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Gleeble Compression Tests on As-cast Alloy 709 Samples

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OAK RIDGE NATIONAL LABORATORY
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Materials Science and Technology Division

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ACRONYMS

ART	Advanced Reactor Technologies
ANL	Argonne National Laboratory
DOE	Department of Energy
ORNL	Oak Ridge National Laboratory
SFR	Sodium Fast Reactor

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ABSTRACT

Compression tests were performed on as-cast Alloy 709 (heat 58776-3) using Gleeble® 3500-GTC system at Oak Ridge National Laboratory (ORNL). The testing temperature range was 900 ^{o}C to 1200 ^{o}C and the nominal true strain rate range was 0.001/s to 40/s. The tested specimens were delivered to Argonne National Laboratory (ANL) for confirmatory microstructure analysis. The test data were provided to ANL for the construction of the processing map for Alloy 709.

This report summarizes the compression tests performed on the as-cast Alloy 709 and fulfills the FY18 milestone M3NT-18OR050502026-"Complete the Gleeble compression tests of as-cast Alloy 709 samples" under the ORNL work package NT-18OR05050202-"A709 Development - ORNL".

1. INTRODUCTION

Nuclear power contributes significantly to meeting the nation's energy, economic, environmental, and national security needs. Sodium Fast Reactor (SFR) is a leading candidate for recycling used fuel to close the fuel cycle and for power generation. While the SFR technology is relatively mature, there must be improvements in the capital cost and economic return before the private sector will invest in the large-scale, commercial deployment of SFRs. Further, greater safety margins and increased flexibility will also be required of any new advanced reactor systems. Flexibility, safety, and economics were all identified as the key needs for advanced reactors.

Advanced materials can have a significant impact on capital costs reduction even if the commodity prices of new materials are higher than traditional steels. This is due to innovative designs and design simplifications that could be made possible using materials with enhanced mechanical properties. Improved materials performance also impacts safety through improved reliability and greater design margins. Improved material reliability could also result in reduced down time.

Due to the significant enhancement in mechanical properties of the austenitic stainless steel Alloy 709 relative to 316H stainless steel (Busby et al., 2008), a reference construction material for SFR systems, code qualification of Alloy 709 was recommended in FY14. Qualification of additional higher performance structural material, the Alloy 709 advanced stainless steel, to expand Fast Reactors (FR) design envelops is one of the key areas that the FR Campaign currently focuses on. A comprehensive plan for the development of a 500,000-hour, 760 ^{o}C ASME Code Case and the resolution of structural integrity issues identified by NRC for Alloy 709 was developed in FY15. A Phase I implementation of this plan that includes a 100,000-hour, 650C ASME code case and the initiation of very long term creep tests, and thermal aging and sodium exposure of Alloy 709 has been established. In collaboration with material vendor, G.O. Carlson Inc. of Pennsylvania, the ART program successfully scaled the production of Alloy 709 from a laboratory heat of 500 pounds to a commercial heat of 55,000 pounds (Natesan, et al.,2017). Hot-rolled plates were fabricated from the first commercial heats to support testing.

Efforts to execute the Phase I plan continued in FY18. The focus of the FY18 Alloy 709 effort involves the development of the processing map to support Alloy 709 fabrication optimization. This report summarizes the compression tests performed on the as-cast Alloy 709 (heat 58776) in support of the development of the processing map.

2. EXPERIMENTAL DETAILS

2.1 MATERIAL

The Alloy 709 material (heat 58776-3) used in this report was supplied by ANL. The material was in as-cast condition and supplied in plate shape. The plate was approximately 420mm in length and 240mm in width. It has a tapered thickness of about 22mm to 50mm. Pictures of the as-received plate are shown in Fig. 1.

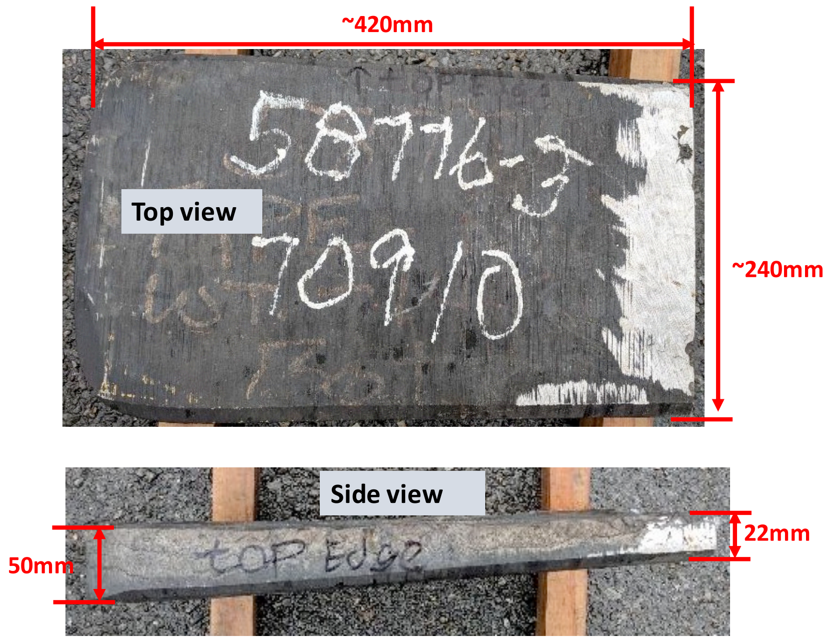

Fig. 1. As-cast Alloy 709 supply material

The compositions of this plate are listed in Table 1.

Table 1. Chemical compositions of the as-cast Alloy 709 (heat 58776-3), wt%

C	Cr	Ni	Mn	Mo	N	Si	P	Ti	Nb	N	Fe
0.066	19.93	24.98	0.91	1.51	0.148	0.44	0.014	0.04	0.26	0.0045	Bal.

2.2 SPECIMENS AND EXPERIMENTS

2.2.1 Specimen geometries

The Gleeble compression specimen was cylindrical shape with diameter of 10mm and length of 15mm. The specimen drawing is shown in Fig. 2.

A 12.5mm all-around edge was cut off from the as-received plate and discarded to avoid any possible edge effect from the preparation of this plate. The Gleeble compression specimens were machined from 12.5mm wide blocks with the cylinder centerline along the plate width direction. The specimens were machined from the center of plate thickness to eliminate the surface effect. The specimen layout is schematically shown in Fig. 3.

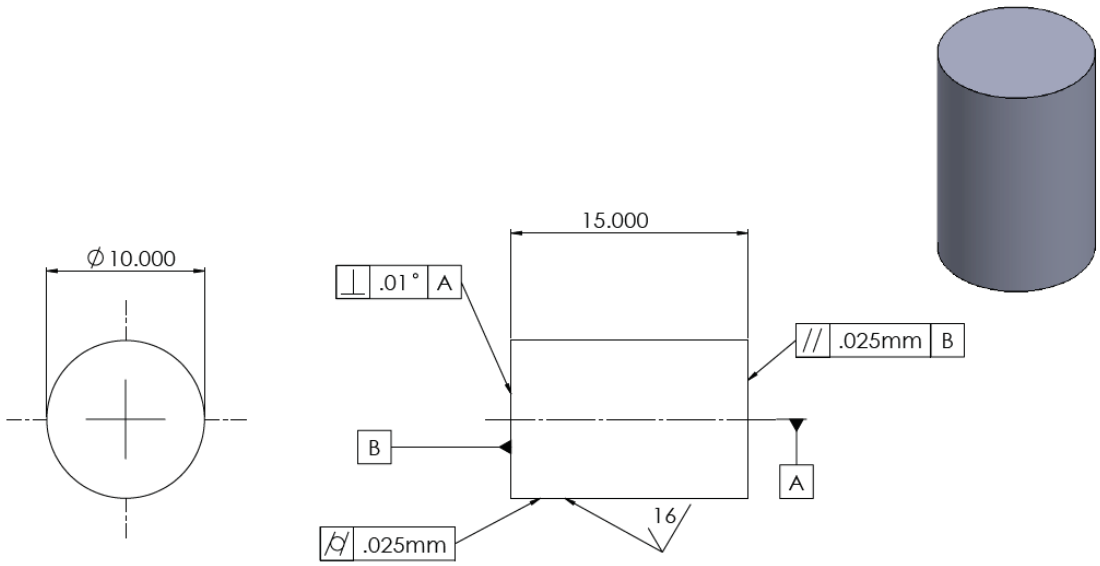

Fig. 2. Gleeble compression specimen geometry.

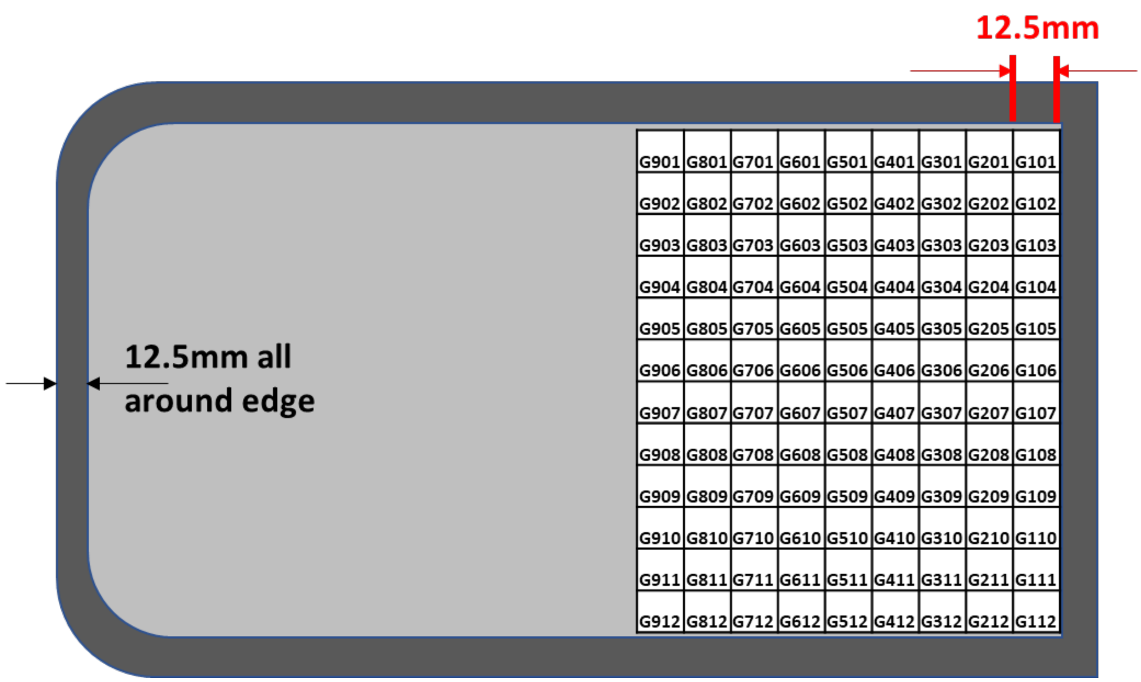

Fig. 3. Layout of the Gleeble compression specimens with respect to the as-received as-cast Alloy 709 plate.

2.2.2 Gleeble compression testing

The compression tests were performed on the Gleeble® 3500-GTC system at ORNL. A picture of the Gleeble® 3500-GTC system is shown in Fig. 4. Prior to the compression testing, the test chamber was evacuated and back filled with pure Argon gas to minimize oxidation of the specimens.

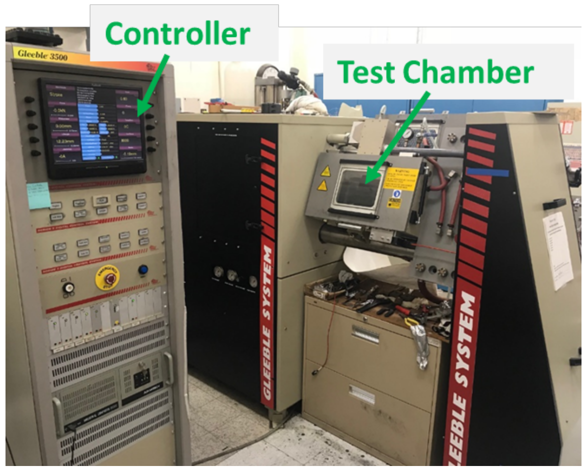

Fig. 4. The Gleeble® 3500-GTC system at ORNL

The testing matrix in support of the construction of the processing map is summarized in Table 2. The testing temperature was from 900 ^oC to 1200 ^oC, and the nominal true strain rate was from 0.001/s to 40/s. The matrix consists a total of 35 compression tests.

Table 2. Gleeble compression test matrix for as-cast Alloy 709

Temperature, C	**Nominal true strain rate, 1/s**				
900	0.001	0.01	0.1	1	40
950	0.001	0.01	0.1	1	40
1000	0.001	0.01	0.1	1	40
1050	0.001	0.01	0.1	1	40
1100	0.001	0.01	0.1	1	40
1150	0.001	0.01	0.1	1	40
1200	0.001	0.01	0.1	1	40

The testing procedure followed ASTM E209. The compression tests were controlled with a computerized program. The compression tests were performed under Argon protection gas environment. A picture of the experimental setup for a scope testing on a compression specimen is shown Fig. 5. The specimen was being loading in a horizontal position. The heating rate was controlled to be 2.5 $^oC/s$ under a small compression load control and the heating mechanism was resistance heating. Graphite foils and tantalum foil spacers were used at the interfaces between the specimen and the tungsten carbide loading anvils to equilibrate the temperature along the specimen length direction. Three thermal couples were spot-welded on to the specimen surface with one at the mid-length for temperature control and two at 2mm away each end to monitor the temperature. The specimens were equilibrated at the target temperature for 2 minutes before the compression process began. During this 2-minute hold period, the temperature difference along the specimen length direction was within the ASTM E209 specification. During compression test, the temperature reading of the two thermocouples close to the end of the specimen was monitored but was not considered as a crucial control parameter because they might contact the loading fixture under large deformation, which would result in false reading.

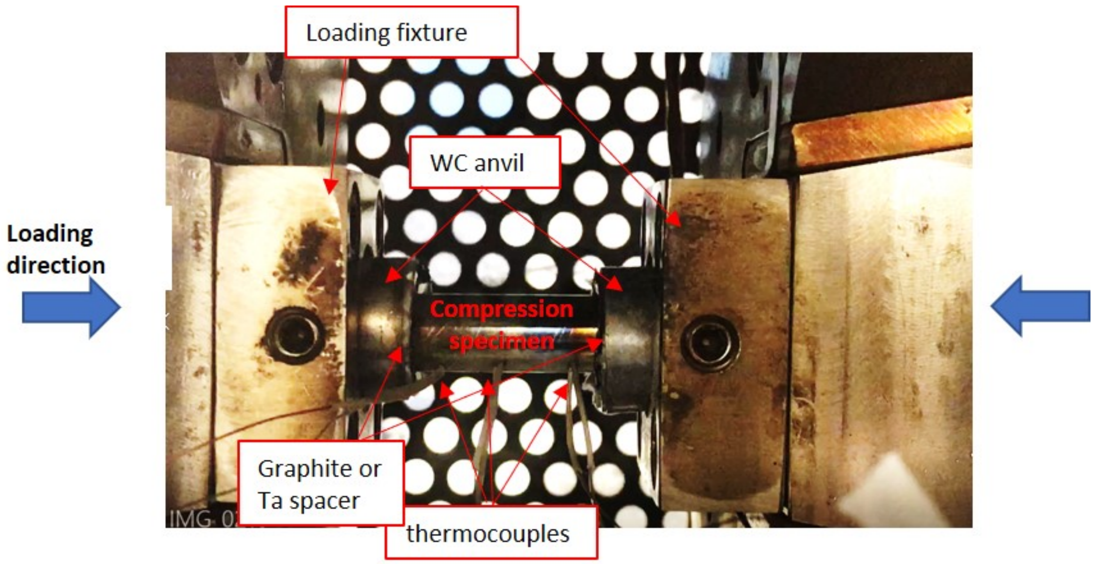

Fig. 5. Gleeble compression test setup

All compression tests with nominal true strain rates of 1/s and lower used constant true strain rate control. The true strain is defined as

$$\varepsilon = \ln\left(\frac{l}{l_0}\right) \tag{1}$$

where ε is the true strain, l is the specimen length and l_o the original specimen length prior to the compression testing. The control software for Gleeble® 3500-GTC system allows control mode be defined as constant true strain rate control.

However, several scoping tests were performed at the highest testing speed under true strain rate control, the results show that the Gleeble® 3500-GTC system responded with much slower speed than the command, and it was then decided to switch to stroke control and over drive the system with a command speed of 600 mm/s to achieve the nominal true strain rate of 40/s.

For construction of the processing map, the stress is expressed as true stress with the following equation,

$$\sigma = \frac{P}{A} \tag{2}$$

Where σ, p and A are the true stress, the load and the cross-sectional area.

Assuming the material volume is constant, i.e,

$$A * l = A_o * l_o \tag{3}$$

Equation (2) can therefore be converted to

$$\sigma = \sigma_e * (1 + e) \tag{4}$$

Where σ_e is the engineering stress and defined as (P/A_o), and e is the engineering strain and defined as (l_o-l)/ l_o. The compression strain is converted to be positive in this case.

Immediately after the compression test, the specimens were water quenched to preserve the microstructure features for further microscopic analysis.

A flow chart of the above described compression test procedure is demonstrated in Fig. 6.

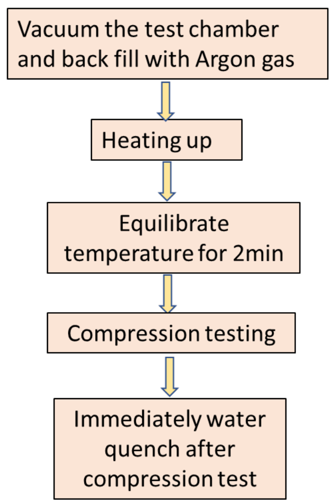

Fig. 6. Flow chart of the Gleeble compression test procedure

3. RESULTS OF THE GLEEBLE COMPRESSION TESTS

Pictures of a specimen before testing and another specimen after compression testing are shown in Fig. 7. The specimens were found to show an irregular shape after compression tests due to the non-homogenous microstructure of the as-cast material, unlike the conventionally barreled shape for specimens with uniform microstructure. The side surfaces of the test specimens were not smooth.

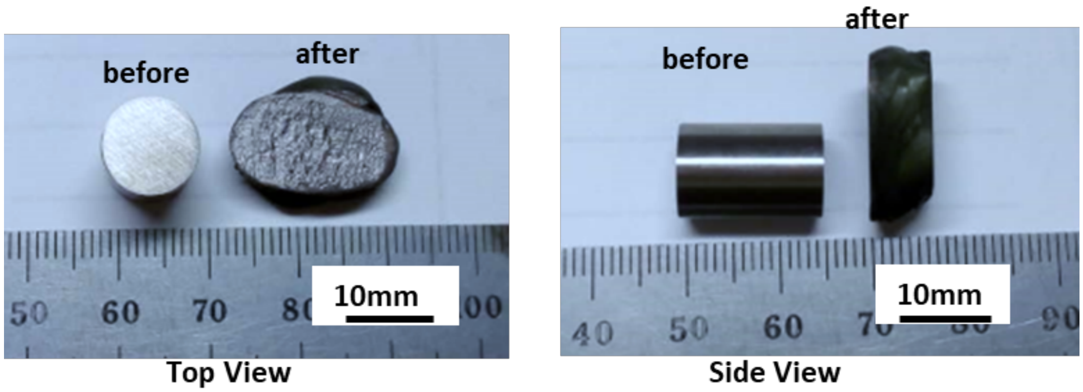

Fig. 7. Pictures of the Gleeble compression test specimens

A series of images of a specimen was recorded during the Gleeble compression testing and shown in the Fig. 8. The specimen was continuously compressed to the final thickness of about 6mm at a prescribed constant true strain rate.

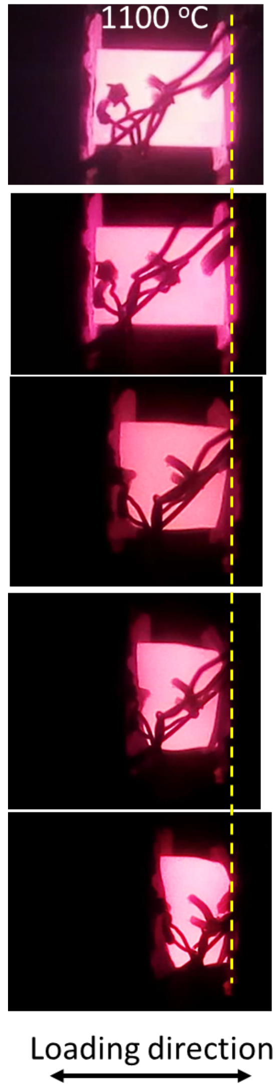

Fig. 8. Pictures of the Alloy 709 specimen during Gleeble compression test at 1100 °C

Examples of the true stress vs. true strain curves at different testing temperatures are plotted in Fig. 9. The nominal true strain rate was 40/s for these tests. The waviness of the true stress vs. true strain curves is due to ringing in the load signal at the high testing speed. As expected, the true stresses were shown to increase as the testing temperature decreased.

All the valid compression tests performed are listed in Table 3. A total of 45 tests were performed, with several extra tests at nominal true strain rate of 5/s and with several repeats for some conditions to confirm the results. After compression tests, the graphite or tantalum spacers were stuck to the specimen, therefore the final thickness reported in this table is only for reference because the value does not reflect the true specimen thickness. All the tested specimens along with the test data (including time, load, displacement) were delivered to ANL for microstructure analysis and for construction of the processing map.

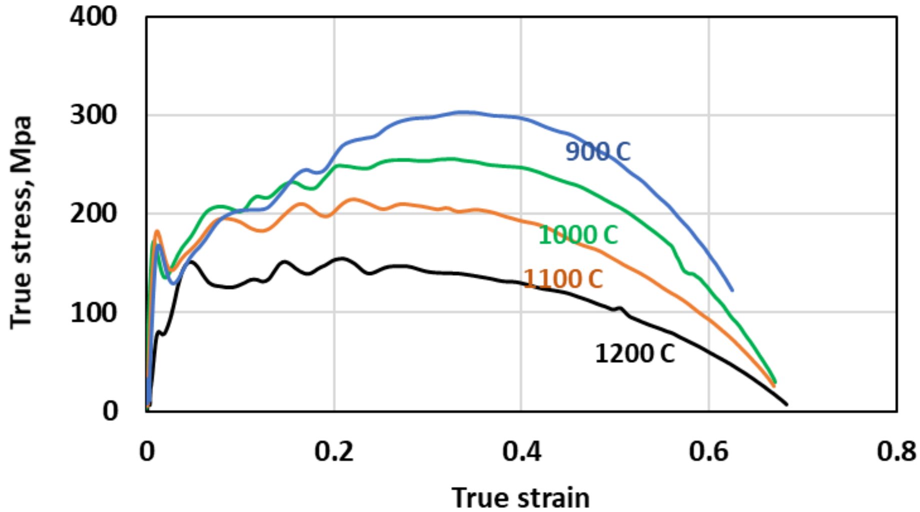

Fig. 9. True stress vs. true strain curves of Gleeble compression tests on as-cast Alloy 709 at nominal true strain rate of 40/s

Table 3. List of the Gleeble compression tests on Alloy 709 (heat 58776-3)

Test No.	Specimen ID	Test Temp. C	nominal true strain rate, 1/s	Final thickness at RT, mm	Notes
1	G910	1000	5	5.83	extra test condition
2	G206	900	5	6.35	extra test condition
3	G808	1200	5	5.84	extra test condition
4	G109	1100	5	6	extra test condition
5	G904	1100	5	5.9	extra test condition
6	G707	1200	1	5.92	
7	G201	1200	0.1	5.9	
8	G403	1100	0.1	5.9	
9	G611	900	0.001	6.04	
10	G106	900	0.1	6.25	
11	G909	1000	0.1	4.5	partial data are valid
12	G310	1100	0.01	6.6	
13	G809	900	0.001	5.81	
14	G108	1000	0.001	6.18	
15	G203	1100	0.001	6.77	
16	G710	1200	0.001	6.81	
17	G202	1200	40	5.84	

Table 3 continued

Test No.	Specimen ID	Test Temp. C	nominal true strain rate, 1/s	Final thickness at RT, mm	Notes
18	G409	1000	40	6.03	
19	G702	1100	40	5.93	
20	G107	900	40	6.78	
21	G111	900	1	6.95	
22	G905	950	1	6.85	
23	G602	1000	1	7	partial data are valid
24	G211	1050	1	7.2	
25	G401	1100	1	5.95	
26	G709	1150	1	5.73	
27	G101	900	0.01	6.2	
28	G604	1000	0.01	6.45	partial data are valid
29	G901	1200	0.01	6.36	
30	G301	1125	2	6.5	
31	G911	1150	40	7.02	
32	G305	950	0.1	7.05	
33	G603	1150	7	6.33	extra test condition
34	G711	950	7	7.15	extra test condition
35	G208	1055	40	5.92	
36	G205	960	40	6.38	
37	G512	1050	0.1	6.2	
38	G110	1150	0.1	5.58	
39	G511	1050	0.1	6.24	repeat # 37
40	G601	950	0.01	7.2	
41	G307	1050	0.01	5.9	partial data are valid
42	G608	1150	0.01	6.7	
43	G605	1150	0.001	6.1	
44	G701	1050	0.001	6.37	
45	G302	950	0.001	6.63	

4. SUMMARY

Gleeble compression tests were performed on as-cast Alloy 709 (heat 58776-3) to generate necessary information to support the development of the processing map for Alloy 709. A total of 45 compression tests were performed at a temperature range of 900 ^{o}C to 1200 ^{o}C and the true strain rates were between 0.001/s to 40/s. All the tested specimens along with the test data were delivered to ANL for microstructure analysis and for construction of the processing map. This report fulfills the FY18 milestone M3NT-18OR050502026-"Complete the Gleeble compression tests of as-cast Alloy 709 samples" under the ORNL work package NT-18OR05050202-"A709 Development - ORNL".

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