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Development of volume deposition on cast iron by additive manufacturing

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Materials Science and Technology Division
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DEVELOPMENT OF VOLUME DEPOSITION ON CAST IRON BY ADDITIVE MANUFACTURING

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ABSTRACT

ORNL partnered with Cummins Inc to demonstrate the feasibility of using additive manufacturing techniques to deposit large volume of new material on cast iron in context of remanufacturing. Remanufacturing at Cummins Inc is carried out to repair any field damage and in some cases provide additional value by adding new features. Large volume deposition on difficult to weld materials is a challenging problem due to involved metallurgy. Phase-1 of this work evaluated the feasibility of using laser directed energy deposition technique to deposit new material layer by layer on cast iron engine blocks. During phase-1 deposits were made using Inconel-718, Nickel, Nr-Cr-B braze filler. Inconel 718 builds showed significant cracking in the heat-affected zone in the cast iron. Nickel was used to reduce the cracking, however the Ni builds did not wet the substrate sufficiently resulting in poor dimensional tolerance. In order to increase wetting the Ni was alloyed with the Ni-Cr-B braze. This however resulted in significant cracks in the build due to shrinkage stresses associated with multiple thermal cycling. Hence the equipment was modified to reduce the residual stresses in the builds and the cast iron block was pre heated using cartridge heaters. Inconel-718 alloyed with Ni was deposited on the engine block. The pre-heated deposits showed a reduced susceptibility to cracking. If awarded the phase-2 of the project would aim to develop process parameters to achieve a crack free deposit on engine block. Such remanufacturing strategy of engine components helps significantly reduce energy required and associated greenhouse gases emissions.

1.0 DEVELOPMENT OF VOLUME DEPOSITION ON CAST IRON ENGINE BLOCKS BY ADDITIVE MANUFACTURING

This phase 1 technical collaboration project (MDF-TC-2016-037) was begun on February 1, 2016 and was completed on October 31, 2016. The results from phase 1 show that laser directed energy deposition process could be used to deposit large volume on cast iron leading to significant cost savings, ability to add new features and reduced emissions. However more research is warranted to reduce the cracking susceptibility in the heat affected zone of the cast iron.

1.1 BACKGROUND

Cummins Inc aims to remanufacture engine blocks by being able to add large volume of material on existing cast iron to repair various service damage and add new features. This is possible by machining away the damage and filling the cavity by new material similar or better in performance. The geometry of the fill up is usually complex and cannot be achieved by traditional manufacturing without any significant post processing. The disruptive nature of the additive process can be well suited for such applications. ORNL has a wealth of experience of using the DMD technology to fabricate complex geometries, functionally graded steels. Researchers have also developed in situ tools to characterize and understand the fundamental aspects of this technology. Thus ORNL expertise can greatly be of use for Cummins Inc in this feasibility study.

The technology used for the proposed application was the directed energy deposition technique. The process uses a high power laser used to melt the substrate and powder is delivered into the melt pool. The deposition substrate or “target” is aligned to the desired start point of the deposit. In this case the substrate is the cast iron engine block. The powder feeder(s) feed the powder delivery nozzle assembly, which creates a powder stream that converges at the point of the deposit. The laser creates a melt pool into which the powder is deposited leading to a deposit height of approximately 0.2-0.5mm/layer. Motion control for the deposit may be programmed manually or may be generated from CAD files that are processed by the system’s software. The major process variables are heat input and powder feed rate. Due to the flexibility of the DMD process it is the preferred additive manufacturing process suitable for repairs.

Cast iron by virtue of its high carbon content is a difficult to weld material [1, 2]. Traditionally cast iron has been welded using high nickel containing fillers to stabilize austenite in the heat-affected zone to prevent cracking [3-6]. In addition high Ni containing alloys are also soft and hence are capable of absorbing the shrinkage stresses [6]. Hence in this work the following fillers (Table-1) were explored to identify the optimum composition.

Table-1: Showing the process parameters used for the deposits

Composition	Laser Power (W)	Travel Speed (mm/min)	Powder feed rate (g/min)	Pre-heat temperature (°C)
Inconel-718	400W	400 mm/min	6 g/min	250°C
Pure Ni	500 W	700 mm/min	6 g/min	250°C
Ni-Cr-B Braze	500 W	700 mm/min	7 g/min	Room temp
Ni-Cr-B+50%Ni	500 W	700 mm/min	7 g/min	Room temp
Ni-Cr-B+70%Ni	500 W	700 mm/min	7 g/min	Room temp
Inconel-718+50%Ni	500 W	700 mm/min	7 g/min	450°C
Inconel-718	500 W	700 mm/min	7 g/min	450°C

Among all the fillers explored the Inconel 718+50%Ni gave the best cracking resistance. If approved the phase-2 would aim to eliminate defects and minimize residual stresses in the part by optimizing the process parameters.

1.2 TECHNICAL RESULTS

1.2.1 Deposition made using Inconel-718

Builds were fabricated using In-718 on engine blocks using the DMD-103D machine. The process parameters are shown in table-1. Figure-1 (a-c) shows the macrographs and the micrographs of the deposits. The deposits showed cracking in the In-718 build deposit and in the HAZ of the cast iron. The cracking in the build region was attributed due to the increase in the Fe content in the dilution zone of the In-718 deposit resulting in the observed solidification cracks as shown in figure 1(c). The cracking in the HAZ is attributed to martensite formation and the shrinkage stresses at the interface due to the rapid cooling rates experienced by the builds.

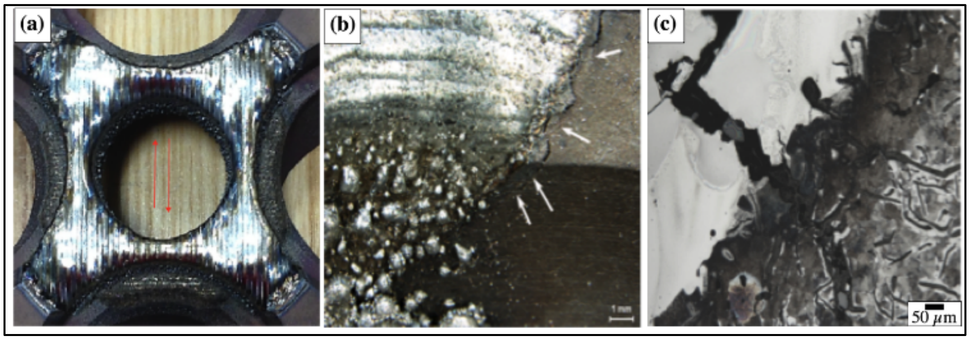
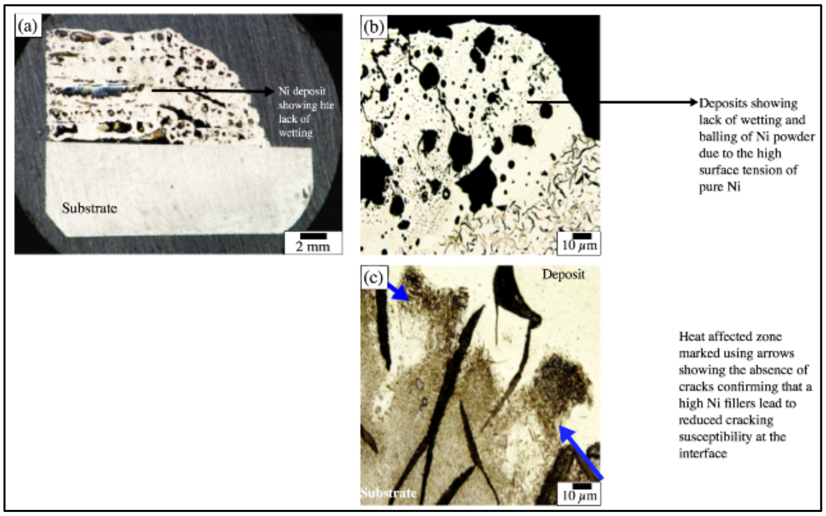


Figure 1 Shows the macro and micrographs of deposits (a) Macrograph of the deposit (b) Macrograph showing cracking in the heat affected zone in the cast iron (c) Micrograph showing the cracking due to martensite formation in the HAZ

1.2.2 Deposits fabricated using pure Ni:

In order to avoid cracking Ni was used. Ni has a lower hardness compared to Inconel and hence can absorb the shrinkage stresses during cooling thereby avoiding cracking in the deposits. The results from the Ni deposits are shown in figure 2 (a-c). The microstructure shows the lack of wetting between the subsequent layers. This has been observed previously and has been attributed to the lack of wetting between subsequent layers. The lack of wetting is a direct result of the high surface tension of liquid nickel, which results in the balling up of the Ni [7].



Deposits showing lack of wetting and balling of Ni powder due to the high surface tension of pure Ni

Heat affected zone marked using arrows showing the absence of cracks confirming that a high Ni fillers lead to reduced cracking susceptibility at the interface

Figure 2 Shows the macro and micrographs of deposits (a) Macrograph of the deposit (b) Micrograph showing the balling of Ni deposit (c) Showing the heat affected zone of the deposit without any cracks

1.2.3 Deposits fabricated using Ni-Cr-B braze:

It is well known that trace additions of B to Ni increases the wettability of the Ni by reducing the surface tension of Ni [7]. Hence a commercially available Ni-Cr-B braze Amdry 775 was used to rebuild the cast iron engine block. The process parameters used for this trail is shown in table-1. Following deposition the builds were sectioned and observed and the results are shown in figure-3 (a-c). The results show significant cracking in the deposit. The cracking in the deposits was attributed to the formation of Cr rich precipitates and the continuous network of eutectic formation [8]. The Cr rich boride phases are brittle and crack due to the solidification stresses induced during the rapid cooling [9-11]. Increasing the Ni content leads to crack deflection and bridging. In addition alloying the braze with Ni leads to a reduction in the weight fraction of borides and prevents the formation of a continuous network of eutectics [10, 12, 13].

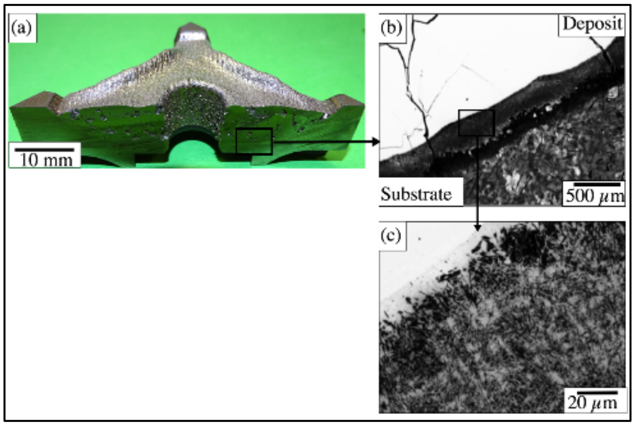


Figure 3 Shows the macro and micrographs of deposits fabricated using the Ni-Cr-B braze (a) Macrograph of the deposit showing significant cracking in the deposit zone (b) Micrograph showing the interface between the substrate and the deposit (c) Micrograph showing the interface between the

substrate and the deposit at higher magnification

Scheil calculations were performed to calculate the fraction eutectic and carbides for various compositions. The various compositions used are summed up in table-2

Table-2 Compositions used for Scheil solidification simulations to calculate the microstructure after solidification

	Trail-1	Trail-2	Trial-3	Trial-4	Trial-5	Trial-6	Trial-7
Ni	83.35	86.125	90.75	92.6	94.45	96.3	98.15
Cr	13.5	11.25	7.5	6.0	4.5	3.0	1.5
B	3.15	2.625	1.75	1.4	1.05	0.7	0.35

The Scheil solidification simulations are shown in figure-4 (a-c). The simulations show that with the addition of Ni the fraction of FCC increases while the borides and Ni_3B decrease. Due to the increase in the fraction of FCC-Ni and reduced Ni_3B phase it was hypothesized that such a solidified microstructure would experience an increased resistance to cracking [8, 9].

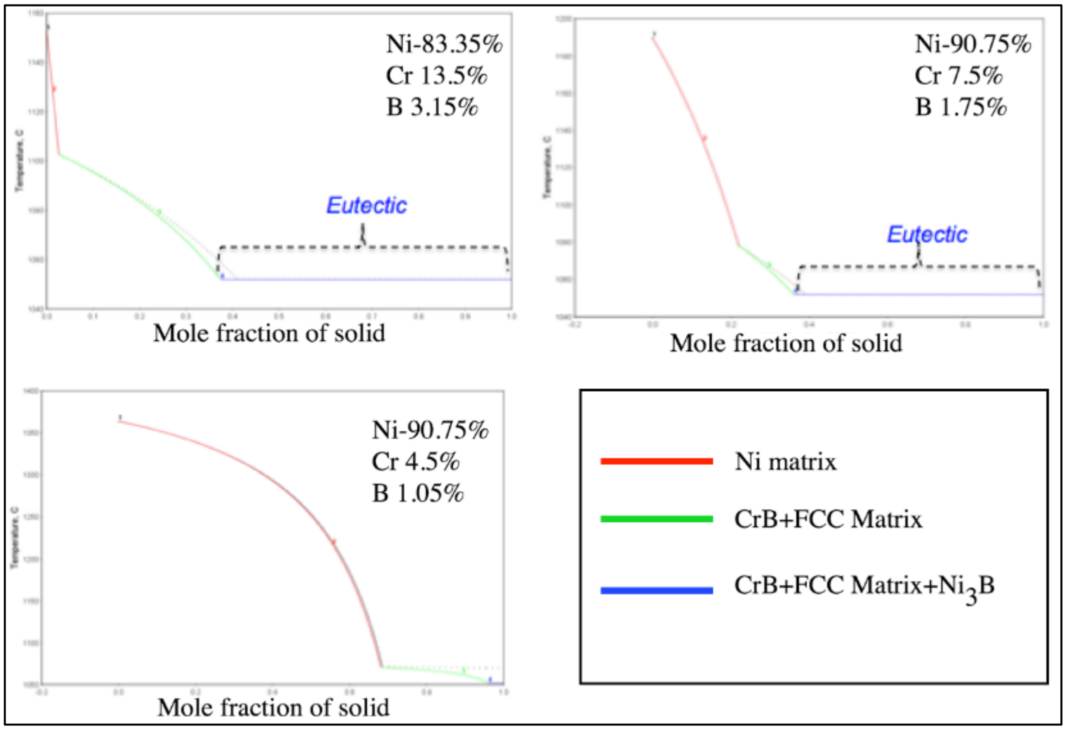


Figure 4 Shows the Scheil solidification simulations of optimized alloy compositions. The composition corresponding to (b) and (c) were ideal

Builds were fabricated corresponding to the compositions detailed shown in trial-3 and trial-7. The composition control was achieved by in situ alloying with Ni filler. The Ni reduced the volume fraction of the brittle phases while the addition of the braze to the Ni improved the wettability of Ni. The resulting micrographs are shown in figure-5. The figure shows that further addition of Ni reduced the cracking tendency of the builds with the 100% braze being highly susceptible to cracking and the other Ni rich compositions being the least susceptible. However it was not possible to eliminate cracking all together by only optimizing the composition. During the laser directed energy deposition the rapid cooling rates experienced by the build induces significant residual stresses in the builds resulting in the nucleation of the cracks in the boride and carbide phases.

1.2.4 Installation of the cartridge heaters:

In the previous section it was mentioned that the rapid cooling rates experienced during the fabrication of the builds resulted in significant residual stresses leading to cracking in the builds.

Hence to effectively decrease the cooling rate in the build a provision for pre heating the cast iron engine block was made. A major modification to the DMD-103D system was performed and a provision was made to utilize cartridge heaters to pre heat substrates to a temperature of 400-600°C. The cast iron engine block maintained the pre heat temperature of 450°C resulting in a decrease in the cooling rate. Figure-5 shows a detailed set up of the installation of the cartridge heaters.

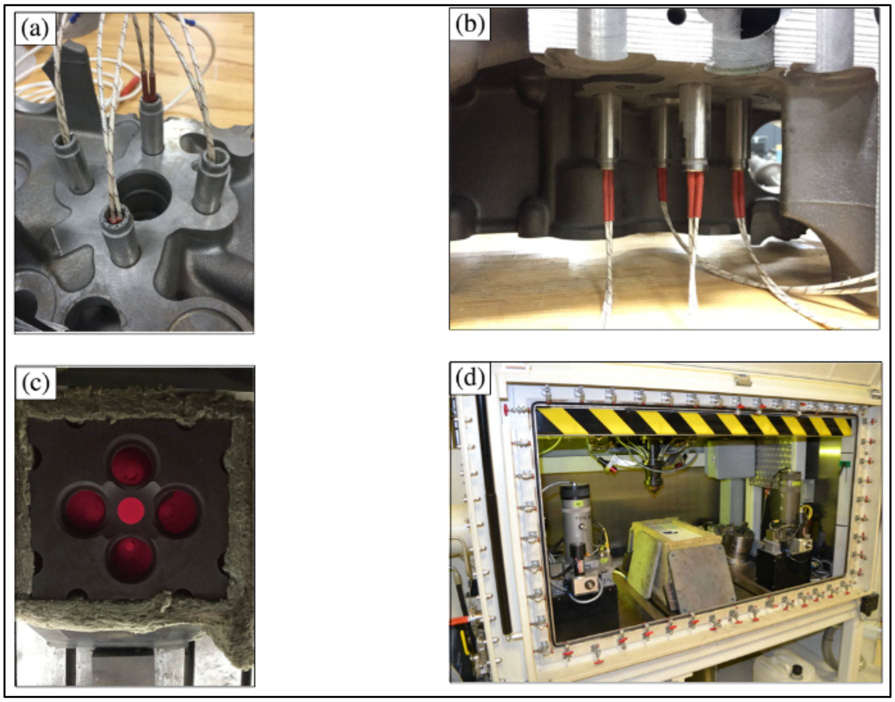


Fig 5 (a)-(b) Showing the cartridge heaters being positioned (c) Pre heated engine block at temperature (d) Installation of the pre heated engine block in the deposition chamber of the DMD-103D

A build with 50% Inconel-718 and 50% Ni and another build with 100% Inconel-718 were deposited using the two hopper system. The process parameters are listed in table-1. The deposits were then sectioned and inspected to evaluate cracking susceptibility. The results are shown in figure-6. The figure clearly shows that the deposits fabricated using 100% Inconel cracked extensively while the deposits fabricated with an increase in the Ni content in the Inconel showed a decrease in the cracking susceptibility. The cracks originate in the edge and propagate through the HAZ of the cast iron at a distance of 3-5 mm from the deposit. This demonstrates that the addition of Ni softens Inconel-718 thereby absorbing the residual stresses generated during the rapid cooling.

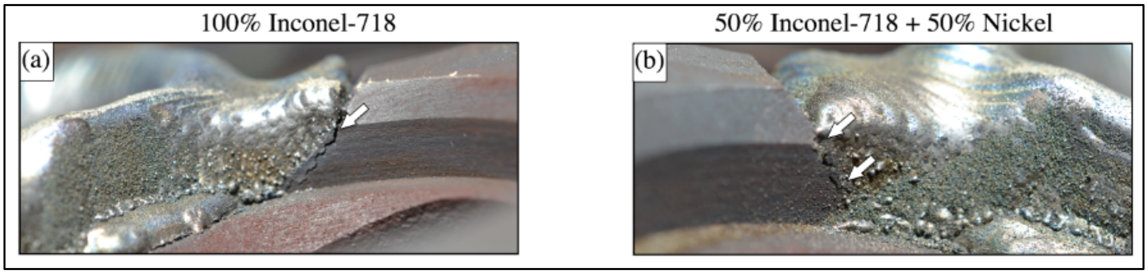


Fig 6 Images showing increased cracking susceptibility in the builds fabricated with (a) pure Inconel (b) Inconel alloyed with Ni.

The builds fabricated with Inconel alloyed with Ni showed a decreased tendency to crack and hence these builds were sectioned for metallography analysis and hardness testing. The results are shown in figure 7 (a-e). Optical microscopy shows that in all the builds the crack initiates along an edge shown in figure 7(a) and then propagates along the HAZ. However there are other regions in the build that aren't susceptible to cracking as shown in figure 7 (b-e).

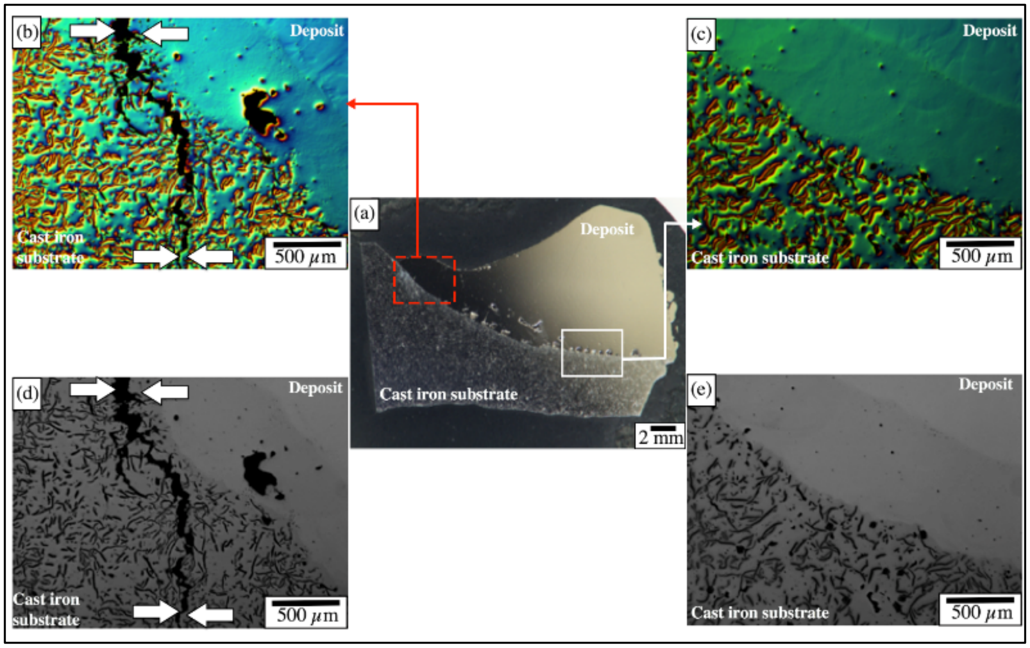


Fig 7 (a) Macrograph of the build the region in the red dashed line marks the regions susceptible to cracking and the white regions correspond to regions which are crack free (b) Polarized light microscope showing a high magnification optical micrograph showing the crack direction of crack propagation (c) Polarized light microscope of the region marked with the white line. Shows the interface and absence of cracks in the cast iron. (d-e) Light optical microscope image of the regions shown in figure (b) and (c)

The cracking could have occurred due to

1. Microstructural differences
2. Residual stress differences [3, 14]

To understand if microstructural heterogeneity contributed to cracking in the builds micro hardness testing and SEM was performed in the cracked and un-cracked regions and the results are shown. The results shown in figure 8 (a-d) show that there is no difference in the hardness and microstructure at the interface. In addition there is no increase in the hardness in the zone where cracks are present confirming that the cracking phenomena cannot be tied to martensite formation in the heat affected zone.

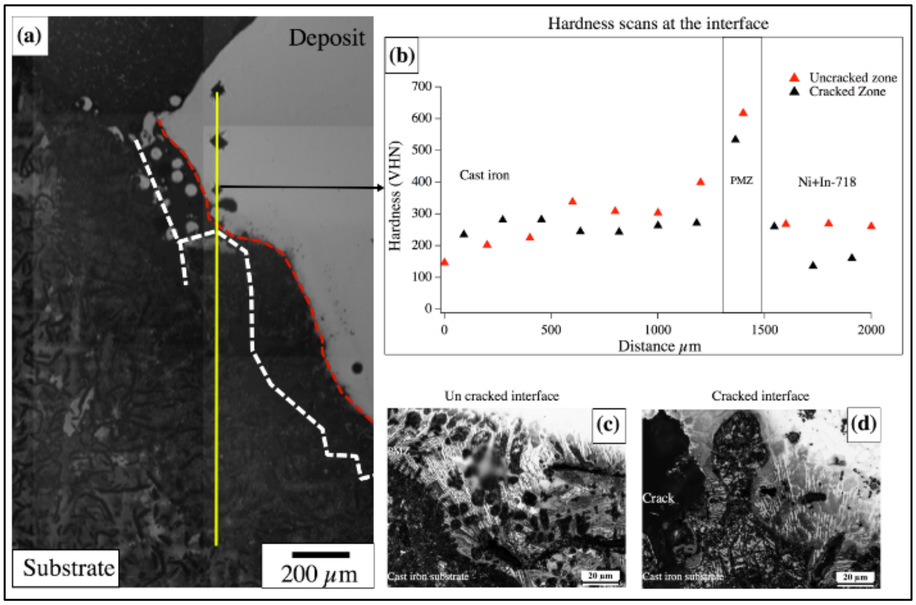


Figure 8 (a) Zone where the hardness testing was performed. The white dashed line marks the cracked zone while the red line marks the interface between the cast iron and the deposit (b) Hardness line scans performed along the yellow line shown in figure (a). No major difference in the hardness in the cracked and in the cracked zone (c) Microstructure of the build in the PMZ in the un cracked high hardness region showing the formation of Fe-Ni martensite (d) Microstructure of the build in the PMZ of the cracked high hardness region showing a similar microstructure.

These results imply that the microstructural heterogeneity in the builds do not contribute to the observed tendency for crack formation. Hence the primary reason for cracking to occur is the presence of residual stresses at the interface. As mentioned above the Phase-1 primarily showed that the DMD-103D directed energy deposition technique can be used for repair applications. A number of trial deposits were fabricated using a range of filler metals to identify the composition that provides good wetting and minimum cracking. Based on the results obtained in the phase-1 of this project the best possible way to obtain a crack free deposit would be to use Inconel-718 alloyed with Ni. The phase-2 for this work if awarded would aim to eliminate cracking by eliminating residual stresses in the part by optimizing the tool path.

1.3 IMPACT

This work has demonstrated the potential of using the laser powder blown DMD system to develop solutions for repair applications and add new features on existing part. Though the laser powder blown process has been used extensively to rebuild worn turbine blades the use of the technology for automotive applications and for difficult to weld materials, is novel. Remanufacturing of engine blocks would result in significant cost savings and also help in reducing the greenhouse gas emissions by 85%.

1.4 CONCLUSIONS

As stated in the background section, the Phase1 goal of the project was to evaluate the feasibility of using the directed energy deposition system for large volume deposition on cast iron engine blocks. To facilitate this objective feasibility studies were made initially using Inconel-718. The builds were fabricated without pre heat and severe cracking was observed in the heat-affected zone of the cast iron and in the Inconel-718 deposit. The cracking in the cast iron was hypothesized to be cold cracking due to martensite formation and shrinkage stresses. Hence to mitigate the stresses deposits were made using Ni powder. Due to the high surface tension of Ni the Ni did not wet the cast iron substrate. Hence deposits were fabricated by alloying Ni with Cr and B to increase the wettability of the Ni powder. However the Ni-Cr-B experienced severe cracking due to thermal stresses in the deposit. To mitigate the thermal residual stresses in the part the DMD system was modified to provide a provision to pre heat the engine block inside the furnace chamber to ~600^{o}C. Pre heated deposits were made using Inconel-718 and Inconel-718 alloyed with 50 wt.% Ni. The results showed that the Inconel alloyed with Ni showed the highest resistance to cracking. While the phase-1 has demonstrated that this technology is a viable technique to fabricate components for automotive applications there is still substantial research and development that needs to be done in terms of optimizing process parameters to mitigate defects and residual stresses in the deposition on cast iron engine block. This will be done in the phase-2 of this work if awarded.

2. PARTNER BACKGROUND

Cummins Inc is a global power leader that designs, manufactures, sells and services diesel and alternative fuel engines from 2.8 to 95 liters, diesel and alternative-fueled electrical generator sets from 2.5 to 3,500 kW, as well as related components and technology. Cummins Inc serves its customers through its network of 600 company-owned and independent distributor facilities and more than 7,200 dealer locations in over 190 countries and territories. The Engine Segment manufactures and markets a complete line of diesel and natural gas-powered engines for on-highway and off-highway use. Its markets include heavy- and medium-duty truck and bus, light-duty automotive and off-highway (ranging from 60 to 755 horsepower). The Engine Segment also provides a full range of new parts and services and remanufactured parts and engines through an extensive distribution network.

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