in.) thick sections were used for machining into Charpy impact and creep specimens. Tensile testing was mostly done in the longitudinal (L) orientation. However, one block of Grade B alloy was also tested in transverse (T) orientation. Tensile tests were conducted at temperatures ranging from RT to 704°C (1300°F) and at a strain rate of $1 \times 10^{-3} s^{-1}$. The same strain rate was maintained throughout the test. Tensile tests were conducted on specimens tempered at 700 and 730°C. Creep tests are being conducted from 482 to 704°C (900 to 1300°F). All creep tests to date are on material tempered at 700°C. Creep tests on material tempered at 730°C will begin in the middle of March 2004. Charpy impact specimens were tested in both L and T orientations. Test temperatures ranged from -51 to +66°C (-60 to +150°F). Both samples tempered at 700 and 730°C were tested.

Optical microstructures of Grade A after 730°C temper are shown in Fig. 1.



(a) (b)

Figure 1: Optical micrographs of forged bar of Grade A (heat 7974-1) after normalizing at 1100°C for 1.5 h and tempering at for 1.5 h at 730°C: (*a*) low magnification and (*b*) high magnification.

RESULTS AND DISCUSSION

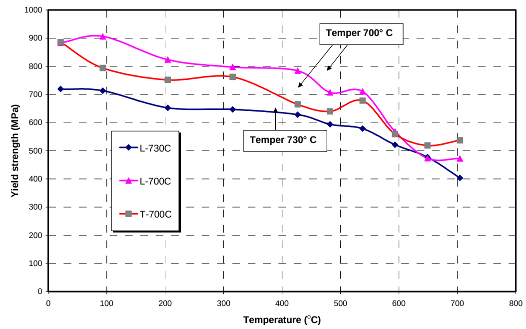
Tensile properties of Grade B (heat 8641-1), melted by electric furnace heat, are plotted as a function of test temperatures in Fig. 2(a) through (d). This figure shows: (1) there is only a small difference in yield and ultimate tensile strength of L versus T properties of the rounded-corner square forging, (2) total elongation and reduction of area of T specimens are somewhat lower than the L specimens, (3) increasing tempering temperature from 700 to 730°C reduces the yield and ultimate tensile strength and improves the elongation and reduction of area values.

Tensile properties of L specimens of Grade B after 730°C temper are compared with those of L specimens of Grade A and the same heat treatment in Fig. 3(a) through (d). These figures show that the yield and ultimate tensile strength of Grades A and B are essentially the same. Figures 3(a) through (d) also include the property data (Arndt et al. 2000[b]) for commercial alloys T22, T23, and T24. These comparisons show the following:

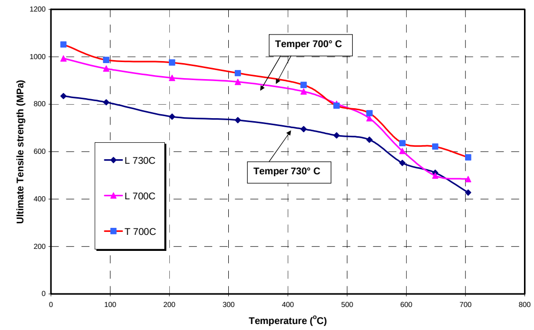
1. Yield strength of both Grades A and B are significantly higher than all competitive alloys. The alloys are over 150 MPa (20 ksi) higher in yield strength than the strongest alloy, T23. This is true for the entire test temperature and is a significant improvement for strength values at 650°C (1200°F).

2. The ultimate tensile strength values of Grades A and B are over 150 MPa (20 ksi) higher than the strongest alloy, T23, at RT. This improvement is nearly 200 MPa (30 ksi) higher than T23 at 650°C (1200°F).

3. Grades A and B show higher strength values while still retaining good ductility values of nearly 20% at RT.

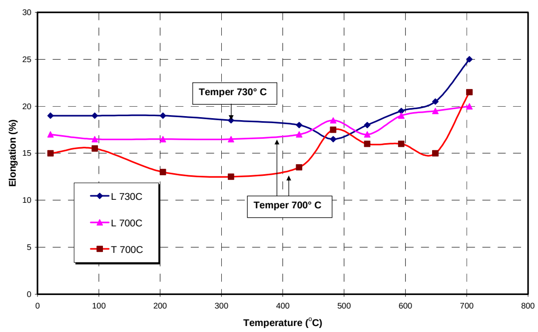


(a)

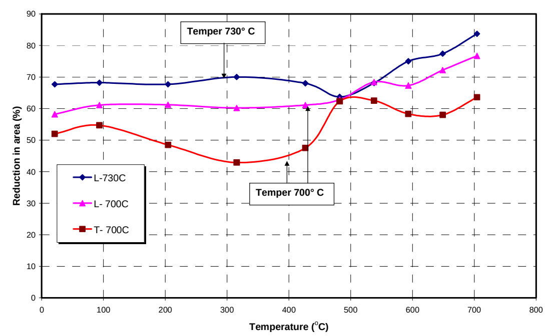


(*b*)

Figure 2. Tensile properties as a function of test temperature for forged bar of Grade B of heat 8644-1 in two specimen orientations and tempering temperatures of 700 and 730°C: (*a*) yield strength and (*b*) ultimate tensile strength.

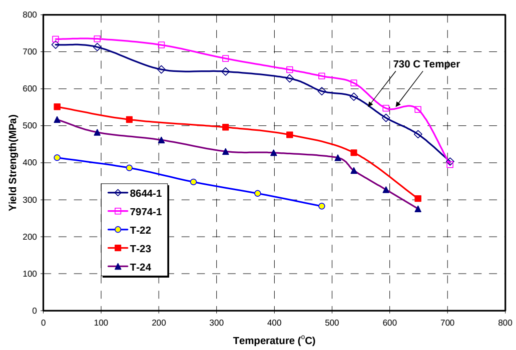


(c)

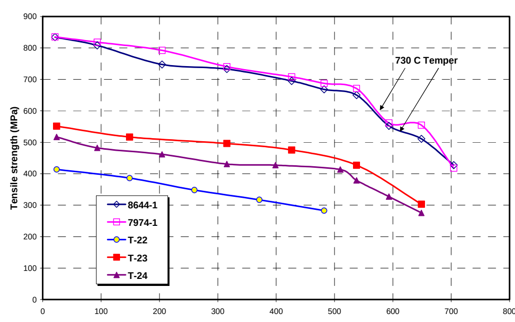


(d)

Figure 2: Tensile properties as a function of test temperature for forged bar of Grade B of heat 8644-1 in two specimen orientations and tempering temperatures of 700 and 730°C: (*c*) total elongation and (*d*) reduction of area.

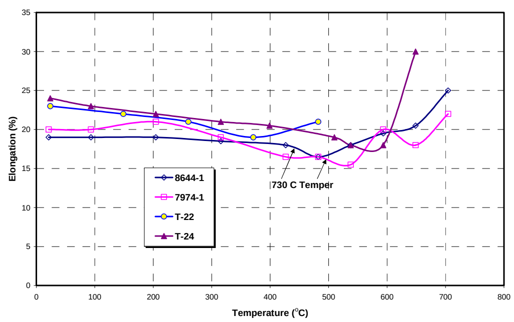


(a)

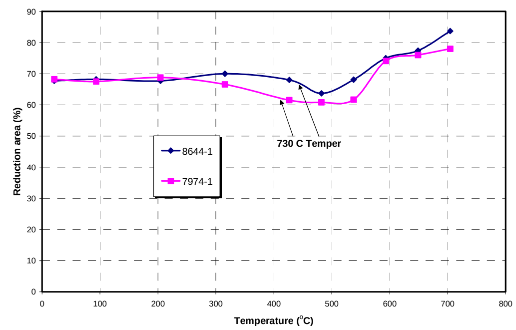


(b)

Figure 3. Comparison of tensile properties as a function of test temperature for forged bars of Grades A and B of heats 7974-1 and 8644-1 after tempering at 730ºC: (a) yield strength and (b) ultimate tensile strength. Tensile properties of commercial alloys T22, T23, and T24 are also included in the figures, where available.



(c)



(d)

Figure 4. Comparison of tensile properties as a function of test temperature for forged bars of Grades A and B of heats 7974-1 and 8644-1 after tempering at 730C: (*c*) total elongation and (*d*) reduction of area. Tensile properties of commercial alloys T22, T23, and T24 are also included in the figures, where available.

Charpy impact data for Grade B (heat 8644-1) are plotted in Fig. 4. This figure clearly shows that acceptable impact properties are obtained when the tempering temperature is increased from 700 to 730°C. For the tempering temperature of 730°C, impact on L specimens is somewhat better than T specimens. The 68 J (50-ft·lb) transition temperature for forgings of Grade B, tempered at 730°C, varies from -40°C for L to -7°C for T (-40°F for L to +20°F for T) specimens. Charpy impact properties of Grade B are compared with Grade A, tempered at 730°C, in Figs. 5(a) and (b). These figures show that both Grades A and B are very similar in their Charpy impact properties, including effects of specimen orientation and tempering temperature. Creep-rupture properties of Grade B are plotted as a Larsen-Miller plot in Fig. 6. The solid line is the LM parameter based on experimental heats of Grade B of Class 1 alloys that are based on Fe-3Cr-3W alloys. Data points are for only those tests that have ruptured thus far. This plot shows good agreement between the data on 50-ton commercial heat and the predicted values taken from data on the experimental heats tested for the same tempering temperature of 700°C. The creep-rupture plot for Grade A is shown in Fig. 7. This figure also shows good agreement between the data on the 50-ton commercial heat and the predicted values for the experimental heat of Grade A from Class 1 alloys.

The 10^5-h creep-rupture properties (extrapolated) of the alloys are compared with the published data for commercial alloys in Fig. 8. It is clear from this figure that Grade B has higher creep-rupture strength than all alloys across the entire test temperature range except Grade 91 (modified 9Cr-1Mo) alloy (Haarmann et al. 1999). The creep-rupture strength of Grade B crosses that of Grade 91 at approximately 615°C. It is believed that the higher oxidation rate in air during creep testing of Grade B, due to its 3Cr at temperatures exceeding 615°C as opposed to Grade 91 that contains 9% Cr, is the reason for its lower creep-rupture strength at > 615°C. Grade A, without 0.10 wt % Ta, has higher creep-rupture strength than T23 up to 600°C, and matches its creep rupture at higher temperature. Grade A also exceeds the creep-rupture strength of Grade 91 up to 600°C.

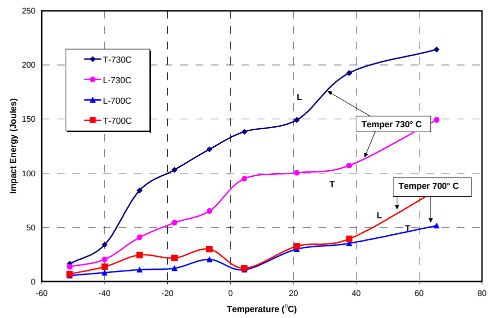
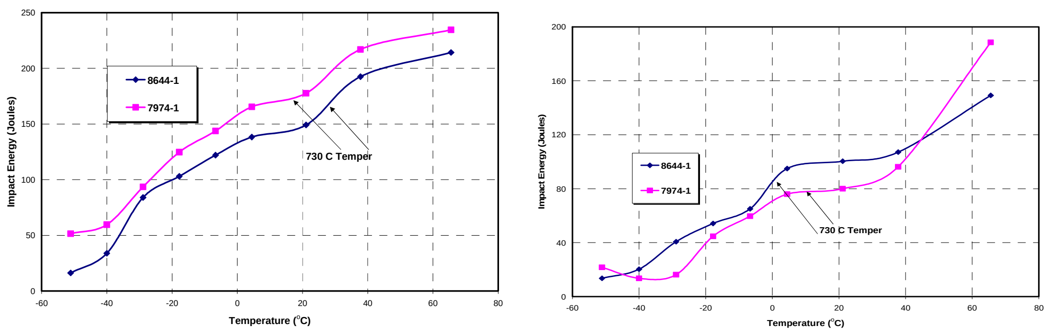


Figure 5. Charpy impact energy as a function of test temperature for forged bar of Grade B. Data are included for two specimen orientations (longitudinal and transverse) and tempering temperature of 700 and 730°C.



(a) (b)

Figure 6. Comparison of Charpy impact energy as a function of test temperatures for forged bars of Grades A and B after tempering temperature of 730°C: (*a*) longitudinal and (*b*) transverse.

Welding and Weldment Properties

A significant effort was devoted towards welding process development and weldment properties during the alloy development phase. The major focus of the development was for the submerged arc (SA) process. However, some effort was also devoted to the gas tungsten arc (GTA) process. The key findings from the development of SA and GTA welding processes are briefly described here.

Submerged Arc Process. Effort during the SA welding was to identify the flux that introduced the least amount of oxygen in the weld deposit. The Lincoln 880 flux was found to be the most desirable for welding of the alloys. Filler wire compositions were optimized that would work with 880 flux and exceed minimum values of 20 J (15 ft·lb) of impact energy and 0.020 mils of lateral expansion at RT without postweld heat treatment (PWHT) of welds. The final optimized resulted in RT values of 34 J (25 ft·lb) of energy and 0.022 mils of lateral expansion, both of which exceeded the targeted minimum values. If PWHT is used, the Charpy impact values will improve significantly. Weld wire has been fabricated for welding commercial heats, which will be initiated by the middle of April 2004.

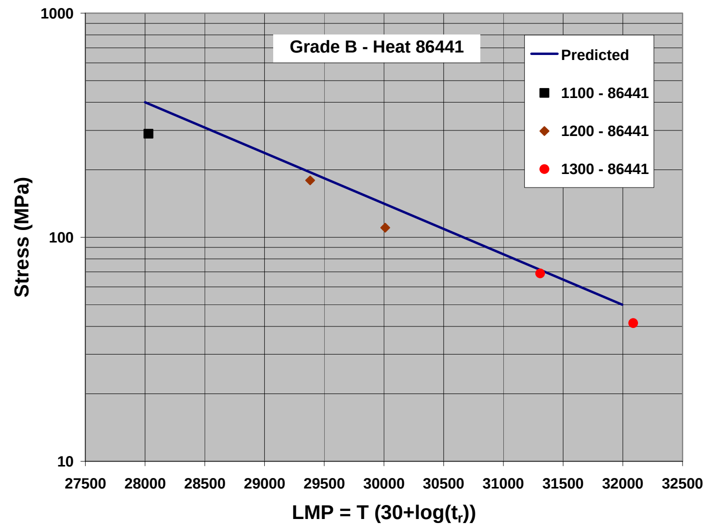


Figure 7. Creep-rupture strength as a function of Larsen-Miller parameter for forged bar of Grade B, heat 8641-1. Data on 50-ton heat are compared with the Larsen-Miller parameter based on data for experimental heats.

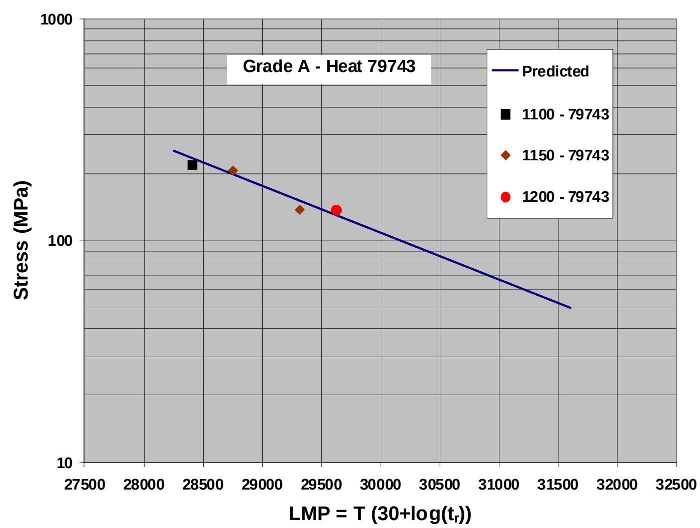


Figure 8. Creep-rupture strength as a function of Larsen-Miller parameter for forged bar of Grade A, heat 7974-1. Data on 50-ton heat are compared with the Larsen-Miller parameter based on data for experimental heats.

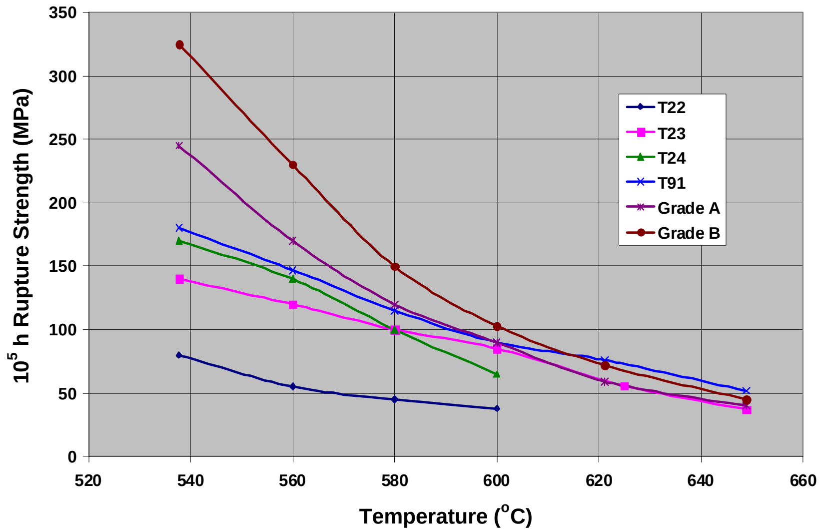


Figure 9. The comparison of 10^5 h creep-rupture strength as a function of temperature of Grades A and B compared with commercial alloys T22, T23, T24, and T91.

Gas Tungsten Arc Process. For the GTA welds, oxygen pick-up in the weld deposit was not an issue as was the case for the SA welds. For these welds, we were able to develop filler wire that yielded impact values of 231 and 258 J (170 and 190 ft·lb) at RT and -40°C (-40°F) for as-welded condition and 245 and 170 J (180 and 124 ft·lb) at RT and -40°C (-40°F) after PWHT at 700°C. Based on these results, it is possible to get GTA welds of good toughness without requiring PWHT.

Larger batches of filler wire have been fabricated for making GTA welds for both alloy Grades A and B. One GTA weld has already been made with the new wire in the plates sectioned from the rounded-corner, forged square bars of 50-ton heat 7974-1 of Grade A. The welded plate is currently undergoing fracture toughness testing.

SUMMARY

The alloys are the new class of Fe-3Cr-3W(Mo) alloys that when tested in normalized and tempered conditions produce an exceptional combination of tensile and Charpy impact properties. The same microstructure also tends to produce creep strength that is higher than the commercial alloy T23 and Grade 91 up to 615°C. Initial data shows that the alloys can be welded by the commonly used SA and GTA processes. The alloys have been successfully melted into 50-ton heats and processed into forged bars and hot-rolled plates and bars. Extensive mechanical property testing of the commercial heats is underway so that data packages can be prepared for the inclusion of these alloys in ASTM and ASME Codes.

CONCLUSIONS

The following conclusions can be drawn from this work:

1. Grades A and B of the Fe-3Cr-3W(Mo) alloys are over 150 MPa (20 ksi) higher in yield strength than the commercial highest-strength alloy of its class T23 for the entire test temperature of RT to 650°C.
2. The ultimate tensile strength of Grades A and B is higher than T23 by 150 MPa (20 ksi) at RT and 200 MPa (30 ksi) at 650°C.
3. Both Grades A and B show good impact properties when tested after a tempering temperature of 730°C.
4. The creep-rupture-strength values of Grade B are higher than T23 for the entire test temperature range. They are also higher than modified 9Cr-1Mo alloy (Grade 91) up to 615°C.
5. The creep-rupture-strength values of Grade A, without 0.10 wt % Ta, are also higher than T23 up to 600°C and match its values at higher temperatures. Grade A rupture strength values are also higher than Grade 91 up to 600°C.
6. Initial results show that the alloys can be welded by the commonly used processes such as SA and GTA.
7. Grades A and B have been successfully scaled up to 50-ton heats and processed into forgings and hot-rolled plate and bar.
8. Testing of commercial heats is under way to gather data for preparing ASTM and ASME Code packages.

ACKNOWLDEGMENT

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Haarmann, K., Vaillant, J. C., Bendick, W., and Arbab, A., 1999, The T91/P91 Book, Vallourec & Mannesmann Tubes, Houston, TX.

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Appendix C

Presentations

1. Application of Neural Network Modeling for Fe-3Cr-1.5W Filler Metal
2. Mechanical Property Evaluation of 3Cr-1.5W-0.75Mo-V(Ta) Steel

Application of Neural Network Modeling for Fe-3Cr-1.5W Filler Metal

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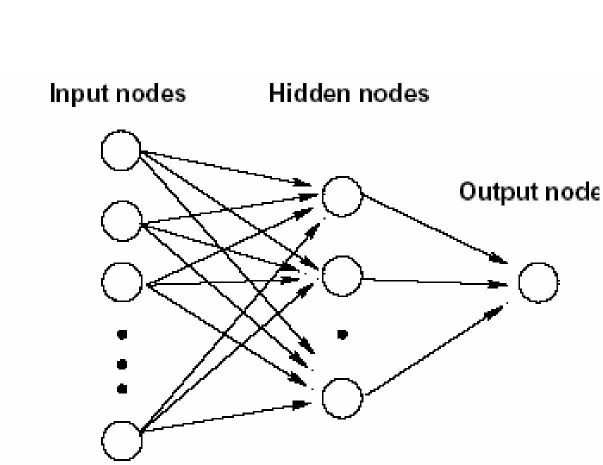
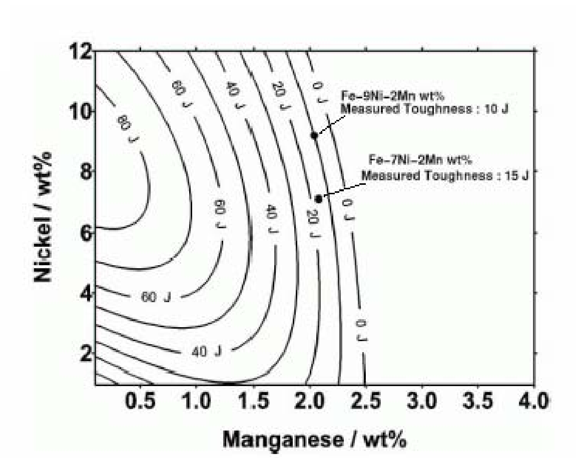
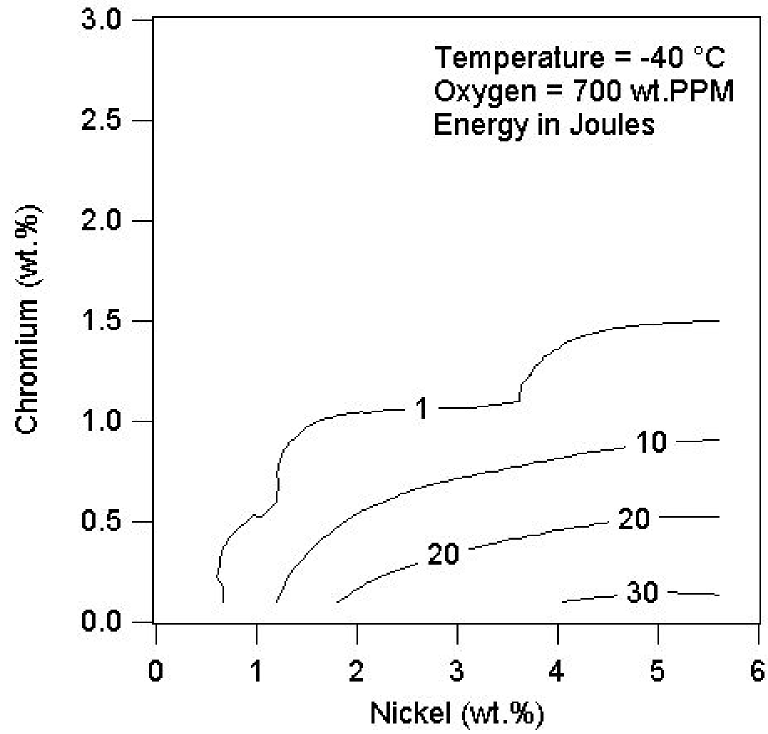
A comprehensive neural network to predict yield strength, tensile strength, ductility and toughness of shielded metal arc weld deposits was developed in University of Cambridge, UK





The model considers alloying element (C, Si, Mn, Ni, Mo, Cr, W, Co, Ti, O, and N) interpass temperature, heat input, and post weld heat treatment conditions.

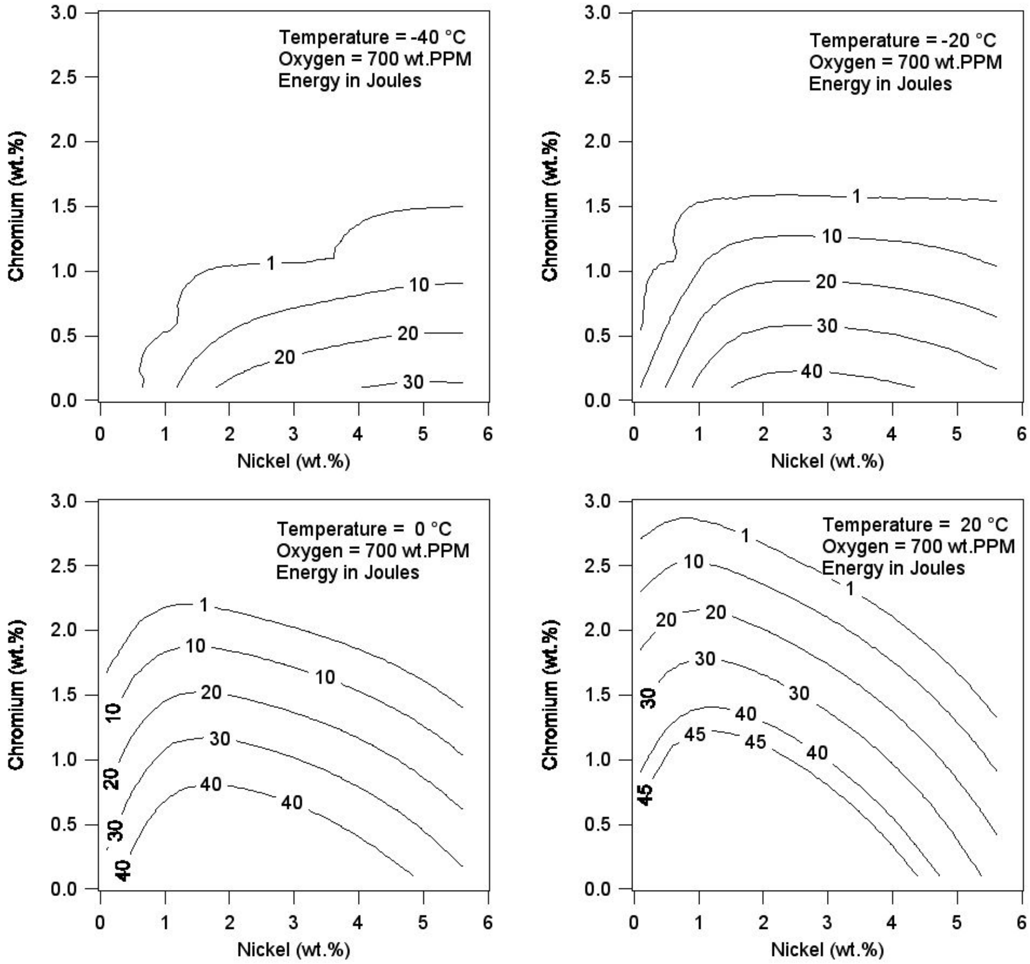
The same model was applied to Fe-3Cr-1.5W (wt.%) weld composition (SAW 18788/880/54624).



- ***The results show that the toughness at -40°C for this alloy is very poor.***

- ***It is important to note that the neural network was developed for SMAW process. So there is some uncertainty in predictions for SAW.***

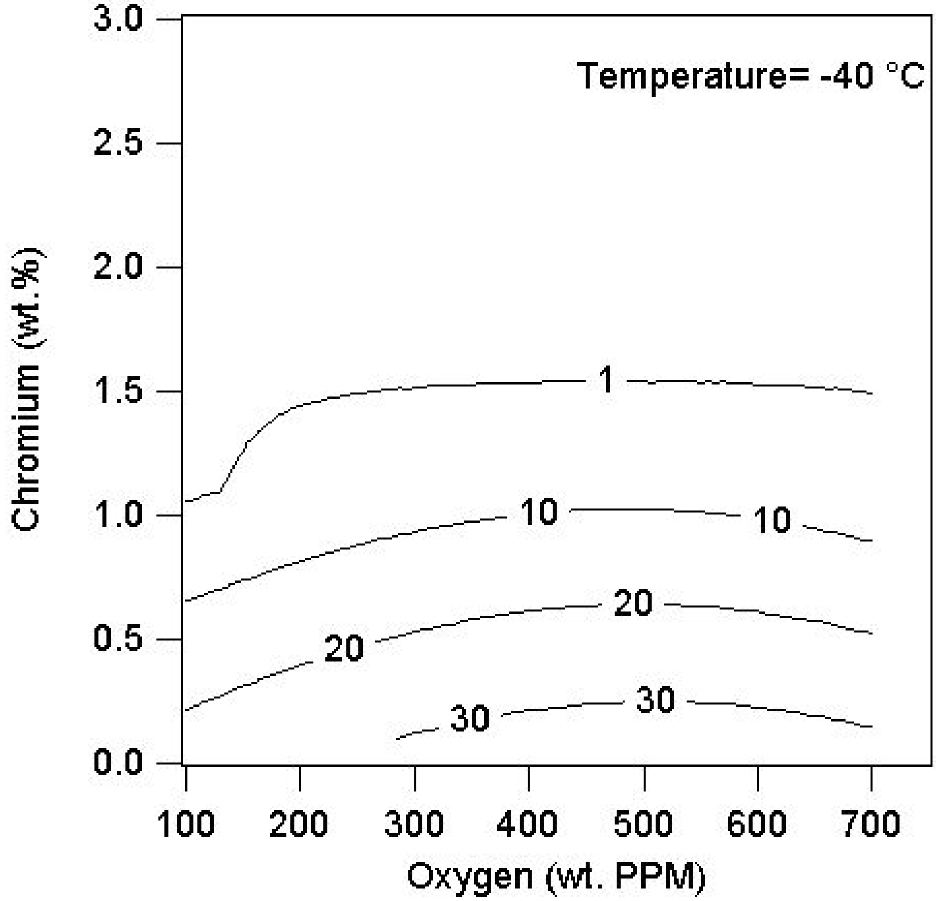
Complex variations of toughness with temperature was predicted.



Chromium concentration seems to have a large effect in reducing the toughness.

How about oxygen effect?

Oxygen seems to have small effect at low chromium concentrations, even with increased levels of nickel (5 wt %).

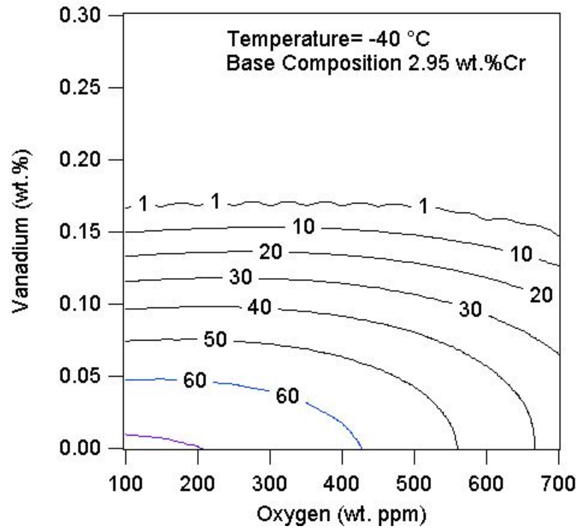


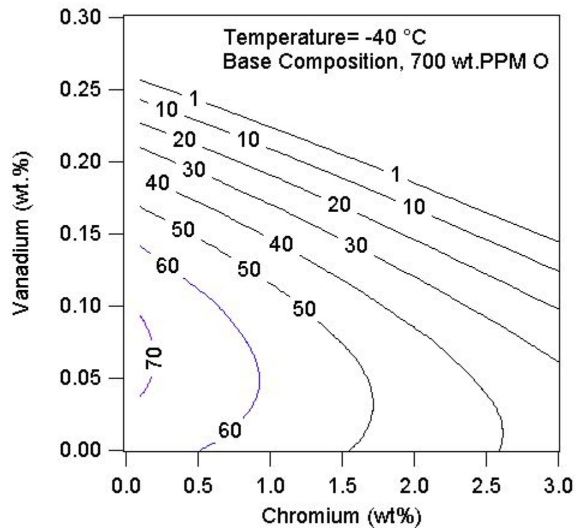
Addition of Nickel has beneficial effect only at low chromium concentrations (< 1.5 wt%).

It appears that chromium may be the crucial factor.

What do we do in the next step?

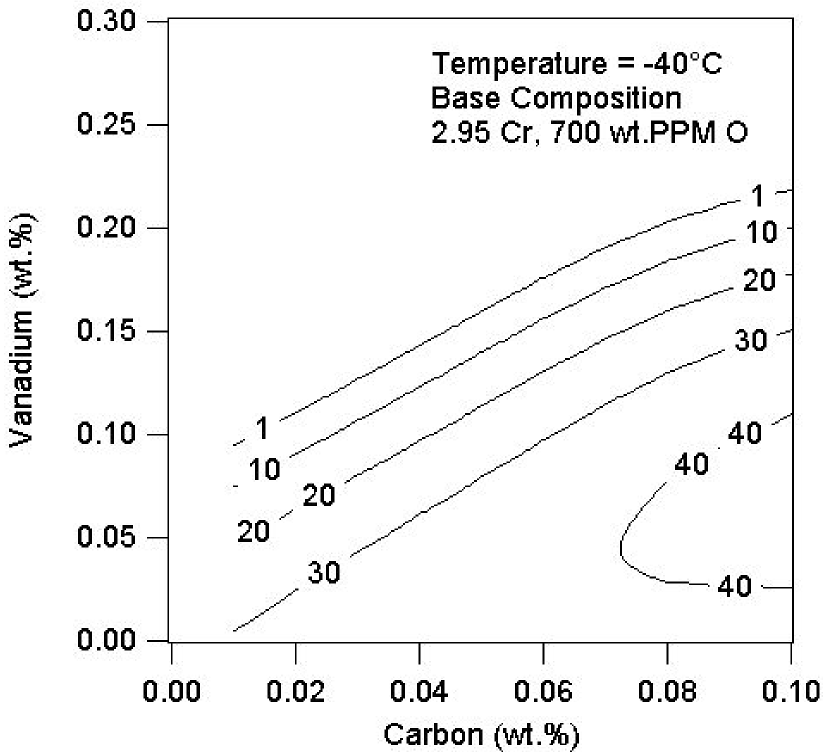
The V-Cr-O interactions are strong on controlling the toughness at -40°C.





The model suggests that at 3 wt % Cr, vanadium and oxygen reduction will lead to better toughness.

The V-C interactions suggests that vanadium in solid solution may lead to poor toughness.

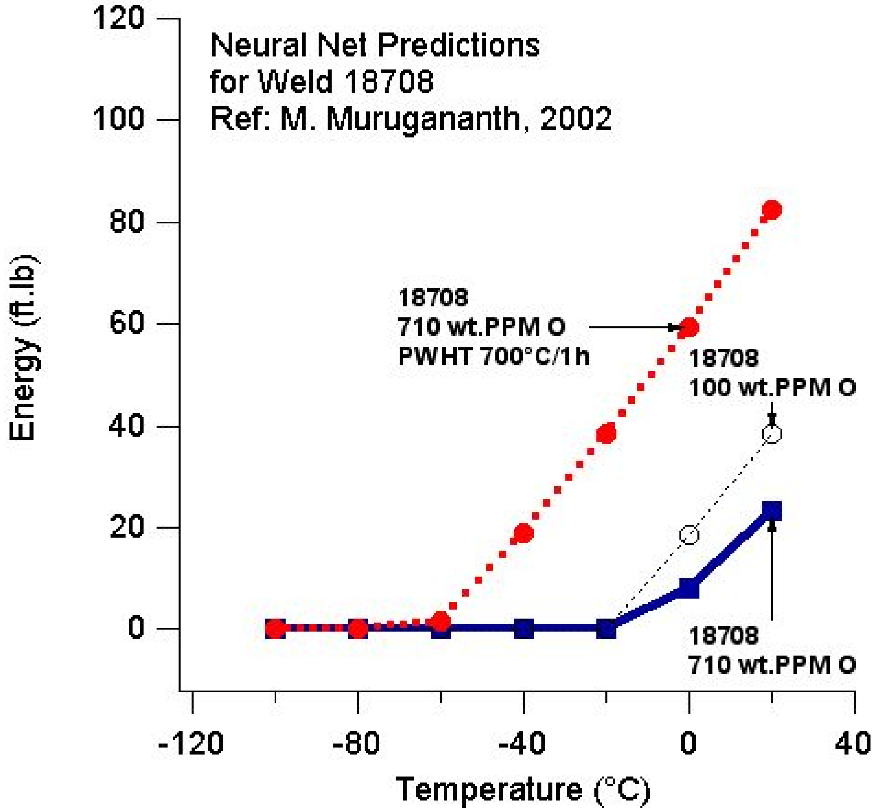


Hypothesis:

Vanadium will form VC at high carbon levels during weld cooling.
With the precipitation of VC, the vanadium in solid solution may decrease.
The above hypothesis needs to be evaluated with careful TEM measurements.

The results so far shows complex interactions between Cr, V, C, Ni and Oxygen content in welds.

Predicted Charpy toughness curves for weld composition based on Weld 18708.



Post weld heat treatment does improve the toughness even with the presence of vanadium.

Reducing oxygen content, only leads to an improvement in upper self energy.

The above results show the design of filler metal for optimum combination of strength, toughness and creep strength are not trivial.

Predictions are based on neural net developed for SMAW welds.

We need careful experimentation to optimize the final filler metal composition.

- ***The neural net was developed based on 3000 data points from SMAW welding literature.***
- ***Such a vast knowledge of experimental data encompassing composition and process parameters are not readily available for developing models in case of SAW.***

- ***The most important step is we need to understand why we have low toughness in these welds.***
- ***Gleeble® thermomechanical simulations and experimental welds with focused weld composition matrix need to be planned and performed.***
- ***Preliminary results show that for toughness PWHT is important.***
- ***This might help us to understand and develop new filler wires.***
- ***If sufficient resources and time are given we can embark on this focused experimentation and theoretical work.***

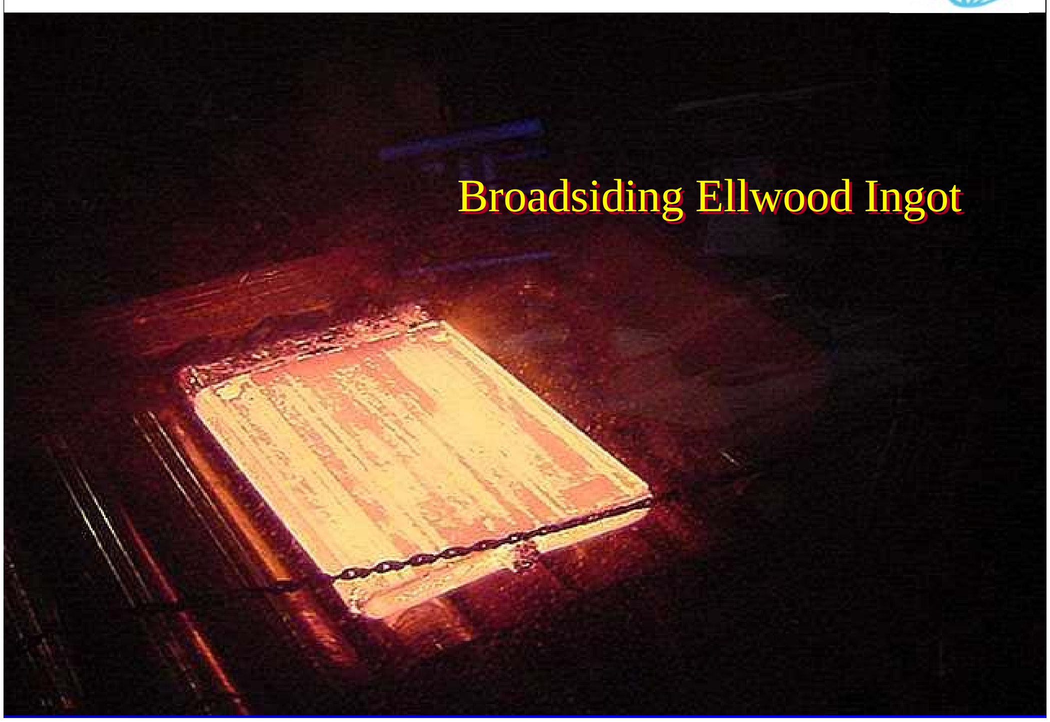
3Cr-1.5W-.75Mo V Ta

OAK RIDGE NATIONAL LABORATORY

Mechanical Property Evaluation of 3Cr - 1.5W - .75Mo - V (Ta) Steel

Ken Orie
ISG Plate
Coatesville, PA

3Cr-1.5W-.75Mo V Ta



3Cr-1.5W-.75Mo V Ta

Rolling to Plate

3Cr-1.5W-.75Mo V Ta

"Snap" Gauge

Plate Cooling

OOPS!!

Heat Treating

3Cr-1.5W-.75Mo V Ta

86369-001	A8141-1	1.5 x 96 x pro	Rolled 104 x 345 315"GM	16"T/14"B
86369-002	A8141-2	3 x 72 x pro	Rolled 79 x 242 211" GM	16"T/15"B
86370-001	A8142-1	1.5" x 96 x pro	Rolled 103 x 359 322" GM	19"T/18"B
86370-002	A8142-2	3 x 72 pro	Rolled 79 x 222 199" GM	15"T/8"B

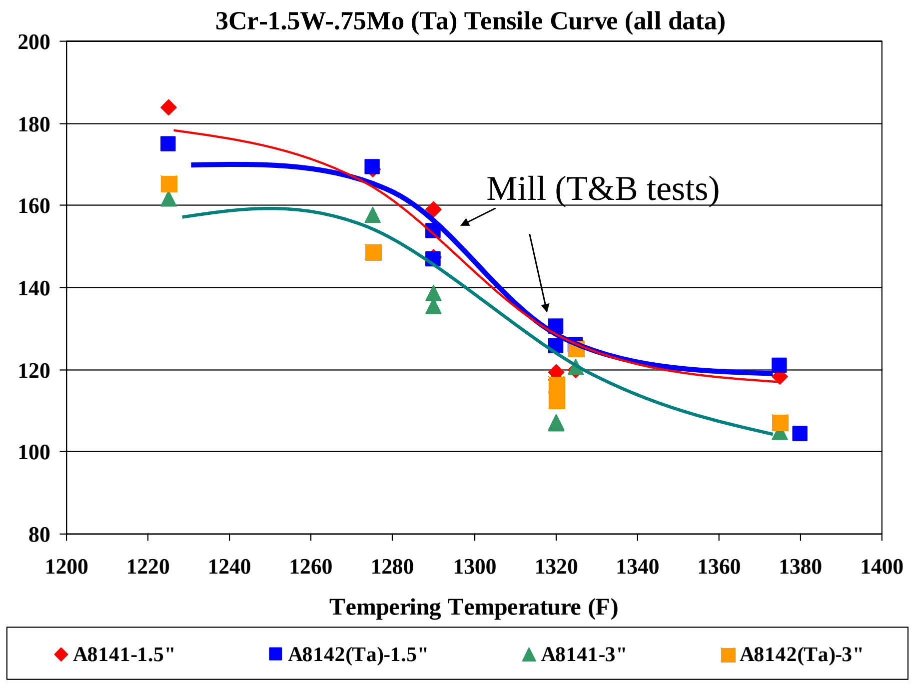
Approx weight 15,300 according to Ellwood to yield 13,000#

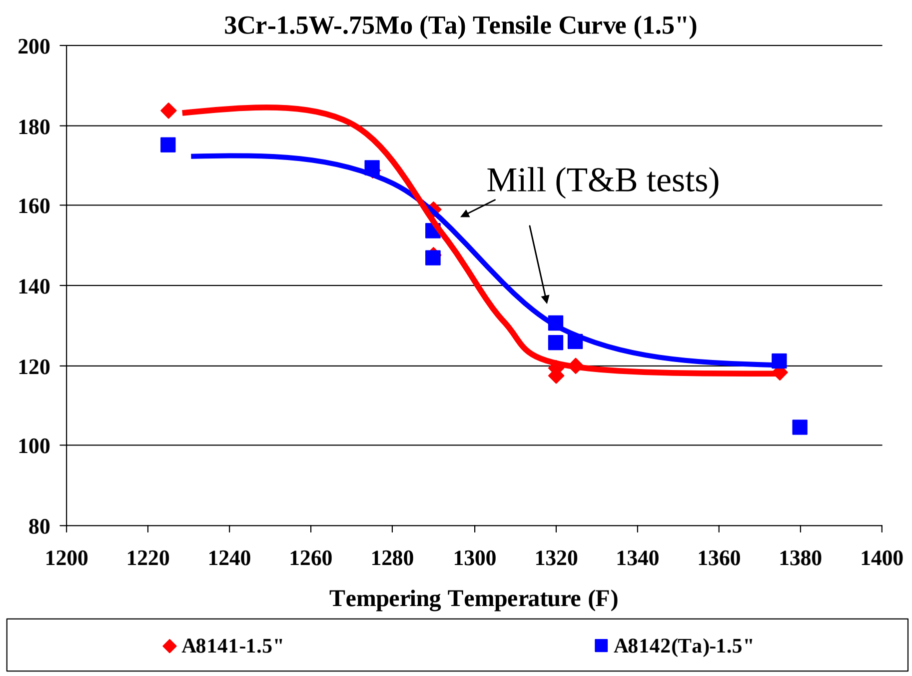
Ingots as received were conditioned by Ellwood

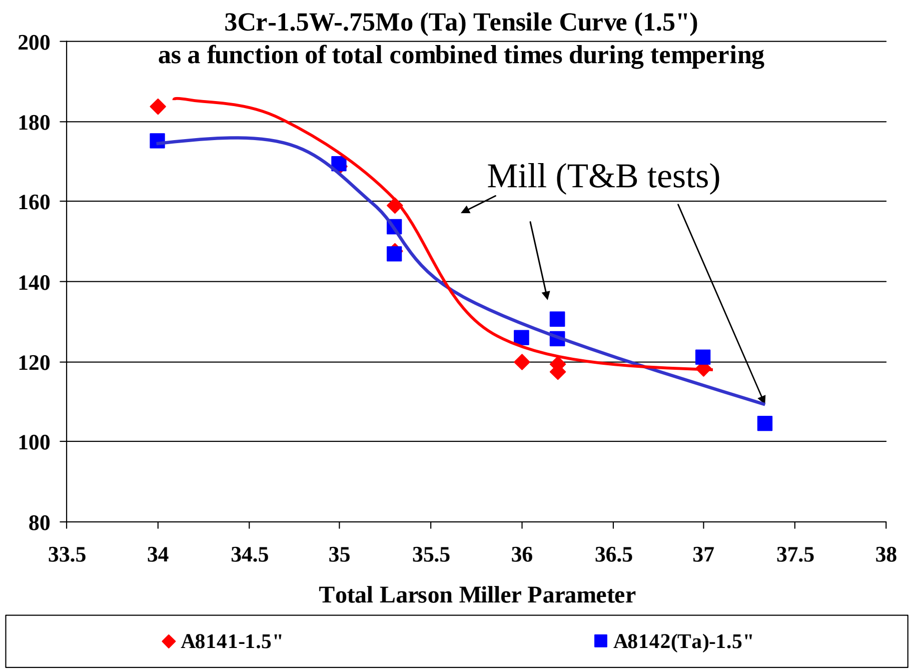
3Cr-1.5W-.75Mo V Ta

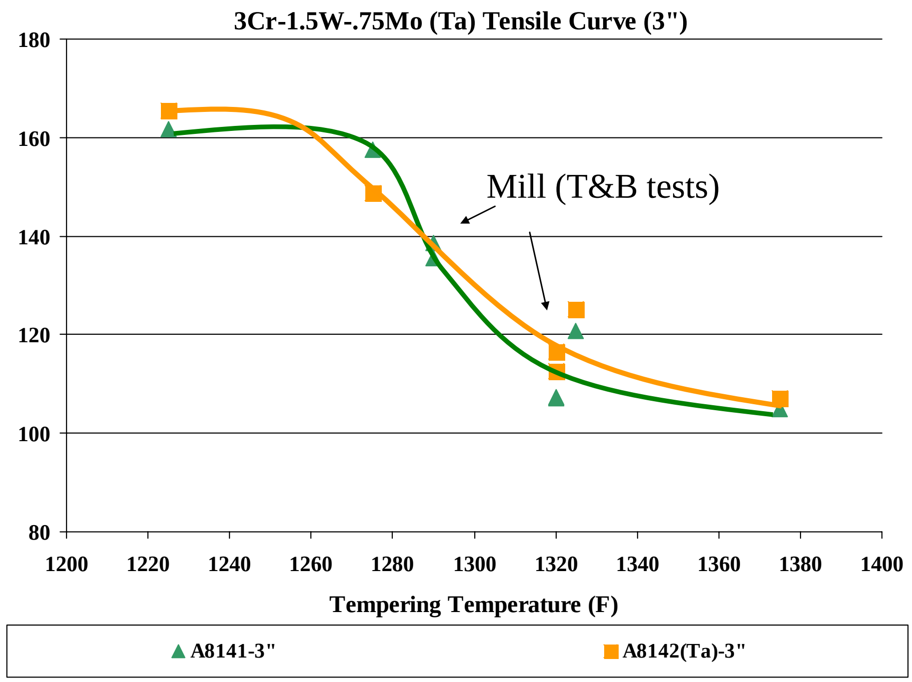
Tensile Results for 3Cr-1.5W-.75Mo (Ta)

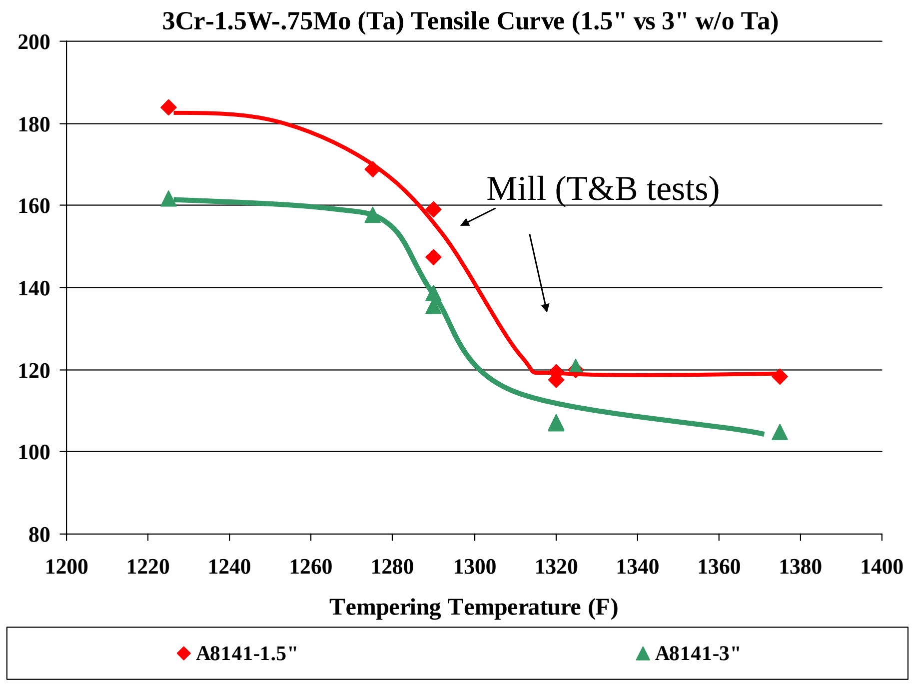
			Lab	Lab	Mill	Mill	Lab	Lab	Mill
Tempering Temperature			1225 F	1275 F	1290 F	1320F (1)	1325 F	1375 F	1380 F (2)
Identity	*Gage*				*Top/Bottom*	*Top/Bottom*			
A8141-1	1.5"	*UTS*	183.8	168.9	158.9/147.5	**117.5/119.3**	120.0	118.3	
(L7974)		*.2% Yld*	161.0	150.9	138.9/134.8	**103.9/104.9**	104.9	103.8	
		El (2")	14.0	14.0	14/16	**15/14**	20.0	20.0	
A8142-1	1.5"	*UTS*	175.0	169.3	153.7/146.8	130.5/125.6	125.9	120.9	**105.2/103.3**
(Ta)		*.2% Yld*	154.6	146.1	130.4/125.3	117.4/113	113.3	108.1	**89.6/89.0**
(L8644)		*El (2")*	16.0	16.0	17/17	15/15	19.0	19.0	**21/19**
A8141-2	3"	*UTS*	161.7	157.6	138.6/135.4	**107/107.3**	120.7	104.8	
(L7974)		*.2% Yld*	147.0	143.5	125.6/122.7	**91.5/93**	106.9	87.9	
		El (2")	13.0	14.0	16/17	**19/21**	19.0	22.0	
A8142-2	3"	*UTS*	165.5	148.8	na	**116.5/112.5**	125.1	107.1	
(Ta)		*.2% Yld*	149.6	134.8	na	**102.3/99.2**	111.7	91.6	
(L8644)		*El (2")*	13.0	15.0	na	**14/14**	18.0	23.0	

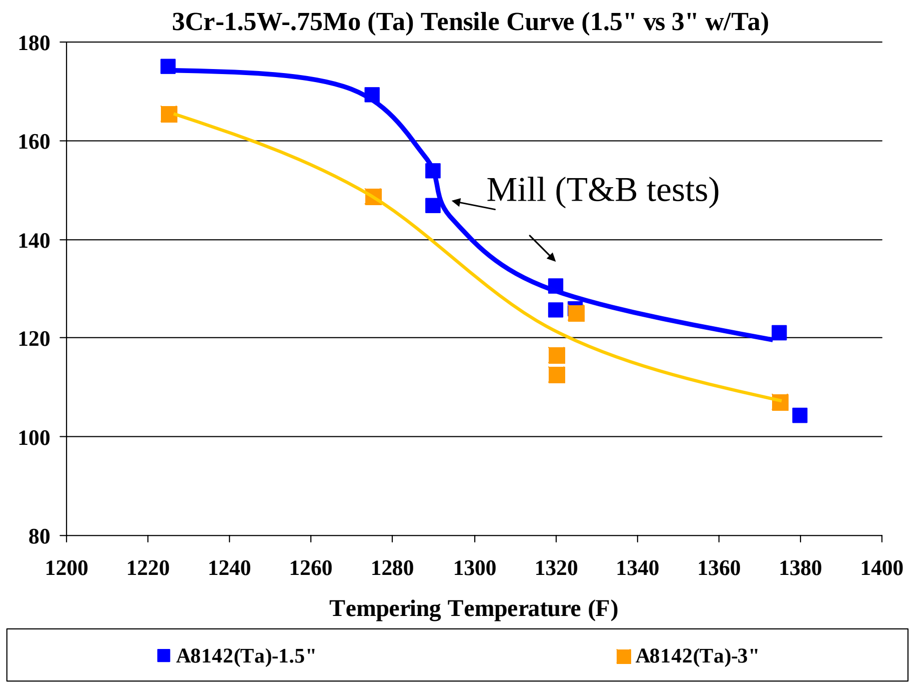

3Cr-1.5W-.75Mo (Ta) Tensile Curve (all data)
200
180
160
140
120
100
80
Mill (T&B tests)
1200
1220
1240
1260
1280
1300
1320
1340
1360
1380
1400
Tempering Temperature (F)
A8141-1.5"
A8142(Ta)-1.5"
A8141-3"
A8142(Ta)-3"

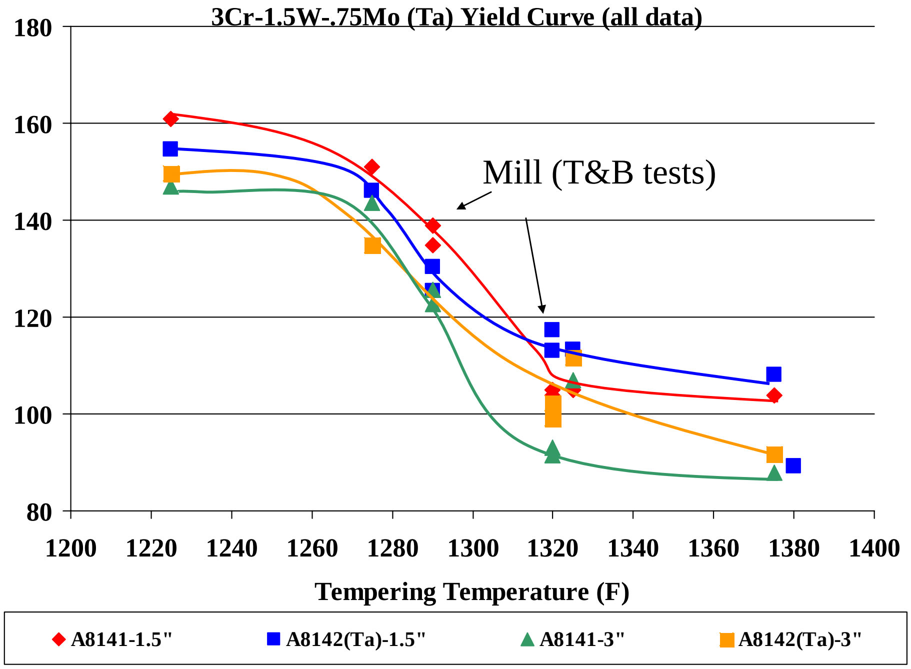

3Cr-1.5W-.75Mo (Ta) Tensile Curve (1.5")
200
180
160
140
120
100
80
Mill (T&B tests)
1200
1220
1240
1260
1280
1300
1320
1340
1360
1380
1400
Tempering Temperature (F)
A8141-1.5"
A8142(Ta)-1.5"


3Cr-1.5W-.75Mo (Ta) Tensile Curve (1.5")
as a function of total combined times during tempering
200
180
160
140
120
100
80
33.5
34
34.5
35
35.5
36
36.5
37
37.5
38
Mill (T&B tests)
Total Larson Miller Parameter
A8141-1.5"
A8142(Ta)-1.5"

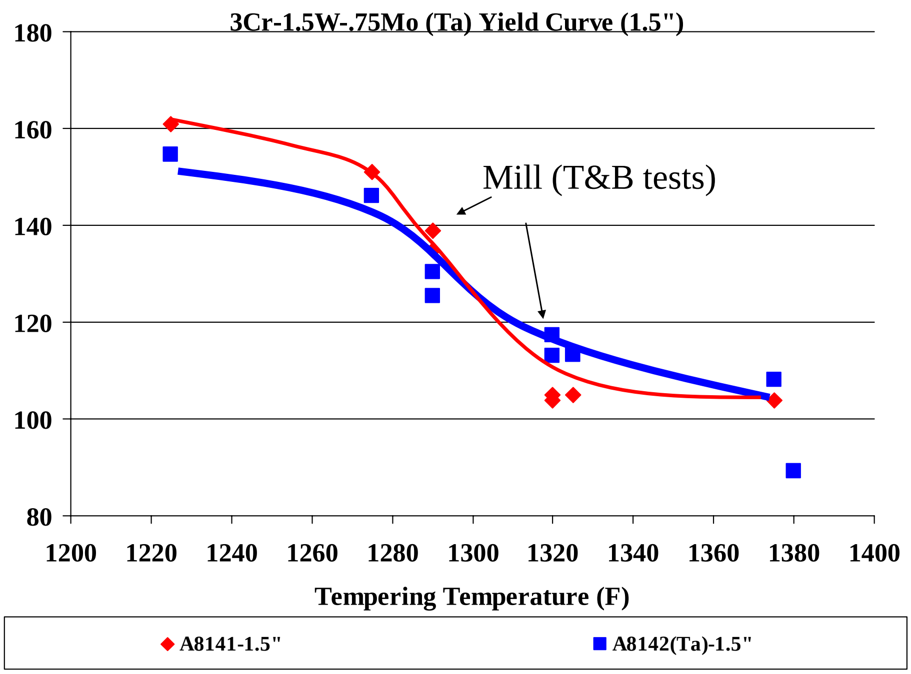

3Cr-1.5W-.75Mo (Ta) Tensile Curve (3")
180
160
140
120
100
80
1200
1220
1240
1260
1280
1300
1320
1340
1360
1380
1400
Mill (T&B tests)
Tempering Temperature (F)
A8141-3"
A8142(Ta)-3"

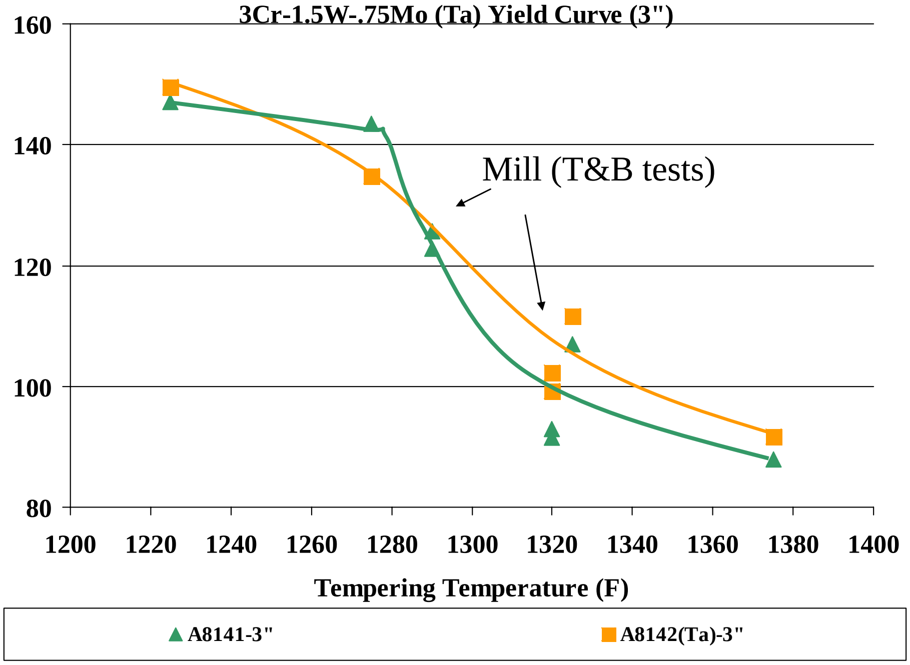

3Cr-1.5W-.75Mo (Ta) Tensile Curve (1.5" vs 3" w/o Ta)
200
180
160
140
120
100
80
1200
1220
1240
1260
1280
1300
1320
1340
1360
1380
1400
Mill (T&B tests)
Tempering Temperature (F)
A8141-1.5"
A8141-3"

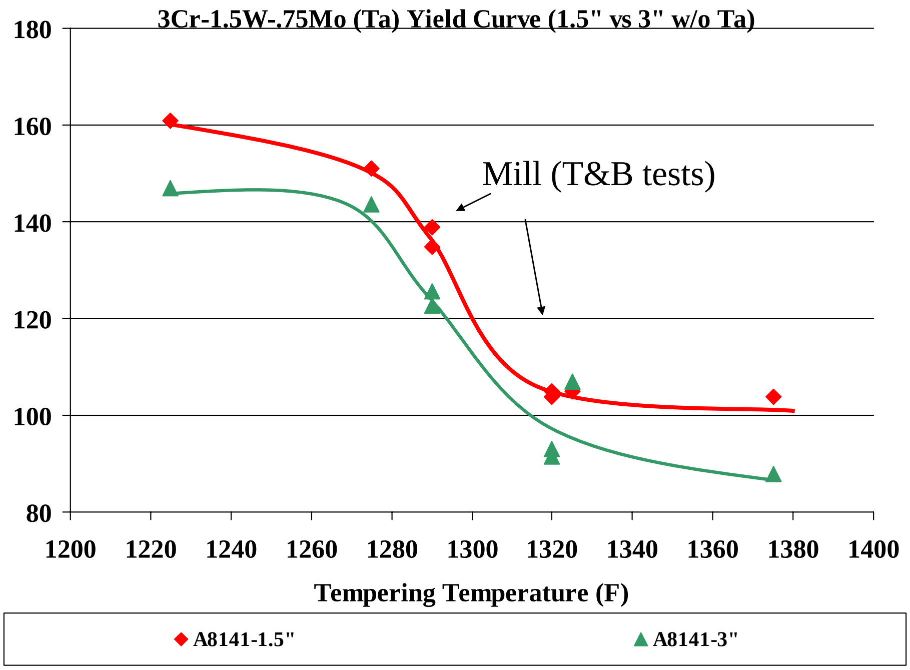

3Cr-1.5W-.75Mo (Ta) Tensile Curve (1.5" vs 3" w/Ta)
180
160
140
120
100
80
1200
1220
1240
1260
1280
1300
1320
1340
1360
1380
1400
Mill (T&B tests)
Tempering Temperature (F)
A8142(Ta)-1.5"
A8142(Ta)-3"

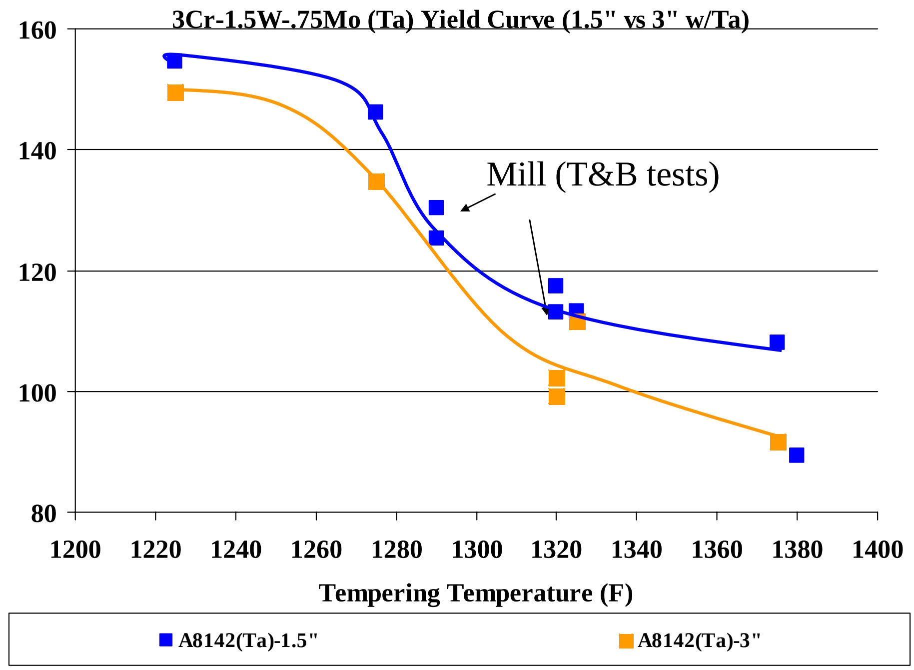

3Cr-1.5W-.75Mo (Ta) Yield Curve (all data)
180
160
140
120
100
80
1200
1220
1240
1260
1280
1300
1320
1340
1360
1380
1400
Mill (T&B tests)
Tempering Temperature (F)
A8141-1.5"
A8142(Ta)-1.5"
A8141-3"
A8142(Ta)-3"

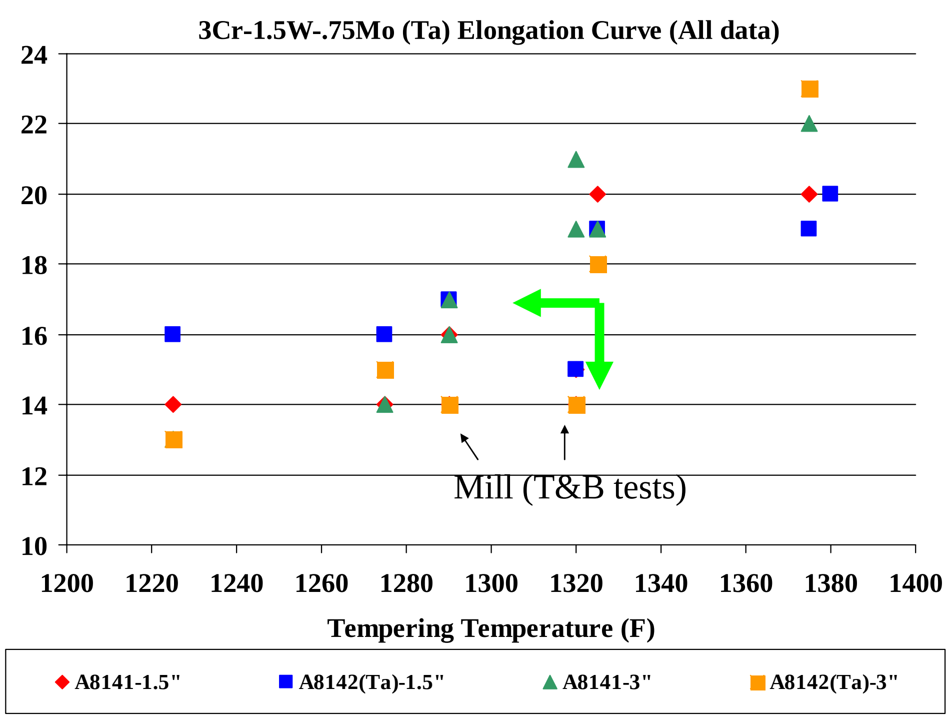
1


3Cr-1.5W-.75Mo (Ta) Yield Curve (1.5")
180
160
140
120
100
80
1200
1220
1240
1260
1280
1300
1320
1340
1360
1380
1400
Mill (T&B tests)
Tempering Temperature (F)
A8141-1.5"
A8142(Ta)-1.5"


3Cr-1.5W-.75Mo (Ta) Yield Curve (3")
160
140
120
100
80
1200
1220
1240
1260
1280
1300
1320
1340
1360
1380
1400
Tempering Temperature (F)
Mill (T&B tests)
A8141-3"
A8142(Ta)-3"


3Cr-1.5W-.75Mo (Ta) Yield Curve (1.5" vs 3" w/o Ta)
180
160
140
120
100
80
1200
1220
1240
1260
1280
1300
1320
1340
1360
1380
1400
Tempering Temperature (F)
Mill (T&B tests)
A8141-1.5"
A8141-3"

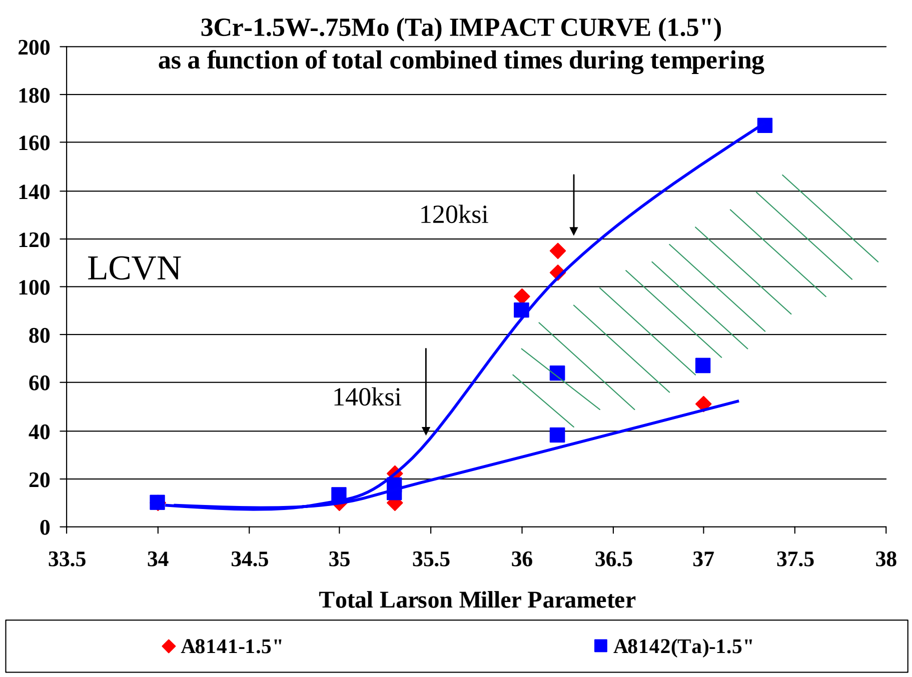

3Cr-1.5W-.75Mo (Ta) Yield Curve (1.5" vs 3" w/Ta)
160
140
120
100
80
1200 1220 1240 1260 1280 1300 1320 1340 1360 1380 1400
Tempering Temperature (F)
Mill (T&B tests)
A8142(Ta)-1.5"
A8142(Ta)-3"


3Cr-1.5W-.75Mo (Ta) Elongation Curve (All data)
24
22
20
18
16
14
12
10
1200 1220 1240 1260 1280 1300 1320 1340 1360 1380 1400
Tempering Temperature (F)
Mill (T&B tests)
A8141-1.5"
A8142(Ta)-1.5"
A8141-3"
A8142(Ta)-3"

3Cr-1.5W-.75Mo V Ta

Impact Results for 3Cr-1.5W-.75Mo (Ta)

Melt	Ga	Temper (F)	Energy (Ft-lbs) +68 F (L)			Energy (Ft-lbs) +32 F (Long / Trans)			Energy (Ft-lbs) 0 F (L)			Energy (Ft-lbs) -40 F (L)		
A8141-1	1.5"	1225	8	8	9	5/4	6/4	12/8	5	11	11	3	5	7
(L7974)		1275	5	6	14	8/8	10/10	11/12	6	10	12	3	5	5
		1290(M)B				8/11	11/14	12/14						
		1290(M)T				20/7	24/12	24/13						
		1320(M)B				105/102	107/105	108/105						
		1320(M)T				112/111	117/111	117/116						
		1325	93	96	104	94/59	95/69	100/71	62	82	88	17	33	34
		1375	84	89	92	40/24	47/26	69/34	44	49	61	26	30	32
A8142-1	1.5"	1225	5	6	17	8/3	9/9	11/11	2	3	13	5	6	7
(Ta)		1275	6	7	24	6/6	14/8	18/14	4	5	8	1	3	5
(L8644)		*1290(M)B*				7/8	19/12	25/17						
		1290(M)T				10/6	11/6	23/15						
		1320(M)B				38/33	30/34	38/30						
		1320(M)T				66/43	65/43	60/45						
		1325	69	86	94	83/57	93/62	96/86	64	74	88	4	5	13
		1375	4	7	11	63/na	67/na	70/na	7	10	38	3	4	5
		1380 (M)B				193/123	193/131	195/131						
		1380 (M)T				149/127	167/152	184/157						
A8141-2	3"	1225	4	7	9	6/5	8/6	17/9	3	4	4	2	2	3
(L7974)		1275	7	8	13	4/5	6/7	8/9	3	5	5	4	4	5
		1290(M)B				6/8	18/10	25/20						
		1290(M)T				10/6	11/10	13/13						
		1320(M)B				128/121	126/122	129/125						
		1320(M)T				110/100	113/107	121/104						
		1325	81	86	88	63/19	69/23	75/25	26	29	42	6	6	8
		1375	97	99	114	109/na	115/na	118/na	43	48	59	20	28	36
A8142-2	3"	1225	9	21	57	5/13	16/16	19/29	3	6	6	4	5	6
(Ta)		1275	4	11	12	6/7	6/9	7/9	4	6	8	5	5	7
(L8644)		*1290(M)B*				na	na	na						
		1290(M)T				na	na	na						
		1320(M)B				69/63	65/64	61/66						
		1320(M)T				96/85	98/88	103/84						
		1325	69	76	93	75/35	82/35	96/40	27	33	39	8	11	18
		1375	105	120	151	111/71	118/98	121/102	73	67	137	76	86	86



3Cr-1.5W-.75Mo V Ta

Subcommittee Ballot Item to be sent out by ASTM

(If no negatives or comments that need to be addressed,
this version may proceed to main committee in August)

To: ASTM A01.11 Members

From: Ken Orie, TG Chairman

Subject: New Standard AXXXX/AXXXXM

WK#: WK 3558

Rationale: New standard providing higher strength Cr Mo W V steel consisting of two grades, one of which contains tantalum.

Item:

3Cr-1.5W-.75Mo V Ta

Standard Specification for

**Standard Specification for
Pressure Vessel Plates, Alloy Steel, Chromium-Tungsten-Molybdenum-Vanadium and Chromium-Tungsten-Molybdenum-Vanadium-Tantalum[1]**

This standard is issued under the fixed designation A XXXX/AXXXM; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification covers chromium-tungsten–molybdenum-vanadium, with or without tantalum, alloy steel plates intended primarily for welded boilers and pressure vessels designed for elevated temperature service.

1.2 Plates are available under this specification in two grades having different alloy contents as follows:

Grade	Nominal Chromium Content, %	Nominal Tungsten Content, %	Nominal Molybdenum Content, %	Nominal Vanadium Content, %	Nominal Tantalum Content, %
315	3.00	1.50	0.75	0.25	
315T	3.00	1.50	0.75	0.25	0.10

1.3 The maximum thickness of plates is limited only by the capacity of the composition to meet the specified mechanical property requirements.

1.4 The specification is expressed in both inch-pound units and in SI units; however, unless the order specifies the applicable "M" specification designation (SI units), the plates are furnished to inch-pound units.

1.5 The values stated in either inch-pound units or SI units are to be regarded separately as standard. Within the text, the SI units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system is to be used independently of the other.

3Cr-1.5W-.75Mo V Ta

2. Referenced Documents

2.1 *ASTM Standards:*

A 20/A 20M Specification for General Requirements for Steel Plates for Pressure Vessels[1]

A 370 Test Methods and Definitions for Mechanical Testing of Steel Products[2]

A 435/A 435M Specification for Straight-Beam Ultrasonic Examination of Steel Plates[2]

A 577/A 577M Specification for Ultrasonic Angle-Beam Examination of Steel Plates[2]

A 578/A 578M Specification for Straight-Beam Ultrasonic Examination of Plain and Clad Steel Plates for Special Applications[2]

3. General Requirements

3.1 Product furnished to this specification shall conform to Specification A 20/A 20M, including any supplementary requirements indicated in the purchase order or contract. Failure to comply with the general requirements of Specification A 20/A 20M constitutes nonconformance with this specification. In case of conflict between the requirements of this specification and Specification A 20/A 20M, the requirements of this specification shall prevail.

3.2 In addition to the basic requirements of this specification, certain supplementary requirements are available if additional control, testing, or examination is required to meet end use requirements. The purchaser is referred to the listed supplementary requirements in this specification and to the detailed requirements in Specification A 20/A 20M.

4. Materials and Manufacture

4.1 *Steelmaking Practice*—The steel shall be killed and shall conform to the fine austenitic grain size requirements of Specification A20/A20M.

3Cr-1.5W-.75Mo V Ta

5. Heat Treatment

5.1 Except as allowed by 5.2, all plates shall be normalized at 1950 to 2050 °F [1065 to 1120 °C] and then tempered at 1290 to 1400 °F [700 to 760 °C].

5.2 Plates ordered without the heat treatment required by 5.1 shall be furnished in either the stress-relieved or annealed condition, and the purchaser shall be responsible for the heat treatment of such plates to conform to 5.1.

6. Chemical Composition

6.1 The steel shall conform to the requirements for chemical composition given in Table 1.

7. Mechanical Properties

7.1 *Tension Test*—The plates, as represented by the tension test specimens, shall conform to the applicable requirements given in Table 2.

8. Keywords

8.1 elevated temperature service, creep resistance, high-strength, tantalum, chromium, molybdenum, tungsten, vanadium, pressure vessels, hydrogen service, alloy steel plates

3Cr-1.5W-.75Mo V Ta

TABLE 1 Chemical Requirements

NOTE—Where ". . . " appears in this table, there is no requirement.

	Composition, %	
Element	Grade 315	Grade 315T
Carbon:		
Heat Analysis	0.08-0.12	0.08-0.12
Product Analysis	0.07–0.13	0.07–0.13
Manganese:		
Heat Analysis	0.25-0.45	0.25-0.45
Product Analysis	0.20-0.50	0.20-0.50
Phosphorus, max:		
Heat Analysis	0.010	0.010
Product Analysis	0.015	0.015
Sulfur, max:		
Heat Analysis	0.010	0.010
Product Analysis	0.012	0.012
Silicon:		
Heat Analysis	0.15-0.40	0.15-0.40
Product Analysis	0.10-0.45	0.10-0.45
Nickel, max:		
Heat Analysis	0.25	0.25
Product Analysis	0.30	0.30

3Cr-1.5W-.75Mo V Ta

Chromium:		
Heat Analysis	2.8-3.2	2.8-3.2
Product Analysis	2.7-3.3	2.7-3.3
Molybdenum:		
Heat Analysis	0.65-0.85	0.65-0.85
Product Analysis	0.60-0.90	0.60-0.90
Nickel, max:		
Heat Analysis	0.25	0.25
Vanadium:		
Heat Analysis	0.20–0.30	0.20–0.30
Product Analysis	0.18–0.33	0.18–0.33
Boron, max:		
Heat Analysis	0.0007	0.0007
Tantalum:		
Heat Analysis	. . .	0.07-0.13
Product Analysis	. . .	0.06-0.14
Tungsten:		
Heat Analysis	1.35-1.65	1.35-1.65
Product Analysis	1.30–1.70	1.30–1.70

TABLE 2 Tensile Requirements

	Grade 315 and 315T
Tensile Strength, ksi [MPa]	105 to 135 [725 to 930]
Yield Strength, Min ksi [MPa]	85 [585]
Elongation in 2 in. [50 mm], %, Min	16

3Cr-1.5W-.75Mo V Ta

SUPPLEMENTARY REQUIREMENTS

Supplementary requirements shall not apply unless specified in the order. A list of standardized supplementary requirements for use at the option of the purchaser is included in Specification A 20/A 20M. Several of those considered suitable for use with this specification are listed below by title. Other tests may be performed by agreement between the supplier and the purchaser.

S1 Vacuum Treatment

S2 Product Analysis

S3 Simulated Post-Weld Heat Treatment of Mechanical Test Coupons

S4 Additional Tension Test

S5 Charpy V-Notch Impact Test

S6 Drop-Weight Test (for Plates 0.625 in. [16 mm] Over in Thickness]

S7 High-Temperature Tension Tests

S8 Ultrasonic Examination in Accordance with Specification A 435/A 435M

S9 Magnetic Particle Examination

S11Ultrasonic Examination in Accordance with Specification A 577/A 577M

S12Ultrasonic Examination in Accordance with Specification A 578/A 578M

3Cr-1.5W-.75Mo V Ta

SO, WHERE DO WE GO FROM HERE ?

APPENDIX D

CREEP DATA ON GRADE A, ALLOY 315

CREEP DATA UPDATE FOR Fe-3Cr-W(V) ALLOY 315 (GRADE A)
DECEMBER 3, 2004

Creep tests were conducted on three commercial heats of Fe-3Cr-W(V) Alloy 315 (Grade A). The product forms tested are forging and plate. All products are tested after a tempering treatment of 1346ºF. One heat (79743) was also tested after 1292ºF temper.

All of the creep data are updated in the following five tables. Creep tests have ranged from 900 to 1200ºF. As shown in the tables, many tests have ruptured. However, there are still 19 creep tests in progress to get the long-term data. The longest term test time as of December 3, 2004 is 6306 h. This test is at 1150ºF/12 ksi. Some of the creep tests in progress are expected to exceed 10,000 h.

Heat No.	79743 (Commercial Heat No. 3) 1292°F Temper
Heat Treatment	N/T 2012°F / 1292°F -1 Hr
Product form	***Forging***- Base metal
Specimen orientation	Longitudinal

Test No.	Specimen No.	Temp° F	Stress (ksi)	Rupture time (hr)	Minimum creep rate (%/h)	Rupture elongation (%)	Reduction of area (%)
C78960	79743-C2-12	1100	32.0	616.7	0.00206	23.0	78.1
C78957	79743-C2-15	1100	22.0	1715.8	0.001	20.2	80.8
C78962	79743-C2-10	1150	30.0	143.5	0.012	16.9	79.0
C78959	79743-C2-13	1150	20.0	613.4	0.00295	25.7	82.5
C78955	79743-C2-16	1150	12.0	5606.8		25.7	50.7
C78961	79743-C2-11	1200	20.0	135.8	0.022	28.3	87.9
C78958	79743-C2-14	1200	12.3	1128.0	0.0056	30.6	88.3
C78956	79743-C2-17	1200	9.5	3098.3	0.0026	25.8	80.2

* Test in progress

All tests have failed. The longest term rupture time is 5606.8 h at 1150ºF/12 ksi.

Heat No. 79743 (Commercial Heat No.3)-1346°F Temper
Heat Treatment N/T 2012°F / 1346°F -1 Hr
Product form ***Forging-*** Base metal
Specimen orientation Longitudinal

Test No.	Specimen No.	Temp° F	Stress (ksi)	Rupture time (hr)	Minimum creep rate (%/h)	Rupture elongation (%)	Reduction of area (%)
C79458	79743-C3-2	900	72.0	251.7	0.0053	14.3	72.3
C79459	79743-C3-3	900	65.0	1610.0		16.3	64.3
C79460	79743-C3-4	1000	62.0	40.6	0.0514	17.8	74.8
C79461	79743-C3-5	1000	55.0	311.9	0.0076	17.4	72.2
C79465	79743-C3-6	1000	49.0	1854.4		17.1	62.5
C79466	79743-C3-7	1000	47.0	2585.6		15.5	59.1
C79533*	79743-C3-8	1000	40.0	3546.0			
C79176	79743-C2-12	1100	32.0	1225.0	0.0013	6.1	15.9
C79183	79743-C2-15	1100	22.0	4425.1		7.1	19.5
C79182	79743-C2-13	1150	20.0	1414.9	0.002	14.7	44.5
C79184*	79743-C2-16	1150	12.0	6306.7			
C79175	79743-C2-11	1200	20.0	325.3	0.0117	24.7	73.1
C79162	79743-C2-14	1200	12.3	1771.7	0.004	28.8	73.6
C79185	79743-C2-17	1200	9.5	4456.6		41.2	76.5

***** Test in progress

Six creep tests are still continuing. The longest term creep test in progress has a test time of 6306.7 h at 1150ºF/12 ksi.

Heat No. 79742 (Commercial Heat No.2)-1346°F Temper
Heat Treatment N/T 2012°F / 1346°F -1 Hr
Product form ***Forging-*** Base metal
Specimen orientation Longitudinal

Test No.	Specimen No.	Temp° F	Stress (ksi)	Rupture time (hr)	Minimum creep rate (%/h)	Rupture elongation (%)	Reduction of area (%)
C79316	79742-C2-13	1100	32.0	719.0	0.0027	15.5	53.0
C79315	79742-C2-16	1100	22.0	1693.0	0.0011	14.4	68.7
C79312	79742-C2-11	1150	30.0	213.2	0.0101	11.8	48.9
C79320	79742-C2-14	1150	20.0	715.9	0.0057	30.4	78.7
C79338	79742-C2-17	1150	12.0	4686.8		24	78
C79319	79742-C2-12	1200	20.0	194.8	0.023	29.2	83.4
C79324	79742-C2-15	1200	12.3	917.9	0.0076	48.8	89.5
C79326	79742-C2-18	1200	9.5	2597.3		38.7	73.7

Six creep tests are still continuing. The longest creep test in progress has a test time of 2923.6 h at 1150ºF/8 ksi.

Heat No. 79741 (Commercial Heat No. 1)-1346°F Temper
Heat Treatment N/T 2012°F / 1346°F -1 Hr
Product form ***Forging***- Base metal
Specimen orientation Longitudinal

Test No.	Specimen No.	Temp° F	Stress (ksi)	Rupture time (hr)	Minimum creep rate (%/h)	Rupture elongation (%)	Reduction of area (%)
C79244	79741-C2-12	1100	32.0	493.3	0.0053	19.1	69.9
C79247	79741-C2-15	1100	22.0	1493.1	0.00215	25.3	76.7
C79242	79741-C2-10	1150	30.0	143.8	0.0218	26.1	79.8
C79245	79741-C2-13	1150	20.0	465.0	0.00916	34.6	82.9
C79248	79741-C2-16	1150	12.0	4552.5		27.5	82.7
C79243	79741-C2-11	1200	20.0	142.7	0.0288	26.4	84.9
C79246	79741-C2-14	1200	12.3	725.3	0.01127	33.6	88.6
C79264	79741-C2-17	1200	9.5	2664.2		29.6	81.5

Four creep tests are in progress. The longest creep test in progress has a test time of 3017.5 h at 1150ºF/8 ksi.

Heat No. 79741(Commercial Heat No. 1)- 1346°F Temper
Heat Treatment N/T 2012°F / 1346°F -1 Hr
Product form ***Plate***- Base metal
Specimen orientation Longitudinal

Test No.	Specimen No.	Temp° F	Stress (ksi)	Rupture time (hr)	Minimum creep rate (%/h)	Rupture elongation (%)	Reduction of area (%)
C79452	741-P-1	1000	62.0	0.6	3.5824	18.2	78.5
C79543	79741-1-2-P8	1000	55.0	7.4	0.3948	24.3	78.0
C79548	79741-1-6-P10	1000	45.0	99	0.03511	21.1	79.5
C79453	741-P-2	1100	40.0	100.7	0.02898	19.8	66.8
C79454	741-P-3	1100	26.0	958.5	0.00278	20.3	64.1
C79554	79741-1-3-P11	1100	20.0	2416.1		27.1	61.9
C79455	741-P-4	1150	20.0	515.7	0.0079	26.9	79.7
C79553	79741-1-1-P9	1150	16.0	1342.1		29.3	76.2
C79562*	79741-2-1-P12	1150	12.0	3349			
C79536*	79741-1-4-P6	1200	6.0	3524.8			
C79541*	79741-1-5-P7	1200	3.0	3450.5			

* Test in progress

Three creep tests are still continuing. The longest creep test in progress has a test time of 3524.8 h at 1200ºF/6 ksi.

APPENDIX E

WELDING REPORT

WELDING AND WELDMENT PROPERTIES OF GTA, SA, AND SMA WELDS

V. K. Sikka, Y. Bhambri, S. Indrakanti, M. L. Santella
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Stoody Company
P.O. Box 90032
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Welding effort was extended from experimental heats to commercial heats. The most significant of this work was carried out on 1-in.-thick plate of heat 79741. The welding methods chosen were: submerged arc (SA), SMA, GTA, and GMA. Filler wire for most of the work was prepared at Stoody Company by a method known as powder core. This method allowed a rapid production of various filler wire compositions because alloying elements were added through powder of pure metals. Flux for all of the SA welds was Lincoln 880. This flux was found to yield the welding characteristics and least O content in the weld deposit.

Weld and Weldment Characterization

SA Welds

A total of five SA welds were made during this project to date. Details of the welds are given in Table 1. Each of the welds was characterized for its chemical analysis, metallography, Charpy, tensile, and creep properties of weldments.

Table 1. Details of submerged arc welds on 1-in.-thick plate of commercial heat 79741 of Grade A (315)

Weld ID	Joint Angle (º)	Preheat Temp. (ºF)	Interpass Temp. (ºF)	Travel Speed (ipm)	Wire Diameter (in.)	Filler Wire
HZ	35	250	<500	19	1/8	25A67-5-1
IA	35	250	<500	19	1/8	25A67-6
IB	14	250	<500	19	1/8	25A67-6
12WG1	55	250	<500	19	1/8	25A67-12
12WG2	55	250	<500	19	1/8	25A67-12

•Base metal of Grade 315.
•All welds used Lincoln 880 flux.
•All welds were given Hydrogen Bake at 600ºF for 2 h.
•All welds except 12WG2 were tested after a 1295ºF postweld heat treatment (PWHT) for 1 h.
•12WG2 was tested in as-welded and after PWHT of 1200 and 1250ºF for 1 h.

The chemical analysis of SA welds are summarized in Table 2 and compared with the base metal analysis. This table shows the carbon content of the weld deposits to be lower than the base metal. Furthermore, the weld chemistry is different from base metal in Mn and pick-up of O content of approximately 0.03 wt %. The welds with the latest wire, 25A67-12, did not contain any Ni as opposed to other welds which have approximately 0.5 wt % Ni.

Table 2. Comparison of weld deposit chemistry of submerged arc welds with base metal

Element	Weight Percent				12WG1	
	79741	SA-HZ	SA-IA	SA-IB	Weld Top	Weld Side 0.5-in. Thickness
C	0.099	0.043	0.046	0.064	0.074	0.087
Mn	0.34	0.44	0.97	0.88	1.05	1.02
P	0.009	0.016	0.018	0.16	0.015	0.014
S	0.003	0.011	0.009	0.004	0.006	0.006
Si	0.21	0.07	0.24	0.24	0.27	0.28
Ni	0.15	0.54	0.53	0.49	0.04	0.04
Cr	2.97	2.97	3.06	3.1	3.38	3.26
Mo	0.73	0.82	0.83	0.83	0.88	0.85
V	0.22	0.21	0.23	0.23	0.253	0.257
Cb	0.002	0.003	0.003	0.003	0.004	0.003
Ti	0.003	0.002	0.002	0.002	0.002	0.002
Co	0.014	0.015	0.015	0.015	0.01	0.009
Cu	0.11	0.04	0.04	0.05	0.11	0.11
Al	0.008	0.012	0.017	0.017	0.013	0.015
B	<0.001	<0.001	<0.001	<0.001	0.001	0.001
W	1.68	1.83	1.56	1.56	1.97	1.72
As	0.005	0.002	0.002	0.004	0.025	0.021
Sn	0.008	0.003	0.002	0.004	0.012	0.011
Zr	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
N	0.009	0.004	0.004	0.005	0.005	---
O	0.004	0.044	0.03	0.029	0.029	---
Ta	---	<0.01	<0.01	<0.01	---	---

Macro sections of the SA welds of Series I and II are shown in Figs. 1 and 2. Series I welds are lower in weld C levels of 0.04 to 0.06 wt % and Series II welds are 0.07 to 0.09 wt % C.

Detailed microhardness profiles across the weld sections of 12WG2 weld in the as-welded and after two PWHTs of 1200 and 1250ºF are shown in Fig. 3. This figure shows how the hardness of the weld is reduced after increasing PWHTs.

The Charpy-impact data on specimens taken from the weld sections of SA welds HZ, IA, and IB are shown in Table 3. For SA welds HZ and IA, base metal sections were also tested. This provided the final impact properties of the base metal plate that had undergone a combination of 1346ºF temper and a 1290ºF PWHT. The base metal data are shown in Table 4.

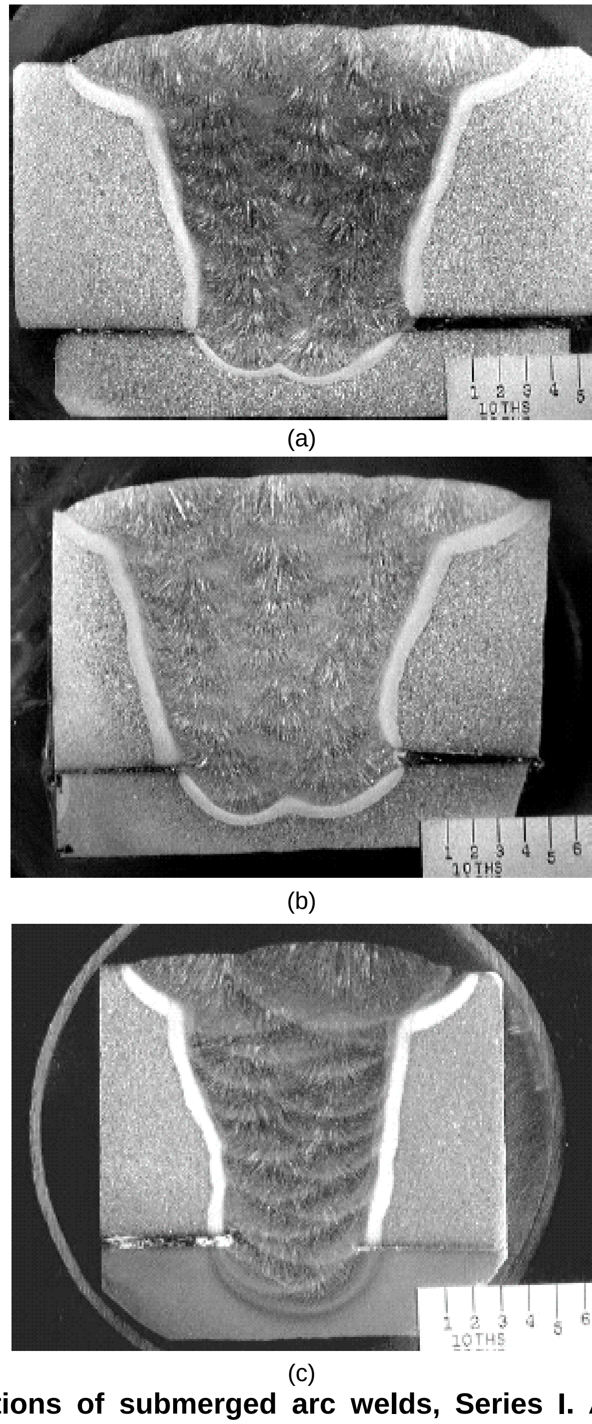
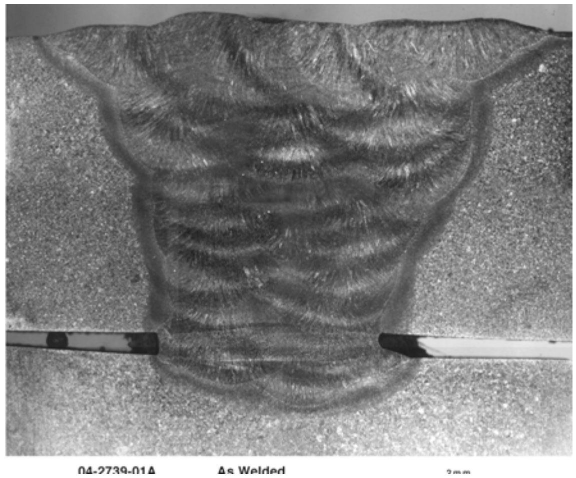
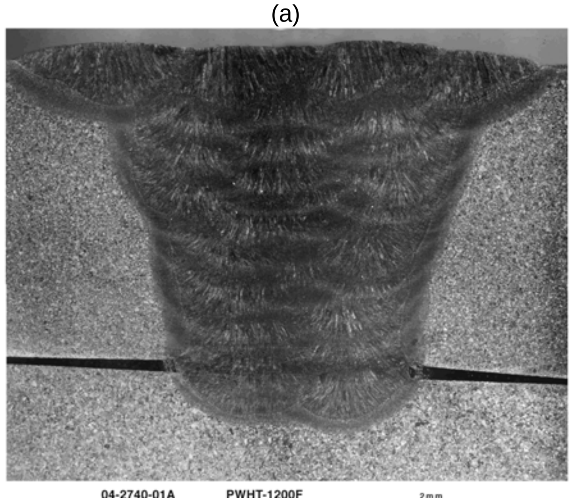


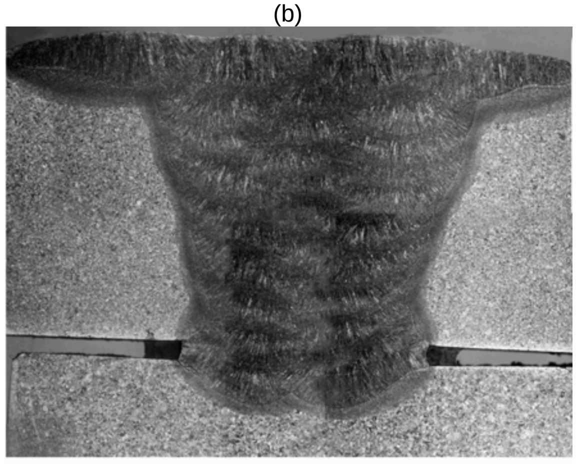
Figure 1. Cross sections of submerged arc welds, Series I. All were postweld heat treated at 1290ºF for 1 h: (a) HZ, (b) IA, and (c) IB.



(a)



(b)



(c)

Figure 2. Cross sections of submerged arc weld, Series II (12WG2). Sections in (a) as welded, (b) postweld heat treatment (PWHT) at 1200ºF, and (c) PWHT at 1250ºF.

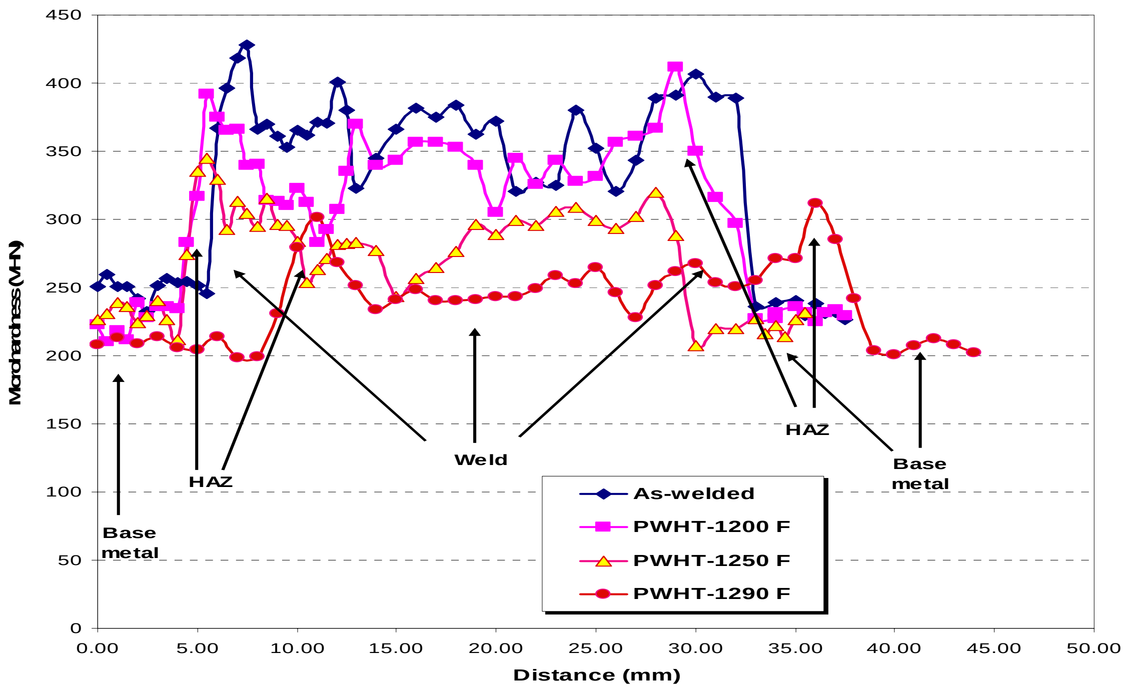


Figure 3. Hardness profile across the submerged arc weld sections of 12WG2 in the as-welded condition and after three postweld heat treatments.

The Charpy-impact data on specimens taken from the weld sections of SA welds 12WG1 and 12WG2 (two plates of identical weld parameters and filler wire) are shown in Table 5.

The Charpy-impact properties of SA welds HZ, IA, and IB (Series I) are plotted as a function of test temperature in Fig. 4, which shows that the IA and IB welds had better impact properties than the HZ weld. The lower properties of the HZ weld are most likely caused by lower Mn of 0.44 wt % and higher O_2 content of 0.044 wt % of this weld. The same data are compared with the base metal section of the plate in Fig. 5. Basically, these data have shown that higher Mn and lower O_2 content of IA and IB welds are more desirable for good impact properties. The impact properties of all SA welds are lower than the base metal sections of the same welds. This is an expected result because weld metal sections different than the base metal in several ways: (1) the weld structure is a cast structure as compared to base metal, which is wrought; (2) the weld chemistries are different and the welds have seen only a PWHT of 1290ºF as opposed to base metal which gets normalized after austenitizing at 2012ºF, tempered at 1346ºF, and PWHT at 1290ºF. Figure 5 also shows that the base metal plate has excellent Charpy-impact properties across the entire test temperature range.

Table 3. Charpy-impact data for submerged arc welds HZ, IA, and IB.
All welds were given a postweld heat treatment of 1290ºF for one hour.

Base Metal	Temperature (ºF)	Foot/Lbs	Lateral Expansion	Percent Shear
HZ – Submerged Arc Weld - Top				
HZ-TW-1	70	13	0.015	20
HZ-TW-2	40	11.5	0.012	20
HZ-TW-3	20	6.5	0.008	20
HZ-TW-4	0	6	0.007	10
HZ-TW-5	-20	7.5	0.006	10
HZ-TW-6	-40	4.5	0.003	0
HZ – Submerged Arc Weld - Bottom				
HZ-BW-1	70	28	0.025	30
HZ-BW-2	40	11	0.013	20
HZ-BW-3	20	9	0.01	20
HZ-BW-4	0	6	0.006	10
HZ-BW-5	-20	7	0.007	20
HZ-BW-6	-40	3.5	0.004	0
IA – Submerged Arc Weld - Top				
IA-TW-1	70	86	0.062	60
IA-TW-2	40	56	0.042	40
IA-TW-3	20	36	0.028	20
IA-TW-4	0	41	0.033	30
IA-TW-5	-20	15	0.014	10
IA-TW-6	-40	10	0.007	0
IA – Submerged Arc Weld - Bottom				
IA-BW-1	70	77	0.056	70
IA-BW-2	40	15	0.015	10
IA-BW-3	20	37	0.029	20
IA-BW-4	0	20	0.02	20
IA-BW-5	-20	11	0.008	10
IA-BW-6	-40	12.5	0.013	0
IB – Submerged Arc Weld - Top				
IB-TW-1	70	70	0.015	20
IB-TW-2	40	89	0.012	20
IB-TW-3	20	55	0.008	20
IB-TW-4	0	38	0.007	10
IB-TW-5	-20	47	0.006	10
IB-TW-6	-40	8	0.003	0
IB - Submerged Arc Weld - Bottom				
IB-BW-1	70	109	0.025	30
IB-BW-2	40	38	0.013	20
IB-BW-3	20	42	0.01	20
IB-BW-4	0	37	0.006	10
IB-BW-5	-20	10	0.007	20
IB-BW-6	-40	15	0.004	0

Table 4. Charpy-impact properties of base metal section of the submerged arc welds HZ and IA

Base Metal	Temperature (ºF)	Foot/Lbs	Lateral Expansion	Percent Shear
Base Metal for HZ Weld - Top				
HZ-TB-1	70	104	0.07	60
HZ-TB-2	40	102	0.072	60
HZ-TB-3	20	100	0.065	60
HZ-TB-4	0	92	0.066	60
HZ-TB-5	-20	92	0.072	50
HZ-TB-6	-40	78	0.058	50
Base Metal for HZ Weld - Bottom				
HZ-BB-1	70	115	0.077	70
HZ-BB-2	40	103	0.07	50
HZ-BB-3	20	96	0.069	50
HZ-BB-4	0	90	0.066	50
HZ-BB-5	-20	87	0.062	50
HZ-BB-6	-40	46	0.032	30
Base Metal for IA Weld - Top				
IA-TB-1	70	154	0.093	100
IA-TB-2	40	108	0.076	60
IA-TB-3	20	104	0.077	70
IA-TB-4	0	95	0.073	60
IA-TB-5	-20	96	0.065	50
IA-TB-6	-40	89	0.067	50
Base Metal for IA Weld - Bottom				
IA-BB-1	70	144	0.092	100
IA-BB-2	40	109	0.078	70
IA-BB-3	20	94	0.066	50
IA-BB-4	0	68	0.051	40
IA-BB-5	-20	89	0.072	50
IA-BB-6	-40	88	0.066	50

Table 5. Impact properties of submerged arc welds (12WG1 and 12WG2) in as-welded condition and after various postweld heat treatments of 1200, 1250, and 1290ºF

Base Metal	Temp. (º)	Foot/Lbs	Lateral Expansion	Percent Shear
As Welded – Top [12WG2]				
T-1	70	6	0.005	10
T-2	0	4	0.008	10
T-3	-20	3	0.005	10
T-4	-40	3	0.006	10
As Welded – Bottom [12WG2]				
B-1	70	4	0.003	10
B-2	0	4	0.003	10
B-3	-20	3	0.003	0
B-4	-40	3	0.002	0
Postweld Heat Treatment – 1200ºF – Top [12WG2]				
T-1	70	5	0.006	10
T-2	0	2	0.003	0
T-3	-20	2	0.003	0
T-4	-40	2	0.003	0
Postweld Heat Treatment - 1200ºF – Bottom [12WG2]				
B-1	70	8	0.006	20
B-2	0	4	0.004	10
B-3	-20	3	0.003	0
B-4	-40	4	0.006	0
Postweld Heat Treatment - 1250ºF – Top [12WG2]				
T-1	70	23	0.018	20
T-2	0	5	0.004	10
T-3	-20	4	0.004	0
T-4	-40	6	0.007	0
Postweld Heat Treatment - 1250ºF – Bottom [12WG2]				
B-1	70	15	0.014	20
B-2	0	5	0.004	10
B-3	-20	4	0.007	10
B-4	-40	5	0.006	10
Postweld Heat Treatment -1290ºF – Top [12WG1]				
12T-1	70	80	0.062	80
12T-2	0	24	0.022	10
12T-3	-20	8	0.006	0
12T-4	-40	4	0.006	0
Postweld Heat Treatment - 1290ºF – Bottom [12WG1]				
12B-1	70	79	0.058	70
12B-2	0	15	0.016	10
12B-3	-20	12	0.011	10
12B-4	-40	15	0.012	10

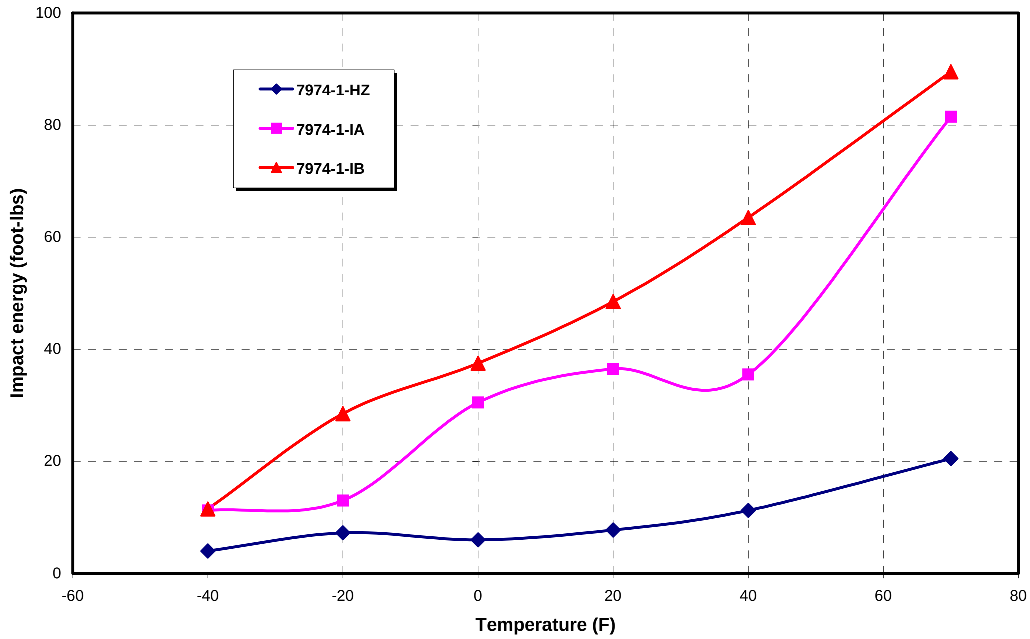


Figure 4. Charpy-impact properties of submerged arc welds HZ, IA, and IB. All welds were given a postweld heat treatment at 1290ºF.

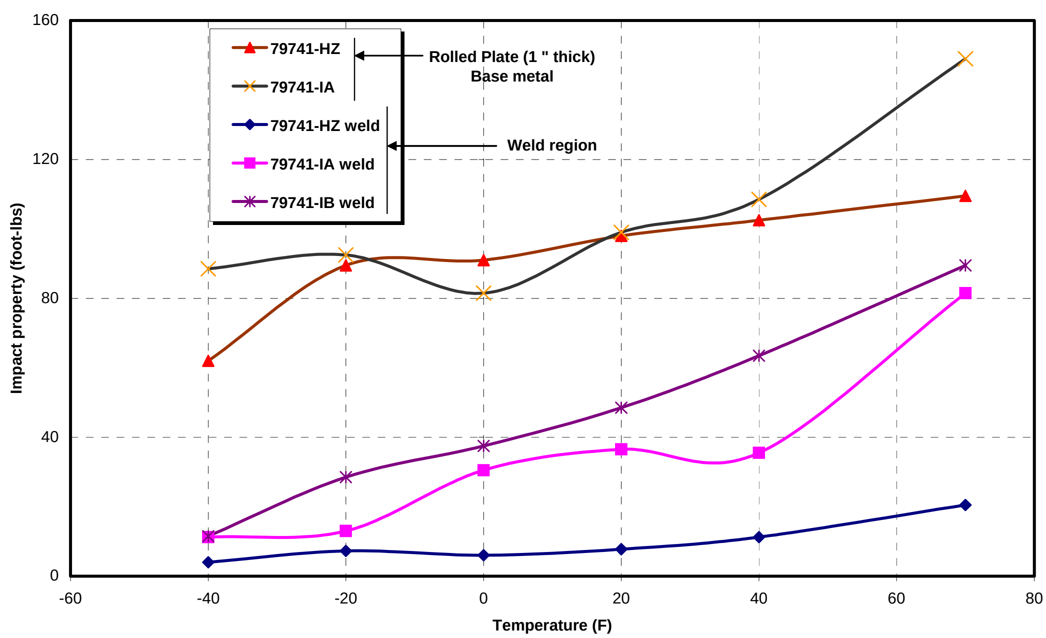


Figure 5. Comparison of Charpy-impact properties of submerged arc welds HZ, IA, and IB with base metal.

The Charpy-impact data for SA welds 12WG1 and 12WG2 are plotted in Figs. 6 and 7. Data for the top and bottom sections of the weld are shown separately in these figures. Data in Figs. 6 and 7 show that impact properties of the weld improve with the PWHT. It also shows that the weld metal properties improve significantly only with a PWHT of 1290ºF which starts to improve the properties but significantly larger improvement only occurs at 1290ºF. Slightly lower properties of SA welds 12WG1 and 12WG2 in Figs. 6 and 7, as compared to SA welds IA and IB (Fig. 4) are most likely caused by its different weld chemistry. The 12WG1 and 12WG2 have higher C and no Ni as opposed to the IA and IB welds.

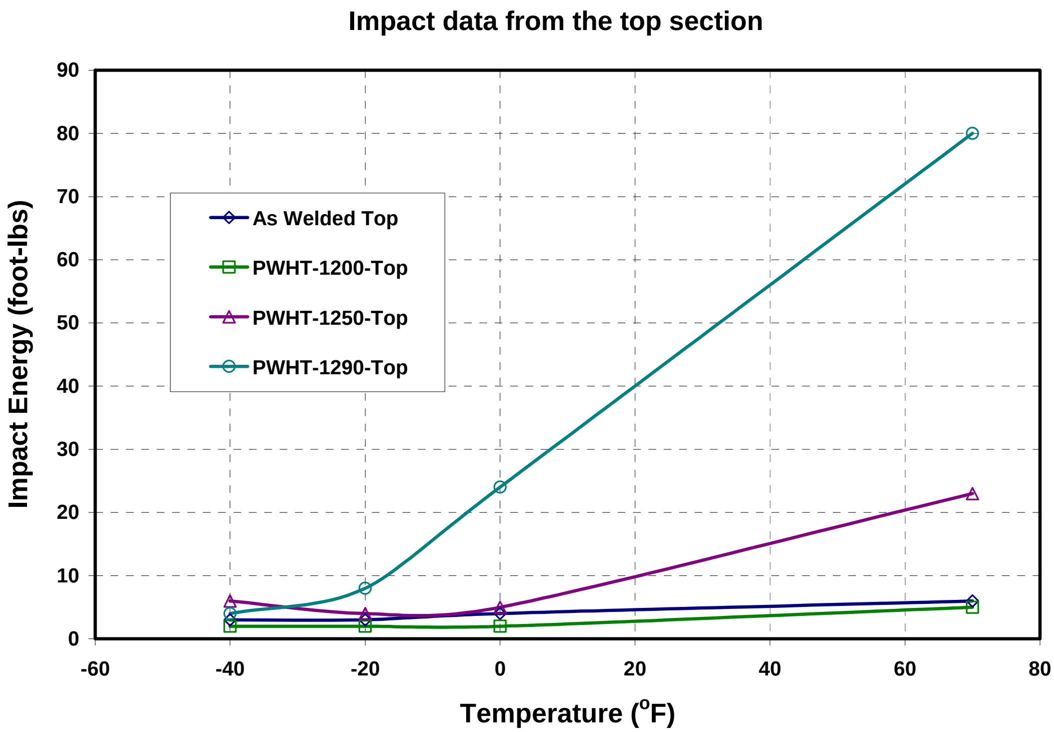


Figure 6. Charpy-impact plots for specimens taken from the top section of the submerged arc welds 12WG1 and 12WG2.

Tensile tests were conducted on 0.505-in. specimens taken transverse to the weld and they represent weldments. Tensile data on Series I SA welds HZ, IA, and IB are summarized in Table 6. For 12WG1 and 12WG2 welds, tensile tests were conducted on the weldment sections and some on the base metal section of the welds (Table 7). Weldment tensile data on SA welds HZ, IA, and IB are plotted in Figs. 8, 9, and 10. Similar plots of weldment data for SA welds 12wG1 and 12WG2 are plotted in Figs. 11, 12, and 13. These figures also include the limited tests run on the base metal sections of the same welds.

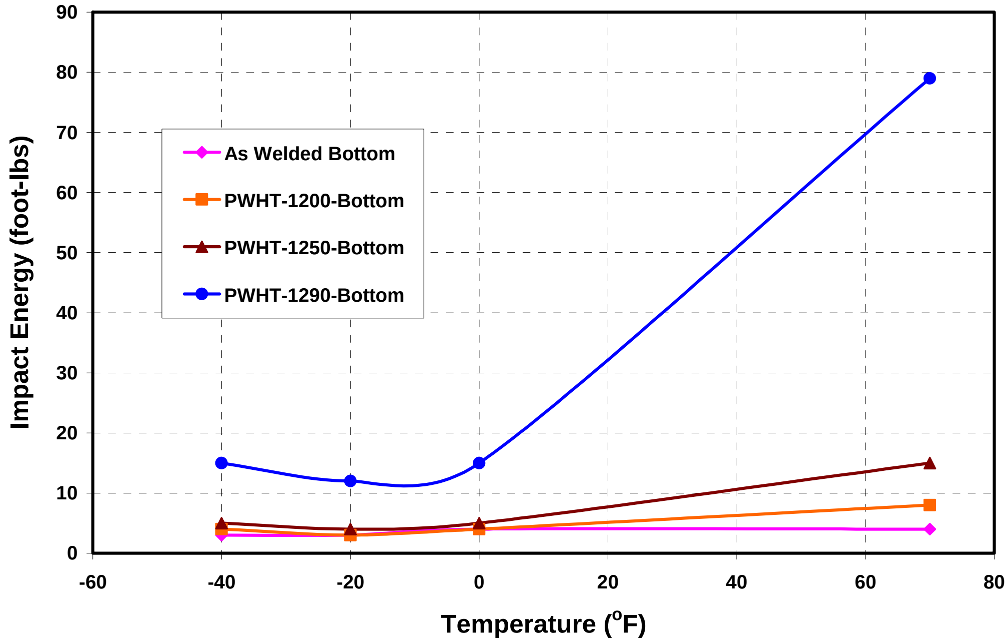


Figure 7. Charpy-impact plots for specimens taken from the bottom section of the submerged arc welds 12WG1 and 12WG2.

Table 6. Tensile properties of the weldment specimens taken from submerged arc welds HZ, IA, and IB. All welds were postweld heat treated at 1290ºF for 1 h.

Test Temperature (ºF)	Yield Strength (ksi)	UTS (ksi)	Total Elongation (%)	Reduction of Area (%)
		HZ Weld		
70	87.8	103.1	19.5	68
800	76.7	84.8	18.5	67.7
1000	77	81.3	18.5	66.8
1100	67.4	73.5	18.5	67.4
1200	66.2	68.2	18.5	68.6
1300	52.5	55.1	22.5	77
		IA Weld		
70	89.8	102.1	20.5	64
800	79.2	88.8	17.5	65.2
1000	72.2	75.9	18	69.7
1100	66.5	71.8	16	68.6
1200	60.9	64.2	20.5	77
1300	49.1	50.9	16.5	83.2
		IB Weld		
70	84.7	100.4	20	69.1
800	84.4	87.9	18.5	70.8
1000	73.4	74.6	18.5	58.6
1100	69.3	70.5	18.5	72.4
1200	67.4	68.1	17.5	74
1300	44.1	44.4	21.5	81.7

Table 7. Tensile data for submerged arc welds 12WG1 and 12WG2 after postweld heat treatments of 1200, 1250, and 1290ºF. Data on base metal section of the welds PWHT at 1200 and 1250ºF are also included.

Temp. (º)	Yield Strength (ksi)	UTS (ksi)	Total Elongation	Reduction In Area (%)	Fracture Location
Postweld Heat Treatment - 1200ºF – Base Metal [12WG2]					
70	90.6	104.7	21.5	72.9	---
1200	72.9	77.7	23.5	72.9	---
Postweld Heat Treatment - 1200ºF – Weldment [12WG2]					
70	88.7	102.6	19	66.6	Base
1000	77.3	82.8	16	60.6	Base
1100	71.8	74.6	15.5	67.6	Base
1200	61.8	61.8	17	70.8	Base
Postweld Heat Treatment - 1250ºF – Base Metal [12WG2]					
70	92.3	106.3	21	72.7	---
1100	71.1	79.6	21	70.2	---
Postweld Heat Treatment - 1250ºF – Weldment [12WG2]					
70	88.3	103	19	65.6	Base
1000	78.7	84.2	16.5	57.7	Base
1100	72.8	75.2	19	65.2	Base
1200	65	65.2	19.5	72.8	Base
Postweld Heat Treatment - 1290ºF – Weldment [12WG1]					
70	82	100.2	19.5	70.2	Base
1000	73.7	81.6	19.5	68.5	Base
1100	71.3	74	17	69.1	Base
1200	59.5	61.3	19.5	73.6	Base

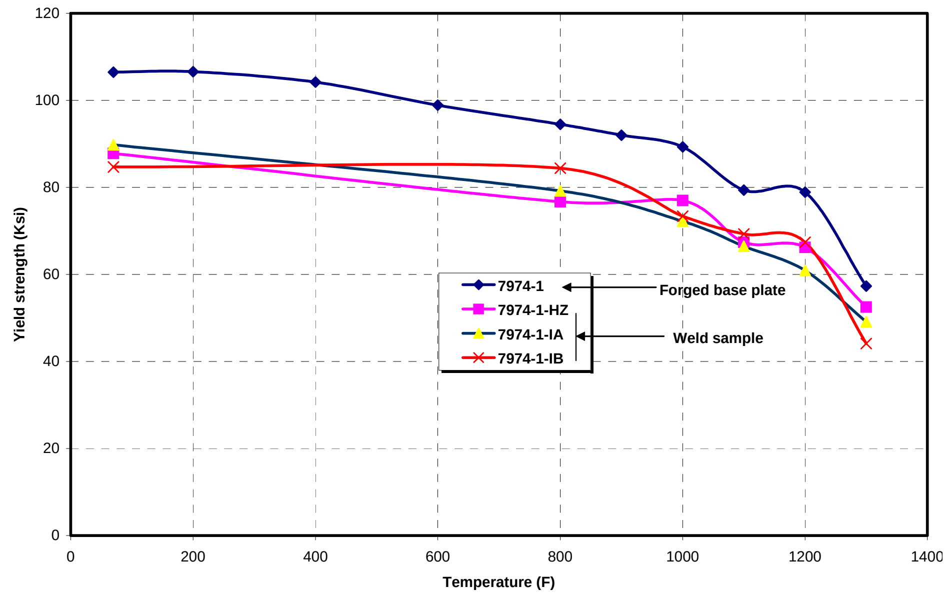


Figure 8. Comparison of yield strength of weldment specimens of submerged arc welds HZ, IA and IB with base metal. All welds were given a postweld heat treatment of 1290ºF for one hour.

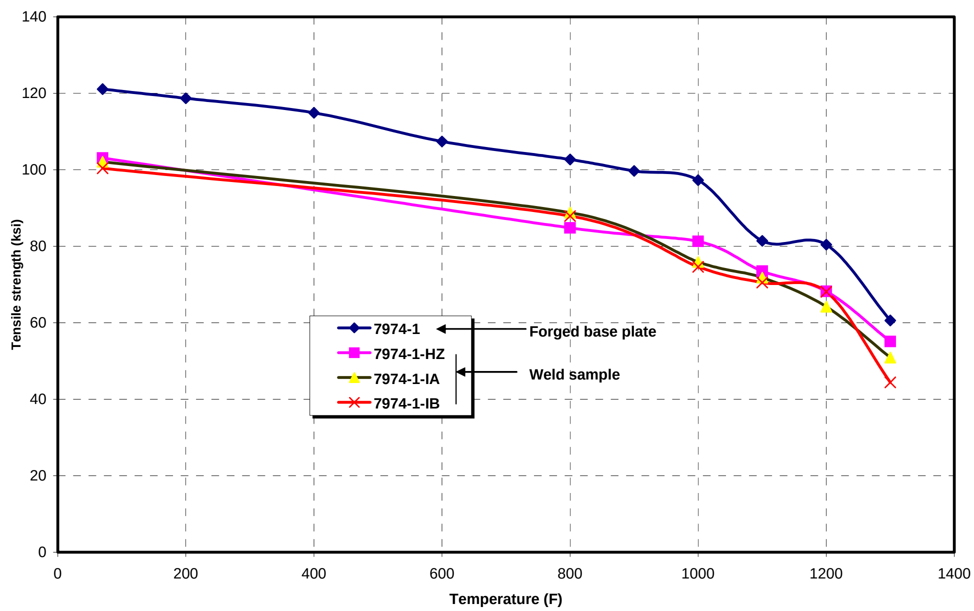


Figure 9. Comparison of ultimate tensile strength of weldment specimens of submerged arc welds HZ, IA, and IB with base metal. All welds were given a postweld heat treatment of 1290ºF for one hour.

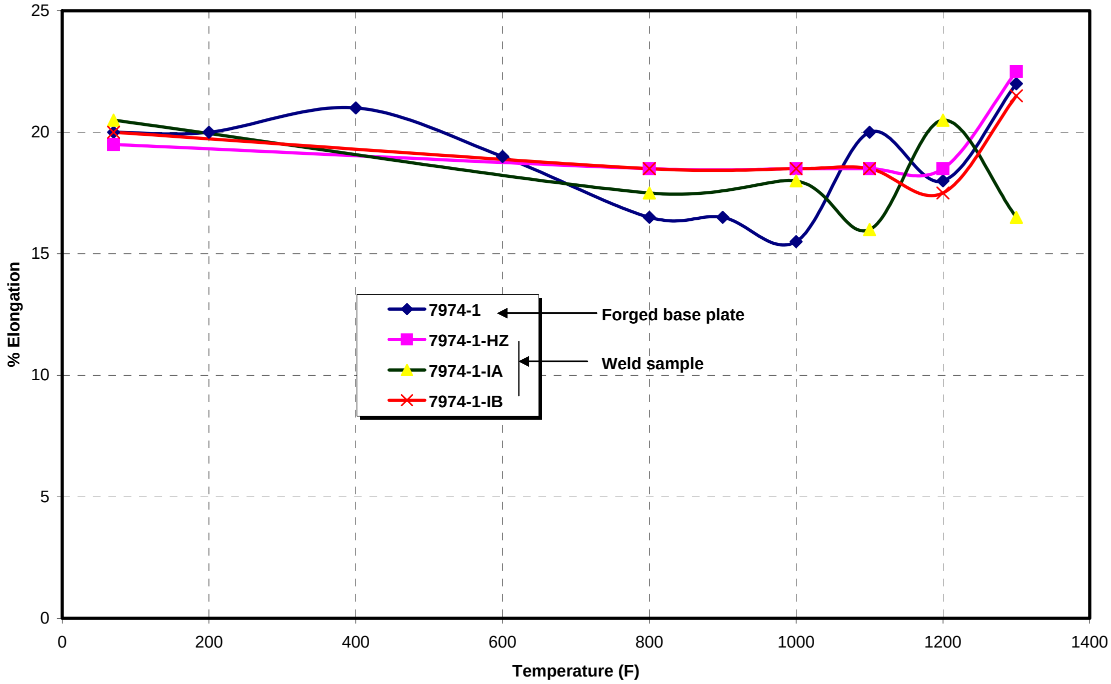


Figure 10. Comparison of total elongation of weldment specimens of submerged arc welds HZ, IA, and IB with base metal. All welds were given a postweld heat treatment of 1290ºF for one hour.

Plots in Figs. 8 and 9 showed that the weldment strengths of SA welds HZ, IA, and IB were lower than the base metal data, which was developed for plate cut from a 6-by 6-in. cross-section forged bar. However, the weldment data for welds 12WG1 and 12WG2 in Figs. 11 and 12 showed that if compared with the base metal sections of the same weld, the difference in the weldment properties were insignificant. This suggests that there is some difference in the base metal data for plate taken from the forged bar versus the rolled plate. Since all failure locations were in the base metal, it is concluded that the weldment tensile properties are controlled by the base metal properties and a small reduction in strength values of weldments compared to its base metal, where some base metal was tested, is probably due to a slightly lower hardness region in the base metal as seen in Fig. 3.

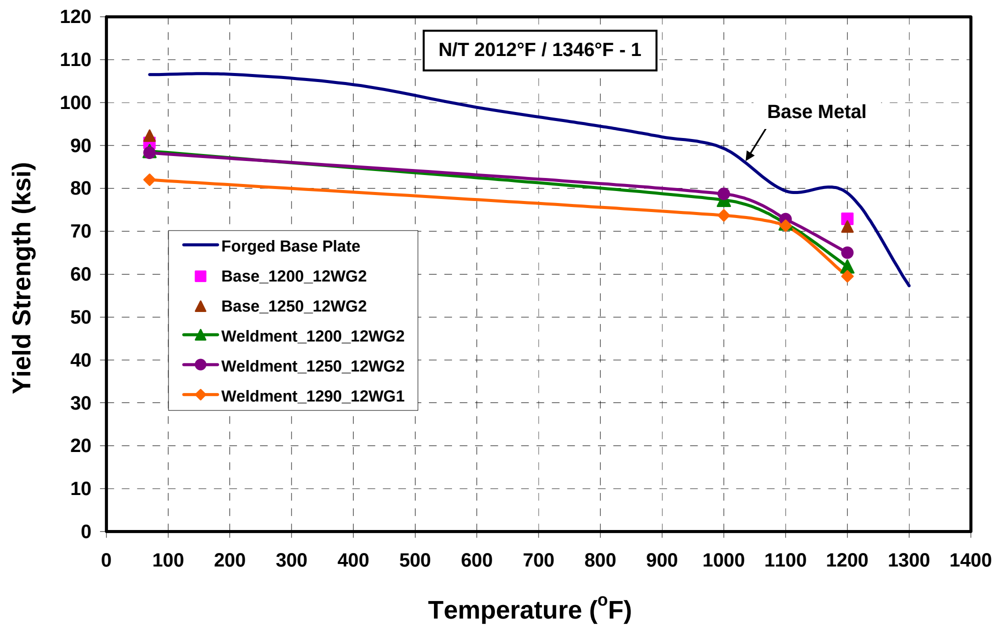


Figure 11. Comparison of yield strength of weldment specimens of submerged arc welds 12WG1 and 12WG2. Data for base metal sections of the same weld are also included.

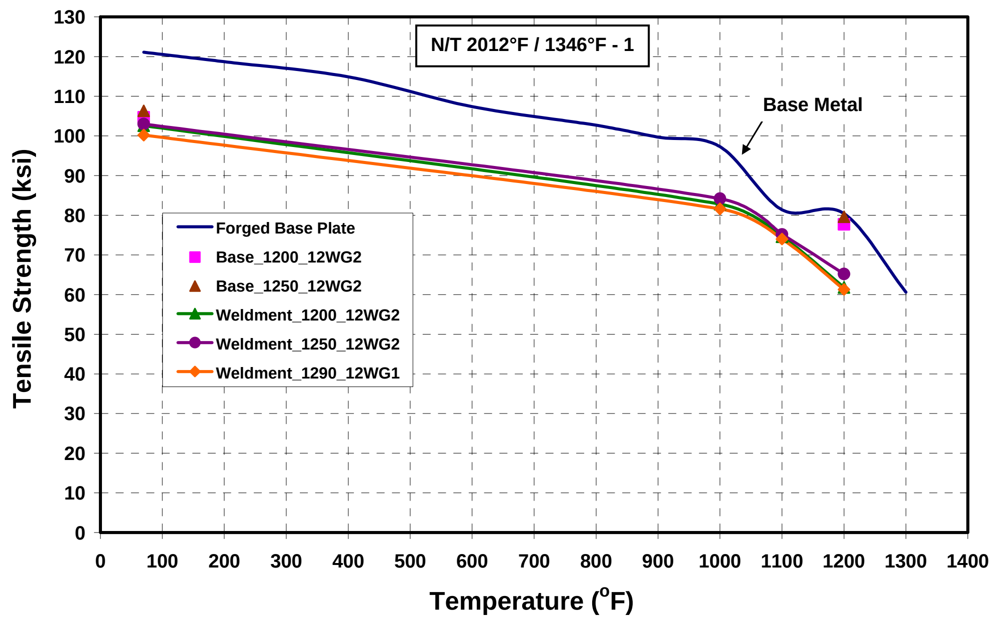


Figure 12. Comparison of tensile strength of weldment specimens of submerged arc welds 12WG1 and 12WG2. Data for base metal sections of the same weld are also included.

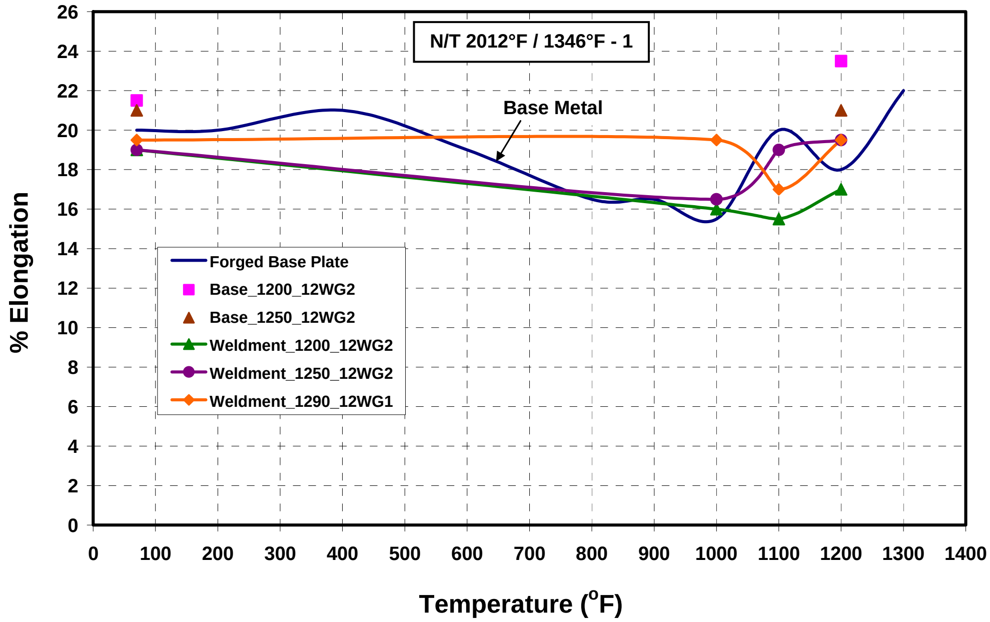


Figure 13. Comparison of total elongation of weldment specimens of submerged arc welds 12WG1 and 12WG2. Data for base metal sections of the same weld are also included.

Creep data on weldment specimens for three SA welds are summarized in Table 8. These data were produced in the temperature range of 900 to 1200ºF. Creep-tested specimens after rupture were photographed to show the rupture locations. These photographs for the weld are shown in Fig. 14; for IB weld, Fig. 15; and for 12WG weld, Fig. 16. Based on the usual examination of each specimen and photographs in Figs. 14, 15, and 16, the failure location was identified and listed in Table 8. It is noted that the rupture location for tests at 800 and 1000ºF were base metal for all welds. The failure location for tests conducted at 1100, 1200, and 1300ºF was in the weld metal.

Table 8. Creep properties on weldment specimens of submerged arc welds HZ, IB, and 12WG1. All welds were postweld heat treated at 1290ºF for 1 h. Creep specimens were 0.25-in. diam by 2-in. gage length and were taken from the center of the weld.

Submerged Arc Welds				
Sample ID	**Temperature (°F)**	**Stress (ksi)**	**Rupture Time (t_r)**	**Fracture Location**
HZ-1	1000	55.0	4.4	Base
HZ-2	1100	26.0	180.4	Weld
HZ-3	1200	16.0	63.1	Weld
HZ-4	1300	6.0	137.8	Weld
IB-1	900	72.0	0.2	Base
IB-2	1000	55.0	2.0	Base
IB-3	1100	26.0	153.5	Weld
IB-4	1200	16.0	44.6	Weld
IB-5	1300	6.0	140.8	Weld
IB-6	1200	10.0	318.7	Weld
12WG1	900	65.0	4.2	Base
12WG2	1000	45.0	22.8	Base
12WG3	1100	26.0	100.2	Weld
12WG4	1200	16.0	33.0	Weld
12WG5	1200	10.0	317.5	Weld

The creep rupture data on weldment specimens from the SA welds HZ, IB, and 12WG1 are plotted as a function of Larsen-Miller parameter in Fig. 17. Data for the base metal plate of the same alloy (shown in Table 9) is also included in this figure for comparison. This figure shows that the weldment data are close to base metal data for test conditions, where failure was located in the base metal. Under such test conditions, the weld filler chemistry does not affect the weldment properties. Figure 17 also shows that the weldment properties are lower than the base metal data, where the failure is located in the welds. In these cases, the filler wire composition can be modified to increase the weldment strength to match more closely to the base metal. A limited number of creep tests were also conducted on the all weld metal specimens from the 12WG1 weld. One of the two ruptured specimens of all the weld metal samples matches the data for weldment of the same weld (see Fig. 17). This confirms that for high temperature, low stresses increase in filler metal strength will provide weldment properties that will be close to base metal properties.

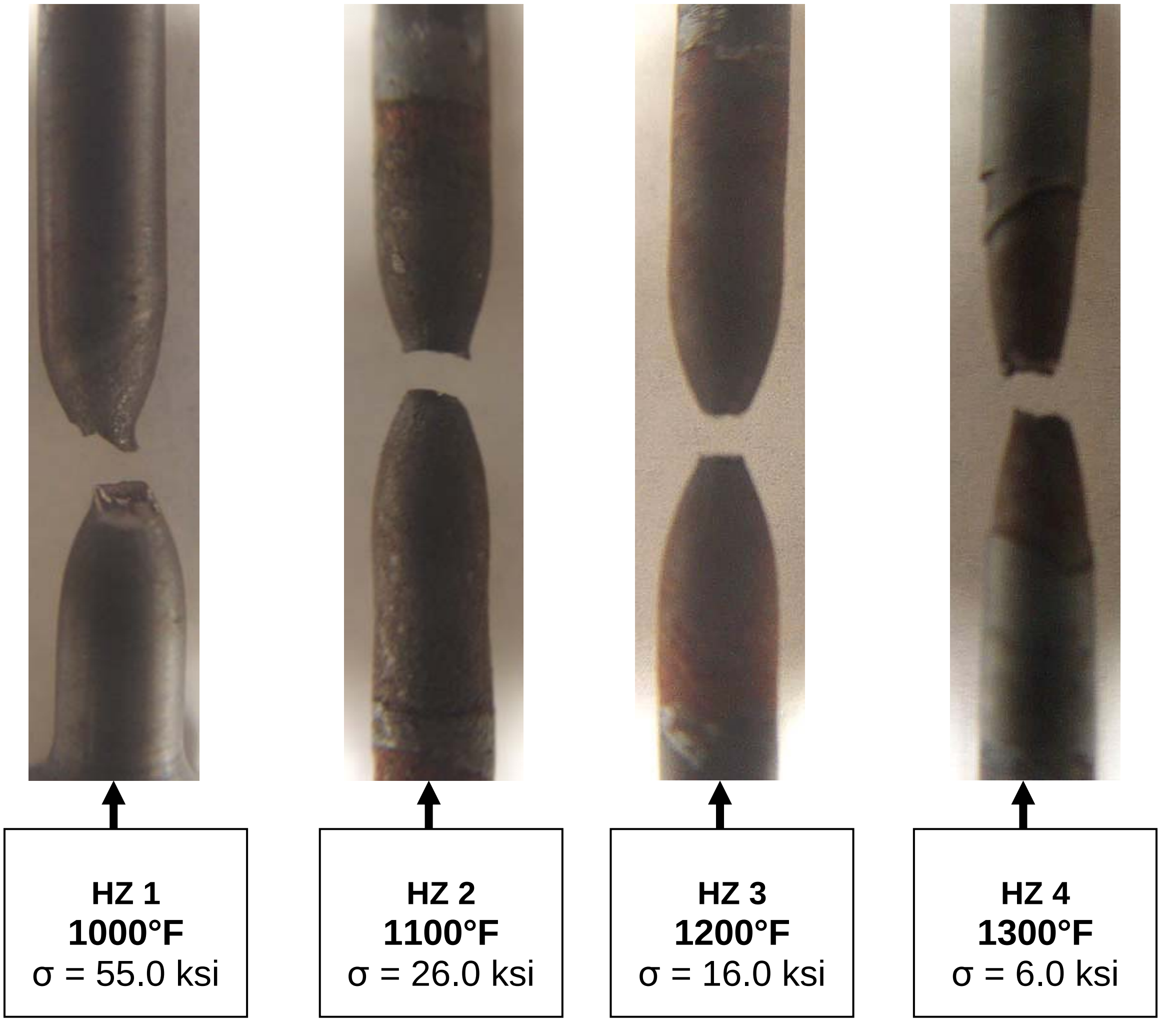


Figure 14. Creep-tested weldment specimens from submerged arc weld HZ.

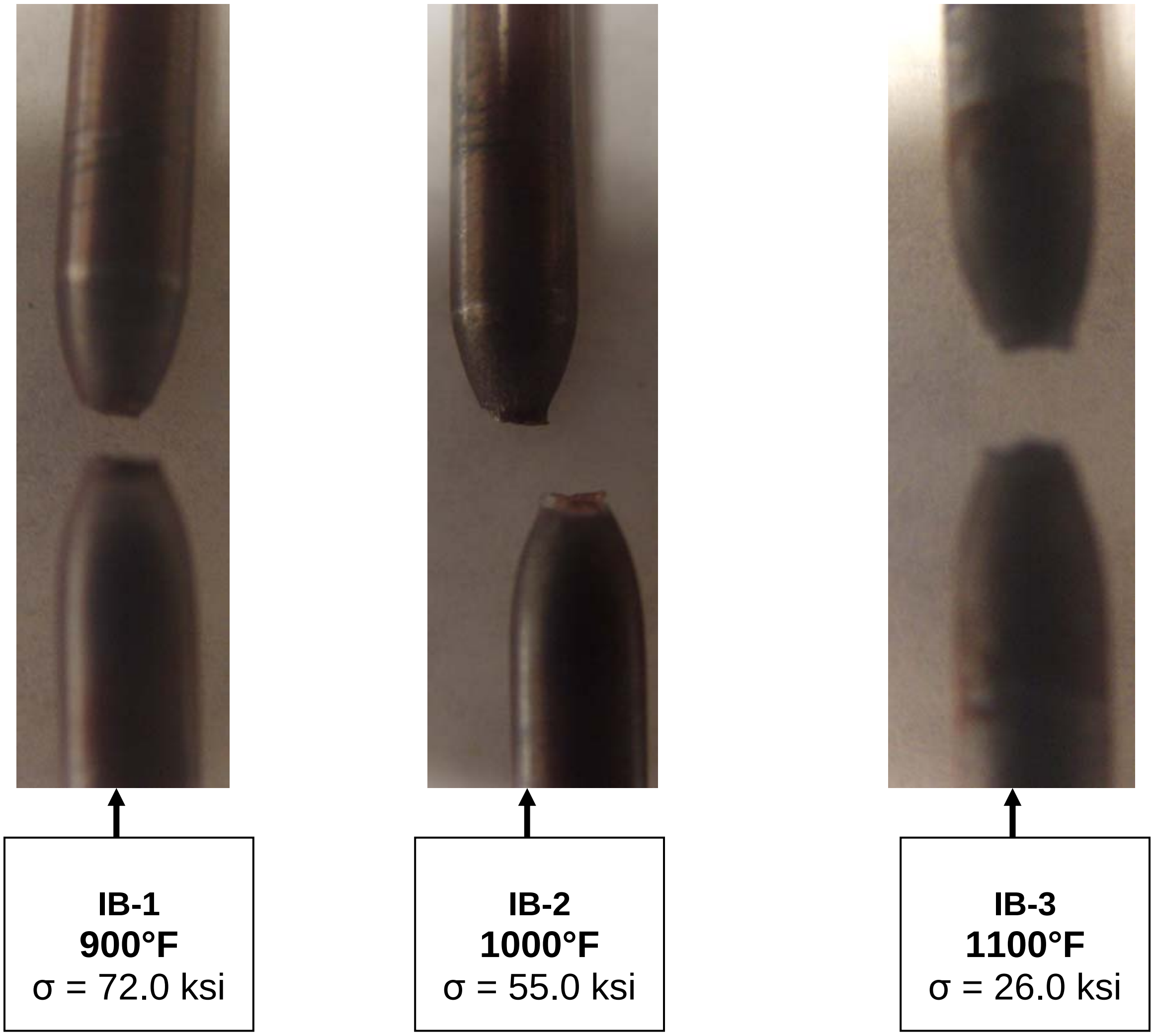


Figure 15. Creep-tested weldment specimens from submerged arc weld IB.

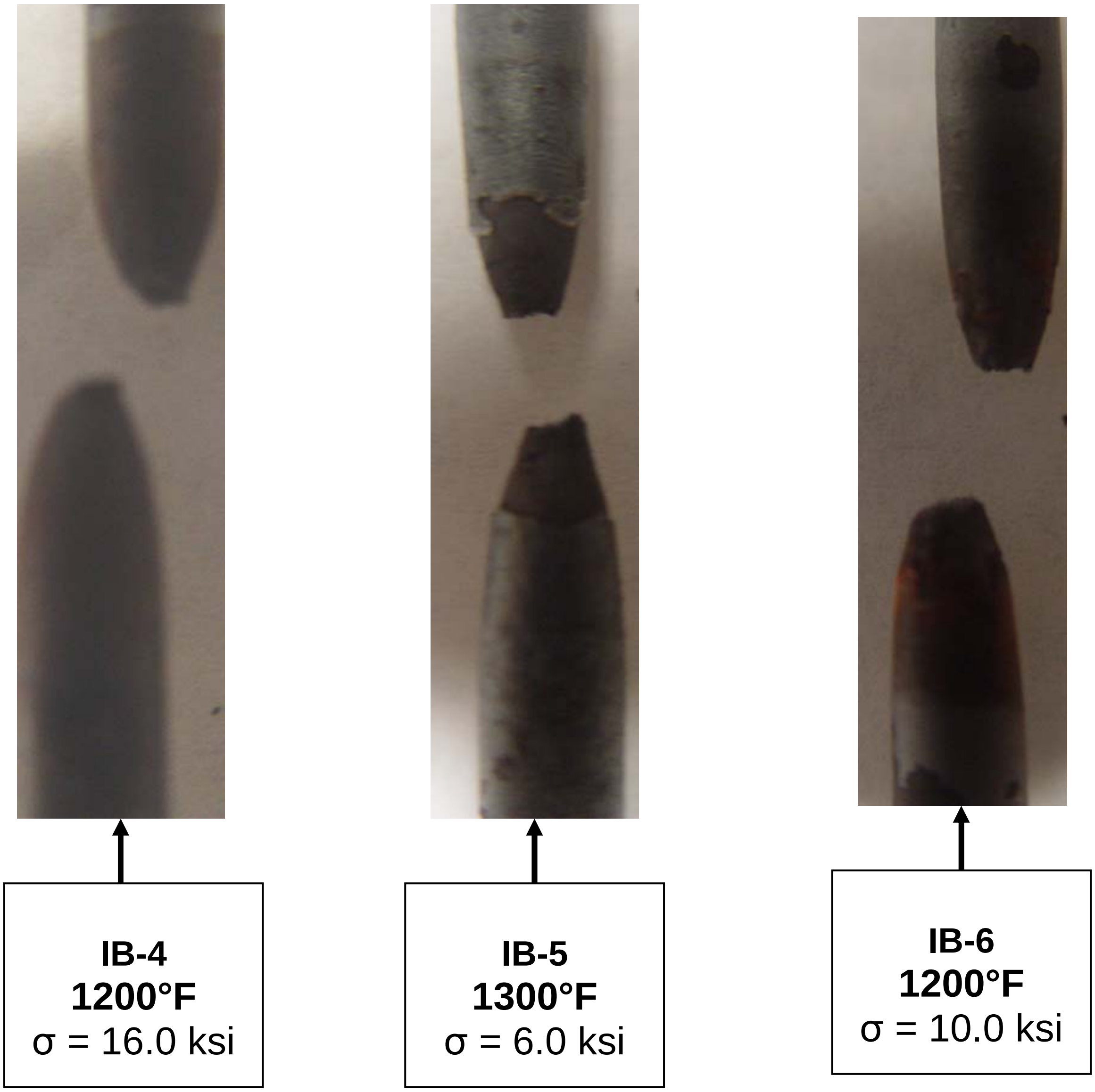


Figure 15. (continued)

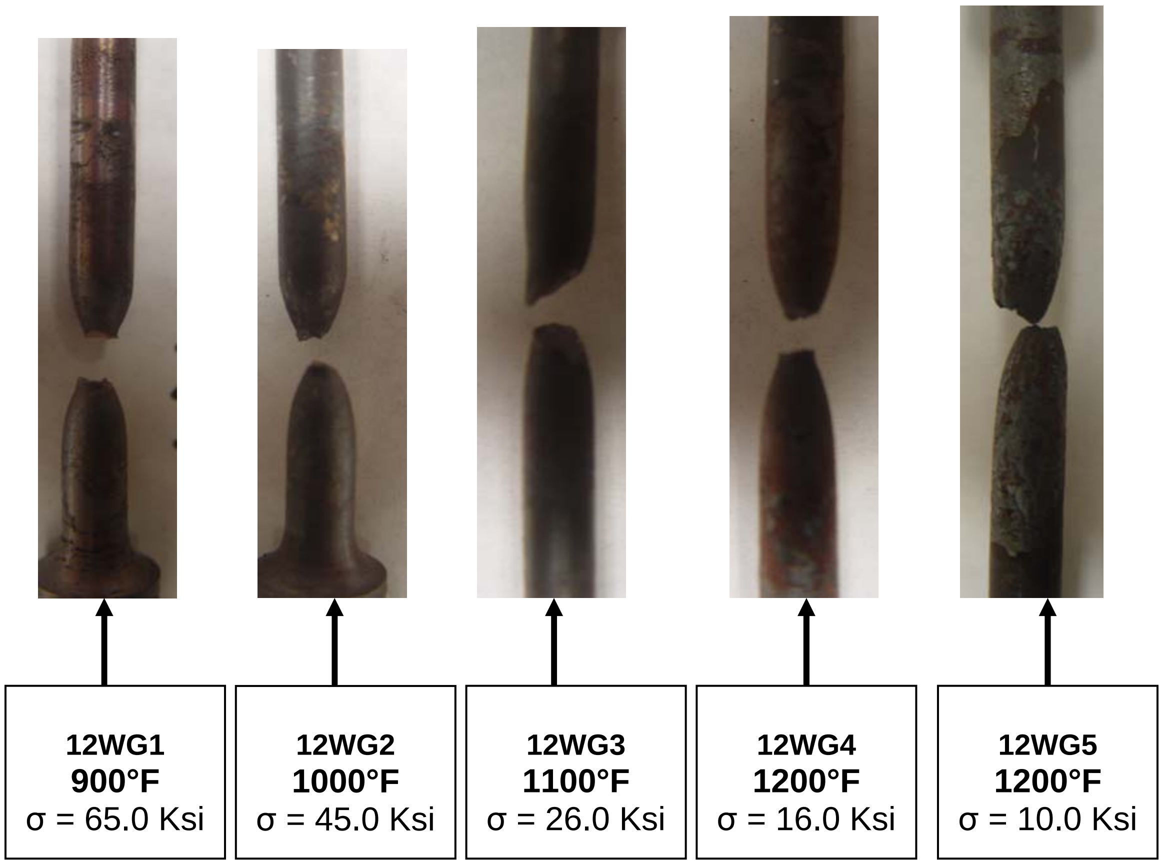


Figure16. Creep-tested weldment specimens from submerged arc weld 12WG1.

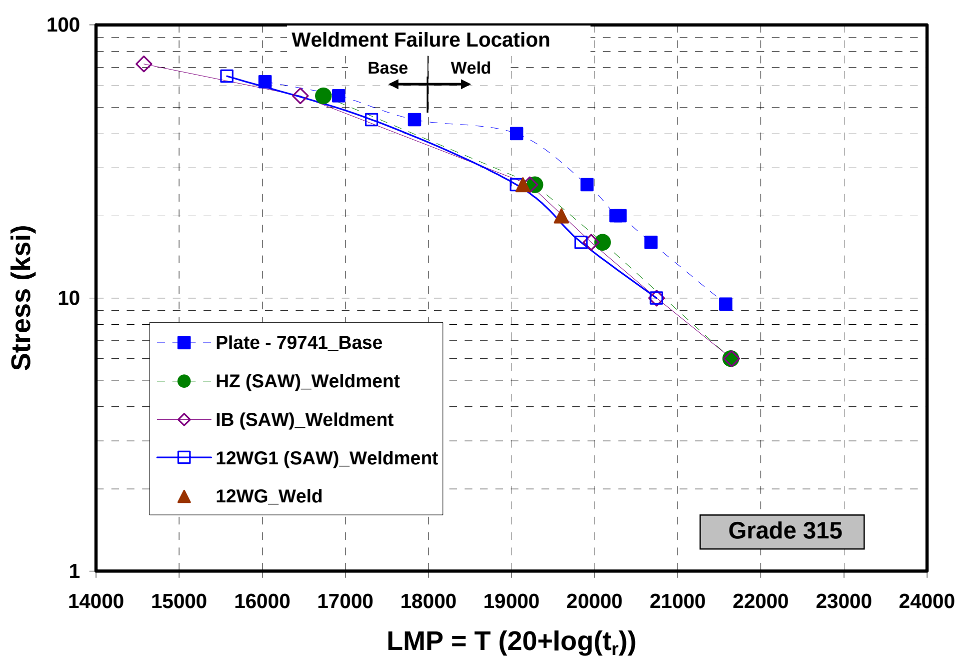


Figure 17. Comparison of creep rupture properties of the weldments of submerged arc welds with the properties of the base plate. Data for two all-weld-metal specimens are also included.

Gas Tungsten Arc Welds

Two gas tungsten arc (GTA) welds were made in the 1-in.-thick plate of the commercial heat. Details of the welding procedure are given in Table 10. The first GTA weld, JA, was made using the powder core wire, which is similar to that used for SA welds. In the second weld, a matching filler wire produced as ~ 1/8-in. strips by shearing the rolled plate was used. Use of strip as filler wire only permitted a slow wire feed rate of 4 ipm. The chemical analysis of the two GTA welds is compared with the base metal analysis in Table 11. It is noted from this table that the powder core wire resulted in nearly ten times higher O in the weld deposit as opposed to the solid wire.

Table 9. Creep data for the base metal of the plate used in thepreparation of the welds

Heat No.	79741(Commercial Heat No. 1)- 1346°F Temper
Heat Treatment	N/T 2012°F / 1346°F -1 Hr
Product form	***Plate***- Base metal
Specimen orientation	Longitudinal

Test No.	Specimen No.	Temp. (°F)	Stress (ksi)	Rupture time (h)	Minimum creep rate (%/h)	Rupture elongation (%)	Reduction of area (%)
C79452	741-P-1	1000	62.0	0.6	3.5824	18.2	78.5
C79543	79741-1-2-P8	1000	55.0	7.4	0.3948	24.3	78.0
C79548	79741-1-6-P10	1000	45.0	99	0.03511	21.1	79.5
C79453	741-P-2	1100	40.0	100.7	0.02898	19.8	66.8
C79454	741-P-3	1100	26.0	958.5	0.00278	20.3	64.1
C79554	79741-1-3-P11	1100	20.0	2416.1	0.0012	27.1	61.9
C79455	741-P-4	1150	20.0	515.7	0.0079	26.9	79.7
C79553	79741-1-1-P9	1150	16.0	1342.1	0.003	29.3	76.2
C79562*	79741-2-1-P12	1150	12.0	3349			
C79536*	79741-1-4-P6	1200	6.0	3524.8			
C79541*	79741-1-5-P7	1200	3.0	3450.5			
C79512	741-P-5	1200	9.5	2542.3	0.0032	32.2	81.8

*****Tests in progress. Longest rupture time is 3524.8 h.

Table 10. Details of two gas tungsten arc welds made on 1-in.-thick plate of commercial heat 79741 of Grade A (315)

Weld ID	Joint Angle (º)	Preheat Temp. (ºF)	Interpass Temp. (ºF)	Wire Feed (ipm)	Wire Diameter (in.)	Filler Wire
JA[a]	60	250	<600	60	0.045	25B64-1[b]
41A	60	250	<500	4	~0.120	79741[c]

[a]Base metal of Grade 315.
[b]Powder-core wire.
[c]Solid wire produced as sheared strips from rolled plate.
•One-half of each JA and 41A was postweld heat treated at 1295ºF for 1 h followed by air cool
•Cover gas used was 100% argon.

Table 11. Weld Deposit Chemistry for Gas Tungsten Arc Welds Made in 1-in.-thick Plate for the Commercial Heat 79741

Element	Weight Percent		
	79741	GTA-JA	GTA-41A
C	0.099	0.043	0.083
Mn	0.34	0.22	0.34
P	0.009	0.008	0.006
S	0.003	0.013	0.003
Si	0.21	0.22	0.20
Ni	0.15	0.99	0.15
Cr	2.97	3	2.93
Mo	0.73	0.77	0.73
V	0.22	0.24	0.232
Cb	0.002	0.003	0.003
Ti	0.003	0.002	0.002
Co	0.014	0.01	0.014
Cu	0.11	0.03	0.11
Al	0.008	0.011	0.004
B	<0.001	<0.001	<0.001
W	1.68	1.82	1.68
As	0.005	0.005	0.008
Sn	0.008	0.004	0.007
Zr	<0.001	<0.001	<0.001
N	0.009	0.014	0.011
O	0.004	0.041	0.005
Ta	---	---	0.01

Charpy-impact properties of the GTA weld, JA, with high O (0.041 wt %) is presented in Table 12 and 13 for as-welded and after PWHT at 1290ºF for 1 h. Similar data for the GTA weld 41A with low O (0.005 wt %) are presented in Table 14. As noted from Tables 12 and 13, the JA weld was tested for Charpy properties over a wide range of temperature in both as-welded and PWHT conditions. Average values of the weld top and bottom are compared with the base metal values in Fig. 18. This figure shows that the impact properties of the JA weld are very poor in the as-welded condition and improve significantly after PWHT. Limited size of the low O weld, 41A, only permitted Charpy testing at two temperatures each in the as-welded and after PWHT of 1290ºF for 1 h. Charpy data for weld 41A is compared with the JA weld in Fig. 19. This figure shows that if the GTA welds can be made with low O, its values are very good in the as-welded condition, which can be further improved at room temperature. Values for -40ºF are the same for both as-welded and PWHT conditions. These data suggest that if O content was controlled (most likely through either the use of solid wire or improved powder core method), the GTA welds have the strong potential for being used without the need for PWHT.

Table 12. Charpy-impact data for gas tungsten arc weld JA in the as-welded condition

	Test Temperature (ºF)	Foot/Lbs	Lateral Expansion	Percent Shear
Sample ID[a]				
JA-TB-1	+70	18	0.019	40
JA-TB-2	+40	9	0.012	30
JA-TB-3	+20	6.5	0.010	20
JA-TB-4	0	7.5	0.007	10
JA-TB-5	-20	3.5	0.003	0
JA-TB-6	-40	3.5	0.003	10
JA-TB-7	-60	3	0.001	0
Sample ID[b]				
JA-BB-1	+70	21	0.020	40
JA-BB-2	+40	13	0.015	30
JA-BB-3	+20	8	0.007	10
JA-BB-4	0	7.5	0.007	20
JA-BB-5	-20	5	0.005	10
JA-BB-6	-40	5	0.005	10
JA-BB-7	-60	5	0.004	10

[a]All specimens from weld top.
[b]All specimens from weld bottom.

Tensile data on the weldment specimens taken from GTA weld JA is summarized in Table 15 and plotted in Figs. 20, 21, and 22. The as-welded specimens failed in the base metal and PWHT in the weld metal. This suggests that the filler metal needs further optimization. First, optimization is needed to keep the O low, which can be achieved by going to solid wire. Second, the chemistry needs optimization to yield a better match of strength properties to the base metal.

No creep tests were done on the GTA welds.

Shielded Metal Arc Weld

Only a limited supply of coated electrodes was produced in this project. These electrodes were used to make a shielded metal marc (SMA) weld in 1-in.-thick plate of the commercial heat 79741. Weld parameters are described in Table 16. The weld was PWHT at 1295ºF for 1 h prior to testing. Macro-etched section of the weld is shown in Fig. 23. Chemical analysis of the weld resulting from the available electrode batch is shown in Table 17. Note that the weld deposit is very low in C content, has high Ni content, and O content of 0.042 wt %.

Table 13. Charpy-impact data for gas tungsten arc weld JA after postweld heat treatment at 1290ºF for one hour

	Test Temperature (ºF)	Foot/Lbs	Lateral Expansion	Percent Shear
Sample ID [a]				
JA-TB-1	+70	70	0.057	80
JA-Tb-2	+40	64	0.053	80
JA-TB-3	+20	53	0.053	70
JA-TB-4	0	49	0.053	50
JA-TB-5	-20	38	0.031	40
JA-TB-6	-40	21	0.034	40
JA-TB-7	-60	22	0.038	40
Sample ID [b]				
JA-BB-1	+70	95	0.074	90
JA-BB-2	+40	83	0.066	90
JA-BB-3	+20	77	0.063	80
JA-BB-4	0	69	0.057	70
JA-BB-5	-20	68	0.057	70
JA-BB-6	-40	20	0.019	20
JA-BB-7	-60	9	0.007	10

[a]All specimens from weld top.
[b]All specimens from weld bottom.

Table 14: Charpy data on gas tungsten arc weld (41A) with and without postweld heat treatment. The weld was made with the matching filler wire composition.

Weld ID	Plate	Filler	Test Temperature (ºF)	Foot/Lbs	Lateral Expansion	Percent Shear
As Welded						
AB-7	79741	79741	+70	110	0.060	60
AT-4	79741	79741	-40	9	0.010	0
Postweld Heat Treatment at 1290ºF/1 h						
PB-7	79741	79741	+70	173	0.095	100
PB-4	79741	79741	-40	7	0.010	0

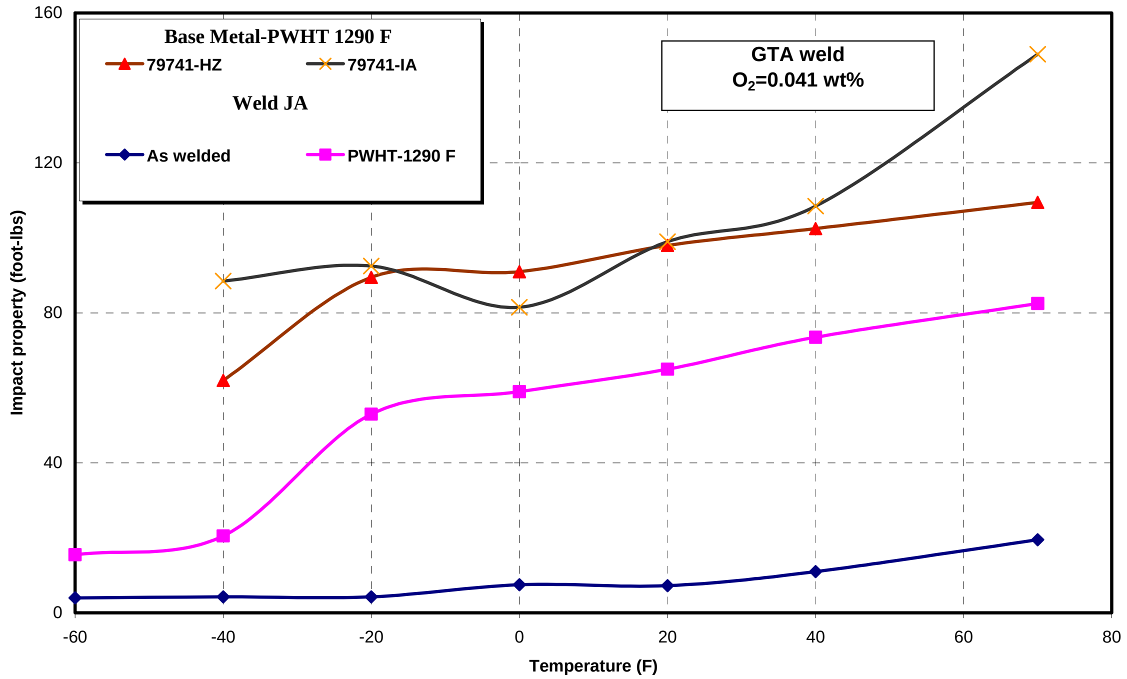


Figure 18. Comparison of impact properties of gas tungsten arc weld JA with base metal. Weld was tested in both as-welded and postweld heat-treated conditions.

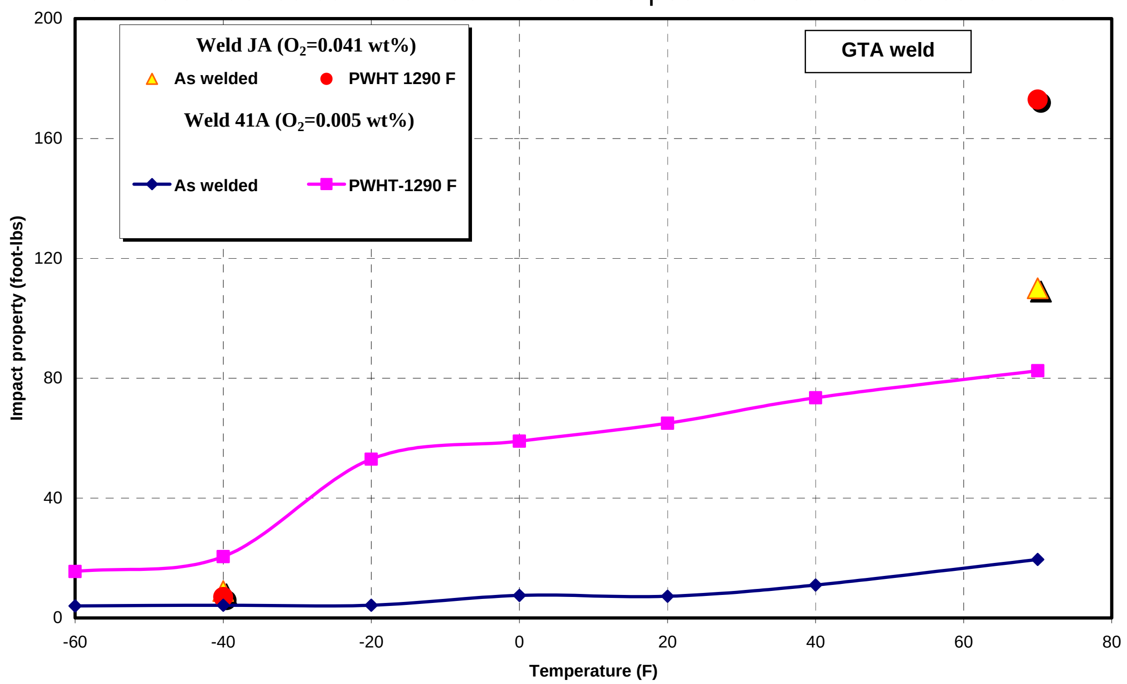


Figure 19. Comparison of impact properties of gas tungsten arc welds of low and high O. The low O weld is made with solid wire and high O with powder core wire. Both welds tested in as-welded and after PWHT.

Table 15. Tensile properties of weldment specimens from gas tungsten arc weld JA welds were tested in as-welded condition and after postweld heat treatment at 1290ºF for one hour

Sample ID	Test Temp. (ºF)	Reduction In Area (%)	Yield Strength (ksi)	Tensile Strength (ksi)	Total Elongation (%)	Fracture Location
As Welded						
JA-AS	+70	66.3	97.7	112.5	16.5	Base
JA-AS	+1000	60.3	82.6	87.1	16.0	Base
JA-AS	+1100	60.9	82.3	84.2	15.0	Base
Postweld Heat Treated at 1290ºF						
JA-Heat	+70	63.8	84.0	99.1	16.5	Weld
JA-Heat	+1000	60.3	71.3	76.8	15.0	Weld
JA-Heat	+1100	60.6	69.3	73.5	17.0	Weld

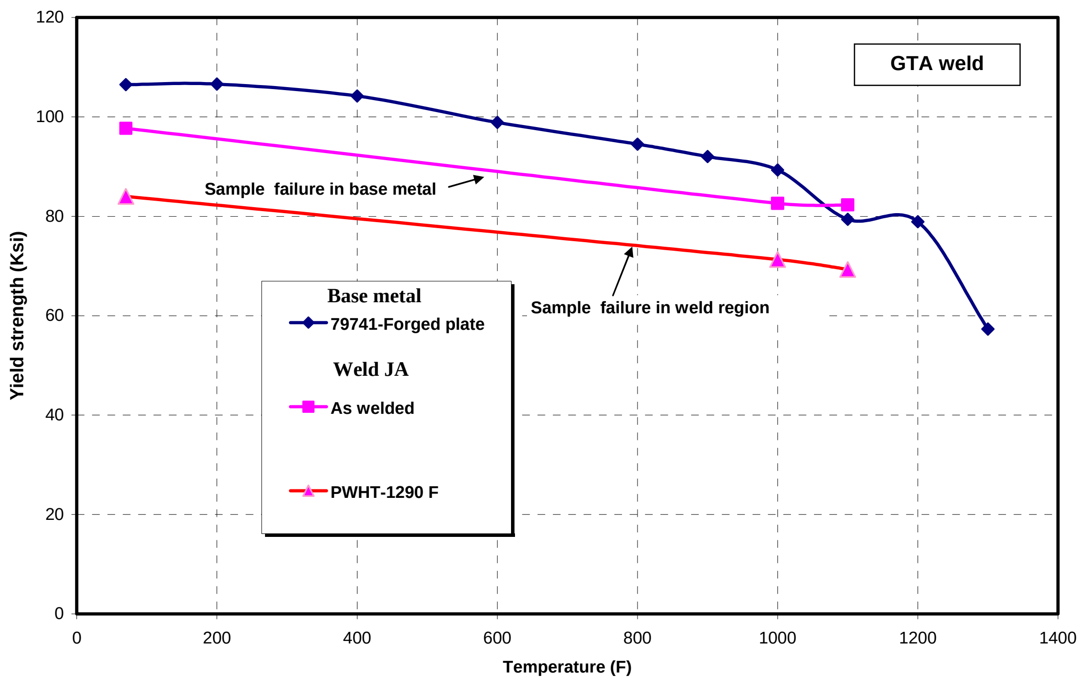


Figure 20. Comparison of yield strength of weldments in gas tungsten arc weld JA. Welds tested in the as-welded condition and after PWHT at 1290ºF for one hour

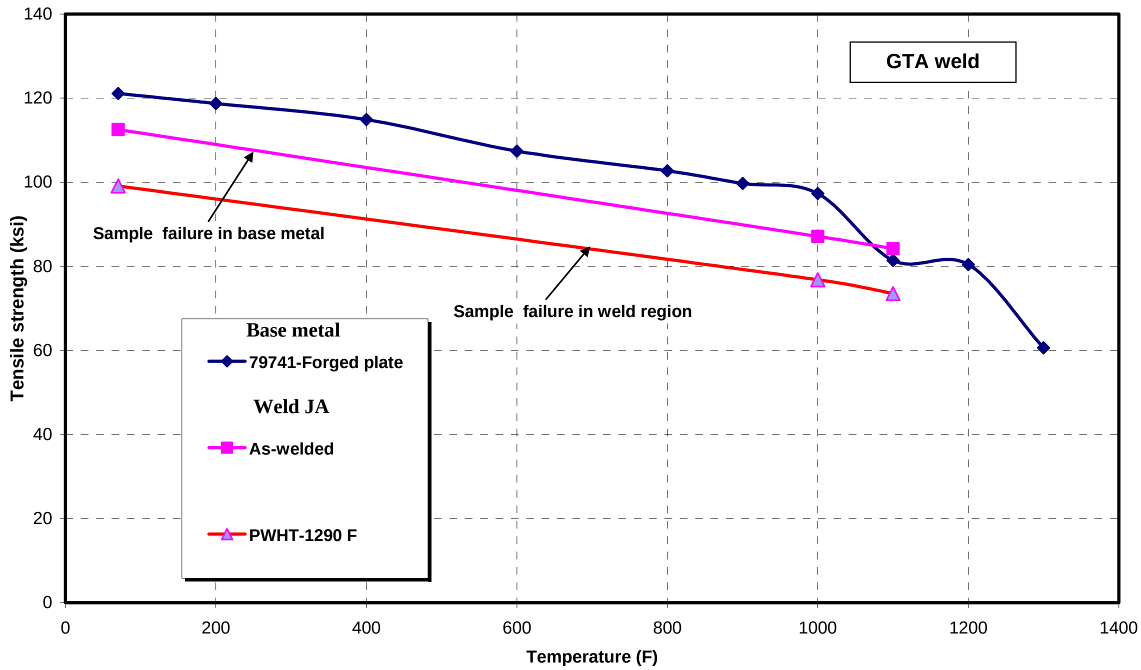


Figure 21. Comparison of tensile strength of weldments in gas tungsten arc weld JA. Welds tested in the as-welded condition and after PWHT at 1290ºF for one hour.

Charpy-impact data for the specimens taken from the top and bottom of the SMA weld are presented in Table 17. The average values of the top and bottom of the weld are compared with the base metal properties in Fig. 24. As expected from the O content, the impact values are significantly lower than the base metal. Furthermore, they are similar to that of the SA weld.

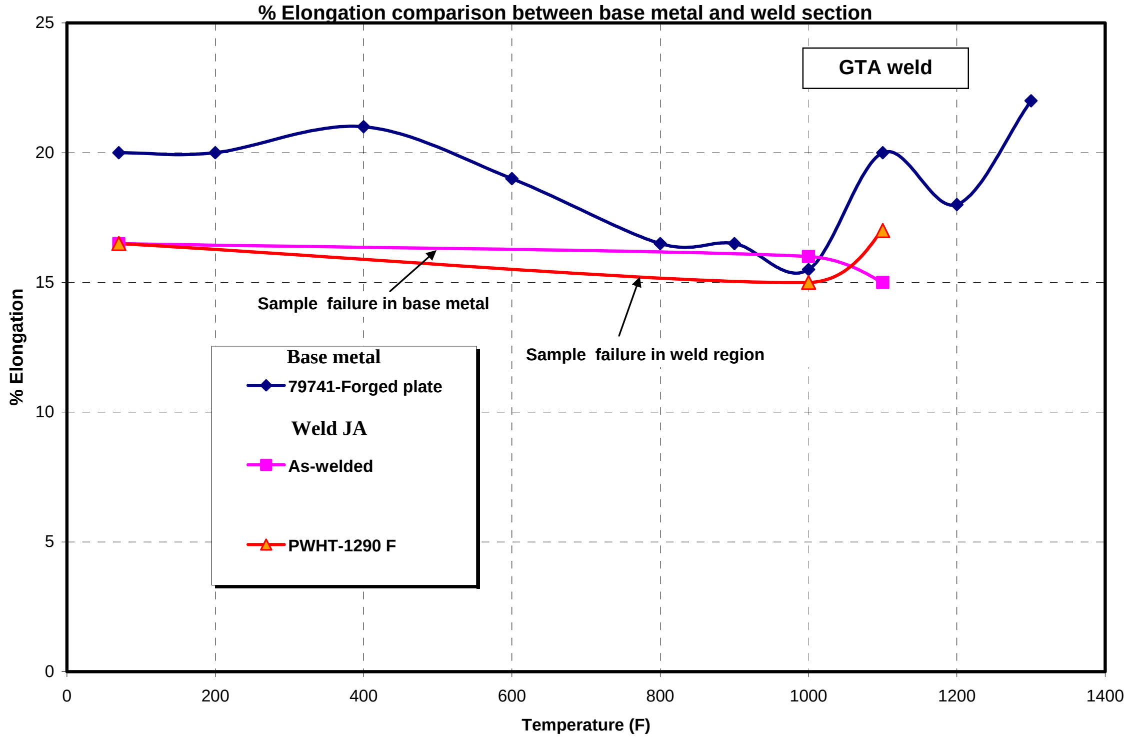


Figure 22. Comparison of total elongation of weldments in gas tungsten arc weld JA. Welds tested in the as-welded condition and after PWHT at 1290ºF for one hour.

Table 16. Weld parameters used for shielded metal arc weld in 1-in.-thick plate of heat 79741

Weld ID	Joint Angle (º)	Preheat Temperature (ºF)	Interpass Temperature (ºF)	Weld Rod Diam. (in.)	Electrode ID
IC	20	250	<600	1/8	15A19

[a]Base metal of Grade 315.
[b]Hydrogen bake at 600ºF for 2 h.
[c]Postweld heat treatment at 1295ºF followed by air cool.

Table 1. Weld deposit chemistry for a shielded metal arc weld made in 1-in.-thick plate of Grade 315, heat 79741

Element	Heat 79741 (wt %)	SMA-IC (wt %)
C	0.099	0.035
Mn	0.34	0.73
P	0.009	0.016
S	0.003	0.014
Si	0.21	0.24
Ni	0.15	1.22
Cr	2.97	2.61
Mo	0.73	0.72
V	0.22	0.23
Cb	0.002	0.004
Ti	0.003	0.006
Co	0.014	0.018
Cu	0.11	0.24
Al	0.008	0.002
B	<0.001	<0.001
W	1.68	1.56
As	0.005	0.011
Sn	0.008	0.016
Zr	<0.001	<0.001
N	0.009	0.021
O	0.004	0.042
Ta	---	<0.01

Table 18. Charpy-impact properties of shielded metal arc weld IC. The weld was tested after postweld heat treatment at 1295ºF for 1 h.

Sample ID	Test Temperature (ºF)	Foot/Lbs	Lateral Expansion	Percent Shear
Specimens from Top of Weld				
IC-TW-1	+70	57	0.046	60
IC-TW-2	+40	39	0.036	50
IC-TW-3	+20	34	0.026	30
IC-TW-4	0	22	0.022	40
IC-TW-5	-20	19	0.016	20
IC-TW-6	-40	13	0.010	20
Specimens from Bottom of Weld				
IC-BW-1	+70	50	0.043	70
IC-BW-2	+40	41	0.034	50
IC-BW-3	+20	20	0.020	30
IC-BW-4	0	22	0.023	40
IC-BW-5	-20	20	0.018	20
IC-BW-6	-40	21	0.018	20

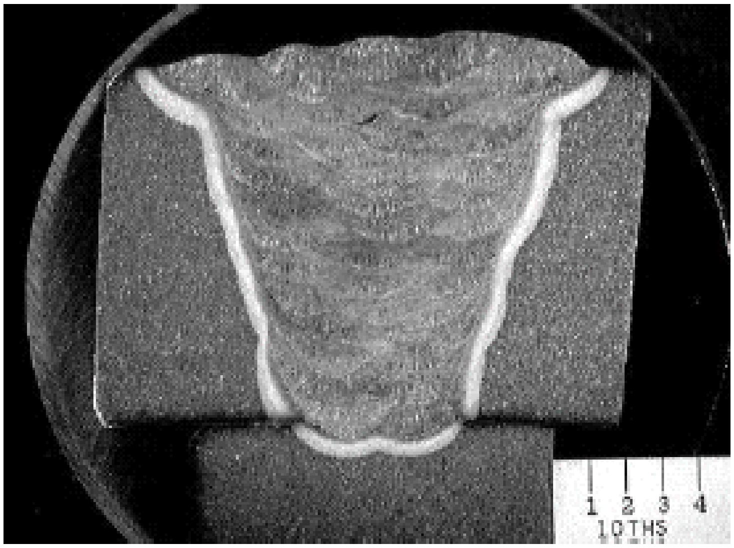


Figure 23. Cross-section of shielded metal arc weld, IC.

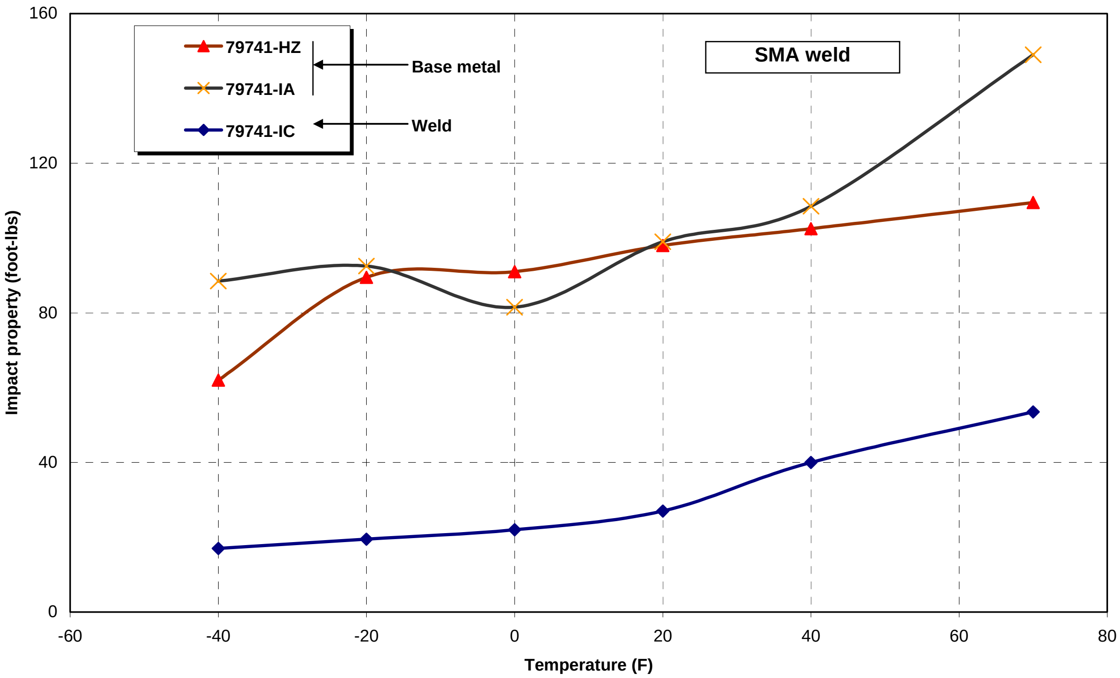


Figure 24.Impact properties of shielded metal arc weld, IC, compared with the base metal properties.

Tensile properties of the weldment specimens from the SMA weld IC are given in Table 19. All failing occurred in the base metal. These data are compared with the tensile properties of the GTA weld, where failures were in the weld after the PWHT (Figs. 25, 26, and 27). The strength data in Figs. 25 and 26 show that values for SMA weldment are higher than the GTA weld after PWHT. These data show that weldments with strength levels between the GTA and SMA will have matching values of strength between the weld and the base metal.

Table 19. Tensile data on weldment specimens taken from shielded metal arc weld IC. Note that all of the specimens failed in the base metal.

Sample ID	Test Temp. (ºF)	Reduction In Area (%)	Yield Strength (ksi)	Tensile Strength (ksi)	Total Elongation (%)	Fracture Location
As Welded						
IC-1	+70	69.7	86.6	104.0	20.0	Base
IC-2	+1000	64.2	80.8	83.8	17.0	Base
IC-3	+1100	67.5	73.2	74.7	17.0	Base
IC-4	+1200	77.3	59.7	60.2	22.0	Base

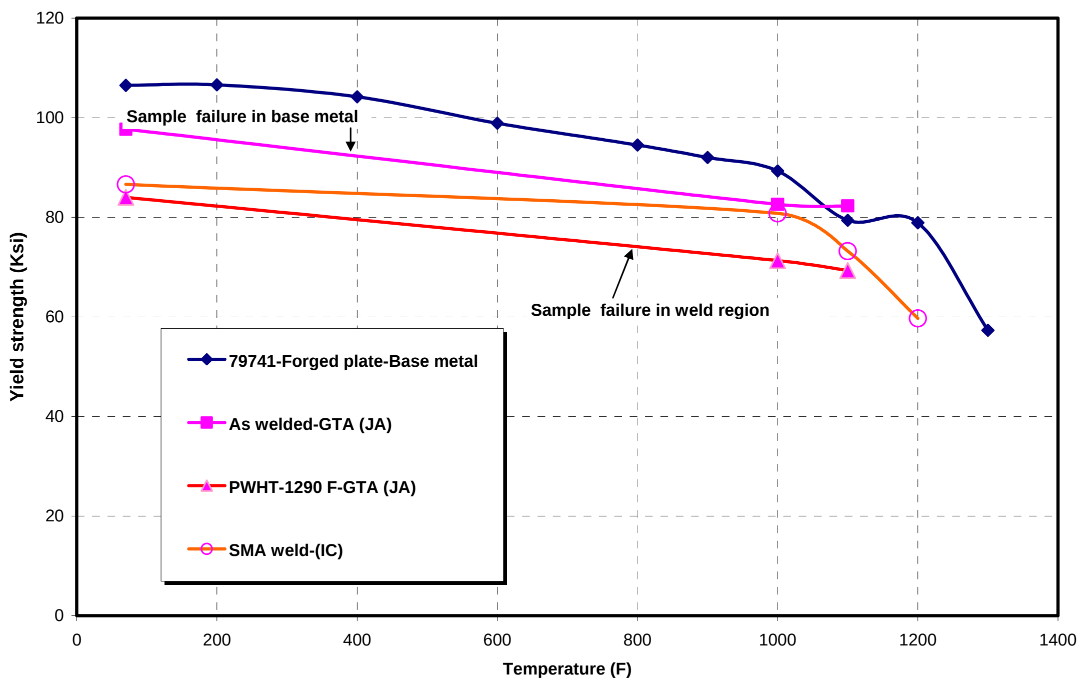


Figure 25. Comparison of yield strength of weldments of shielded metal arc weld, IC, with gas tungsten arc weldments and the base metal.

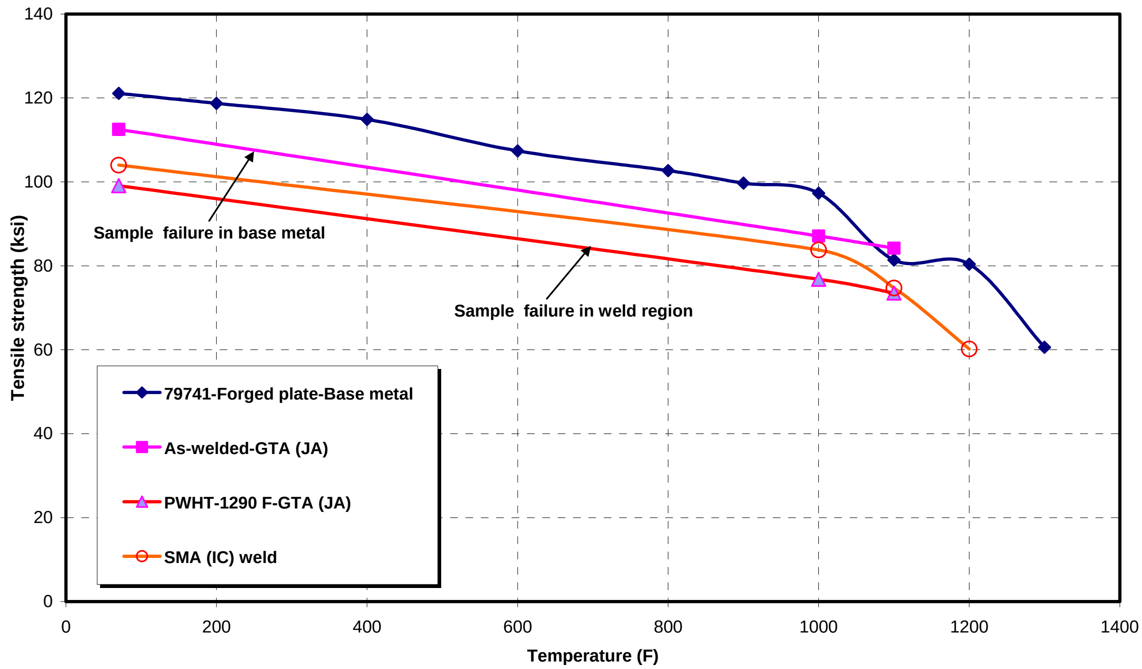


Figure 26. Comparison of ultimate tensile strength of weldments of shielded metal arc weld, IC, with gas tungsten arc weldments and the base metal.

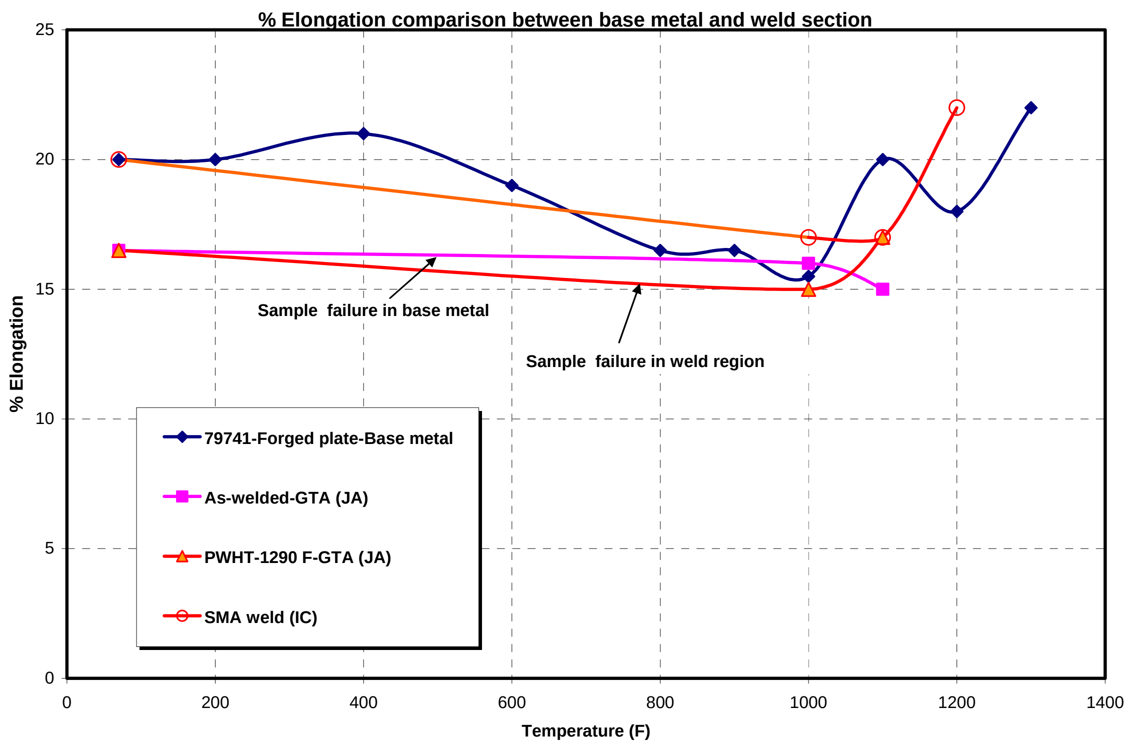


Figure 27. Comparison of total elongation of weldments of shielded metal arc weld, IC, with gas tungsten arc weldments and the base metal.

Three creep tests were done on the weldment specimens taken from the SMA weld IC. Data on these weldments are compared with weldments and all weld specimens of SA welds in Fig. 28. This figure shows the lowest creep values. Based on the location of these data points, failures are expected in the welds. All failed specimens matched the expected failure location. This suggests that the weldment properties are controlled by the weld deposit properties. As stated earlier, this batch of electrodes had the lowest C and contained a significant amount of Ni. Both elements are expected to lower the creep strength. Based on these data, it is clear that the next batch of electrodes need chemistry modification.

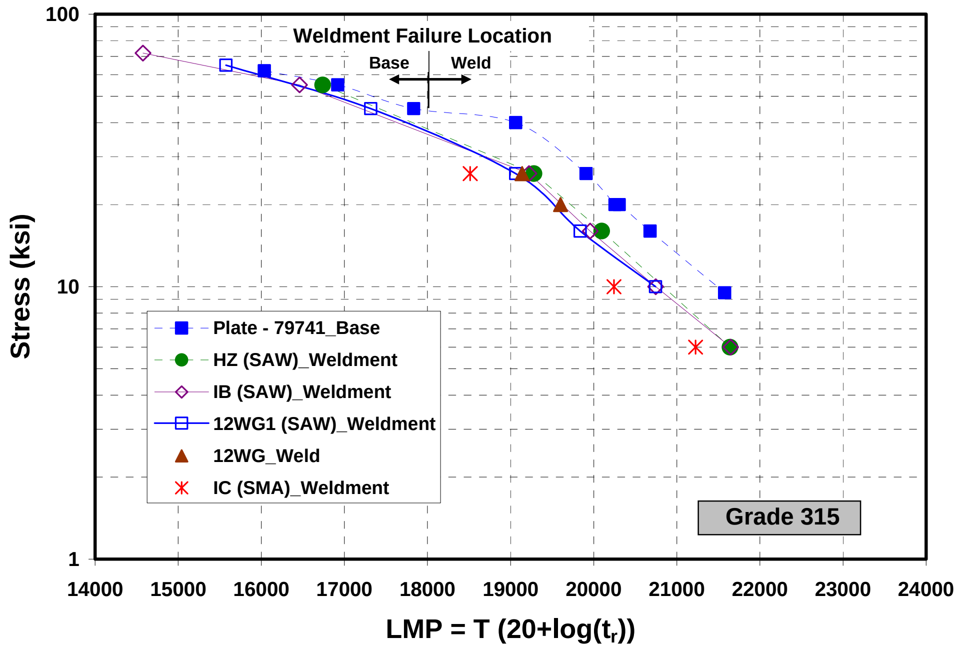


Figure 28. Comparison of creep rupture properties of weldment specimens of shielded metal arc weld IC with weldments of submerged arc welds HZ, IB, and 12WG1 and all weld metal submerged arc welds 12WG.

Summary

This report has summarized all of the welding details and weld characterization results that have been developed to date on the welding of 1-in.-thick plates of commercial heat 79741. The main focus was on the SA welds with limited focus on the GTA and SMA welds. The following are the key observations:

1. Good quality welds can be made by all three processes: SA, GTA, and SMA.
2. For SA welds, flux of choice is Lincoln 880.
3. For SA welds, a PWHT of at least 1290ºF is required to achieve acceptable impact properties.
4. Failure location studies of creep specimens show that at low temperatures (900 to 1000ºF) and high stresses, failure location is base metal, while at higher temperatures and low stresses, failure locations are in the weld. This suggests that the filler metal composition needs further improvement.

5. GTA welds yield low O weld deposits with solid wire. It is desirable to see if the powder core approach can be used to produce low O GTA welds.
6. GTA welds of low O (~0.005 wt %) have a strong potential for not requiring any PWHT.
7. SMA welds with the only batch of electrodes produce deposits with very low C, high Ni, and high O. Electrode chemistry modification is needed to increase C and reduce Ni contents.
8. SMA welds produced lowest creep strength because of weld deposit chemistry.
9. The recognition of the weld failure during creep testing is critical in optimizing filler wire composition so that weldment rupture strength can be brought closer to the base metal.
10. All weld deposits with high O content (SA, GTA, and SMA) need PWHT to get the acceptable impact properties.

Future Work

1. Optimize filler wire compositions for SA, GTA, and SMA processes.
2. Prepare welds in 1- and 3-in.-thick plates with the optimized filler chemistries and develop properties used in design and fabrication of components.