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MECHANICAL PROPERTIES AND MICROSTRUCTURE STUDY FOR DIRECT METAL DEPOSITION OF TITANIUM ALLOY AND TOOL STEEL

by

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A THESIS

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ABSTRACT

Direct metal deposition is a process capable of producing fully dense and net shape metal productions, and it could also be used on repairing various metal components in different engineering applications. For the fabrication and repair of components in difficult-to-machine materials such as titanium alloys and tool steels, this layer by layer additive manufacturing technique realizes significant decrease of material and machining costs. The first paper investigated the effect of surface treatments including aggressive milling and high pressure burnishing on DMD Ti-6Al-4V work pieces. The microstructure, micro-hardness and surface roughness were explored to verify the surface properties improvement and the possibility of creating a recrystallization layer near the surface. The second paper focused on characterizing DMD technique used as a repair process for die casting molds in H13 tool steel. It was compared with the most commonly used molds repair process, TIG (Tungsten Inert Gas) welding, in terms of microstructure, hardness and failure mode. Based on this paper, the desired uniform microstructure and properties are the main advantage of DMD repair process.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my advisor, Dr. Frank Liou, for his advice, guidance and encouragement during my master study at University of Missouri-Rolla. I am very grateful for the financial support he provided for my research and study.

I would also like to thank Dr. Joseph Newkirk for his ideas and suggestions in helping me complete the papers. I would also like to thank Dr. K. Chandrashekhara for serving as committee members and commenting on the thesis. I would also like to acknowledge Dr. Hai-Lung Tsai and Dr. Robert Landers for allowing me to work on their lab equipment.

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I would like to thank Jianzhong, Todd, Zhiqiang, Lan, Yu, Zhan, Anand, and all members in LAMP lab for offering discussions and assistance on various topics. They made my study and research experience in UMR interesting and memorable. I also want to express my appreciation to Bob Hribar and Max Vath for their help to my research.

Last but not least, I am very grateful to my parents who have supported and encouraged me unconditionally throughout my education.

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INTRODUCTION

This thesis is focused on the research about DMD (Direct Metal Deposition) which is an additive manufacturing process and used in various engineering applications such as producing fully dense and net shape productions in difficult-to-machine materials. In this study, the microstructure was analyzed through optical microscopy and some mechanical properties were tested with different equipments such as SEM (Scanning Electron Microscopy) and micro-hardness tester. The first paper investigated the effect of three surface treatments on enhancing mechanical properties for DMD parts. With the same analysis method, the second paper evaluated DMD technology as a repair process for die casting molds. In summary, this thesis validated that DMD process can be improved through surface treatments and is capable of repairing molds for die casting industry.

PAPER I

EFFECT OF MECHANICAL SURFACE TREATMENTS ON TI-6AL-4V DIRECT METAL DEPOSITION

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Abstract

The effect of surface treatments including aggressive milling, rotational burnishing and non-rotational burnishing on the Ti-6Al-4V DMD (Direct Metal Deposition) parts was investigated. Particular emphasis is devoted to the question of whether these surface treatments can induce the plastically deformed and work hardened layer which is proved to be able to enhance the fatigue resistance of titanium alloys and is a key step for recrystallization. Through the micro-hardness examination and microstructure analysis, it is found that the rotational burnishing process is able to work harden the material deeper than 1000μm, while the work hardened layer generated by non-rotational process is ~600μm and that for aggressive milling is less than 10μm. Since the surface finish is another critical factor for the resistance of fatigue crack initiation, it was also evaluated for these treatments.

Keywords: Ti-6Al-4V, direct metal deposition, surface treatment, recrystallization, fatigue strength, burnishing

1. Introduction

DMD (Direct Metal Deposition) process can be used to construct engineering components in titanium alloys, and realize time, labor and material savings over traditional processes. Due to the high strength and severe temperature rise at the toolchip interface, titanium alloys are very difficult to be machined with traditional processes such as lathe and milling. DMD is capable of producing net shape parts, so the machining volume is significantly decreased. It is well known that the mechanical properties of titanium alloys are very sensitive to the microstructure. The fully lamellar microstructure of Ti-6Al-4V generated with DMD process could be recrystallized to the bi-modal microstructure which possesses smaller α colony size and is beneficial for various mechanical properties including yield stress, ductility, crack nucleation resistance (HCF strength) and microcrack propagation resistance (determining the LCF strength together with the crack nucleation resistance) [1]. Thus, recrystallization is an important process in improving the mechanical properties for DMD work pieces. Moreover, surface treatments such as rolling and shot peening are proved to be effective for increasing the resistance to the initiation and propagation of fatigue cracks, and thus enhancing the fatigue strength of components used in a variety of engineering applications [2,3]. In this work, three surface treatments including aggressive milling and two types of burnishing were implemented on the deposited work pieces in order to improve surface mechanical properties and demonstrate the possibility of recrystallizing the near surface layer. The micro-hardness and surface roughness of the samples under different treatments were evaluated. The microstructure was examined with optical microscopy.

2. Experimental Procedures

2.1 Materials

Commercially pure titanium transfers from the close-packed hexagonal structure (α phase) to the body-centered cubic structure (β phase) at 882.5°C. Alloying elements change the α to β transformation temperature, and thus may produce α, α + β and β equilibrium phases. In this way, titanium alloys can be broadly classified as α, α + β and β alloys [4]. The material used for this study, Ti-6Al-4V, is a α + β alloy.

Both the substrate materials and the powder used for DMD were provided by the Boeing Company. The actual composition of Ti-6Al-4V is listed in Table 1. Figure 1 is a micrograph of as received substrate material, and it shows the bi-modal structure of globular α grains and the equiaxed lamellar α + β structure.

Table 1. Chemical composition of Ti-6Al-4V

Element	Ti	Al	V	Fe	O	N	H
Wt.%	Balance	6.27	4.19	0.20	0.18	0.012	0.0041

2.2 Direct Metal Deposition

The DMD system mainly consists of a 5-axis CNC machining center, 1.0 KW Diode laser, the powder feeder system from Bay State Surface Technologies Inc, and the real–time control system from National Instruments. The titanium powder is injected into the focal point of the laser beam and melted by the laser power to generate the deposition. Meanwhile, the substrate moves in x and y direction to form the desired cross-sectional deposition shape which is pre-planned by decomposing the 3D CAD model. After one layer of deposition, the laser and powder feeder system which are fixed on Z axis of CNC are raised and then start to deposit the next layer. Layer by layer, this additive process is able to produce net shape titanium parts and save on material and machining costs notably.

The microstructure of the deposition mainly exhibits the basketweave Widmanstätten α morphology (shown in Figure 2) and colony Widmanstätten α morphology (shown in Figure 3). The lamellar HCP α phase is outlined in the retained BCC β phase (dark). Moreover, the continuous α phase (also shown in Figure 3) grows along with the prior β grain if the cooling rate is low enough [5].

2.3 Surface Treatments

In order to improve the surface mechanical properties of the work piece produced with DMD system, three types of surface treatments are implemented in this study. It is known that with the recrystallized finer bi-modal microstructure several mechanical properties including the yield stress, the ductility, the HCF strength and LCF strength are improved [1]. Recrystallization can be completed through two steps, (1) inducing plastic deformation to create deformed grains containing tangled dislocations, (2) heat treating the material at its recrystallization temperature [6,7]. This paper is focused on creating the plastic deformation layer near the surface and evaluating its function.

2.3.1 Aggressive milling

The milling process was carried out on a Fadal VMC3016L CNC with more aggressive parameters than those commonly used to machine titanium alloys. The cutting speed was separately set to 0.025, 0.05, 0.075 and 0.1 mm/tooth and the depth of cut was kept constant at 2.5mm. The coupons were cut with a wire-EDM and Knoop micro-hardness was tested on the cross section. As the work hardened layer was too thin to be revealed by the cross-sectional evaluation, the thickness of work hardened layer was estimated through Vickers micro-hardness test with different loads. Figure 4 schematically shows the working principle of this estimation. With lower load, the indenter cannot penetrate the work hardened layer, so the results recorded are the hardness of the hardened layer. With higher load, the results are from both the work hardened layer and the substrate, so the hardness recorded is lower. By checking when the hardness is remarkably reduced, the work hardened layer thickness can be estimated through the indentation depth which derives from equation (1).

$$IndentationDepth = \frac{L}{7} \qquad \text{Eq. (1)}$$

Where L is the mean diagonal of the indentation.

2.3.2 High pressure burnishing

The burnishing process was carried out on the same CNC with a tool setup shown as Figure 5. A bearing ball, the roller, was fixed to the tool holder through a thrust bearing. It should be noted that because the surface was too rough to be burnished, the deposited parts were machined with mild parameters (0.0125mm/tooth cutting speed, 0.25mm depth of cut) first. The burnishing pressure was set to 3, 5, 7 and 9KN and monitored by a Kistler table-type 3-component piezoelectric dynamometer. Considering that the burnishing track width is ~1.5mm, the stress put on the surface exceeds the yield strength of Ti-6Al-4V (815MPa). One group of work pieces were burnished with the tool rotating at 50rpm, the other group was burnished without tool rotation. The micro-hardness and surface finish were also investigated.

2.4 Sample Preparation and Evaluation

In order to evaluate the change of surface properties from the cross-section, work pieces were cut into small samples and mounted in epoxy thermosetting material. The scratch-free and mirror-like surface is required by the subsequent microscopy observation and Knoop micro-hardness test, so samples were grinded and polished on LECO Spectrum1000 automatic polisher.

To reveal the microstructure, the samples were etched for 8s by the reagent composed of 5 parts HNO_3, 10 parts HF and 85 parts of H_2O. The micro-hardness was examined with LECO MHT200. The displacement increment of this equipment is 25um. To make the indentations concentrated in a small surface area, 50g load was selected. Surface Finish was evaluated with Mitutoyo Surftest-212.

2.5 Data Analysis for Micro-hardness Test

Knoop Hardness is calculated by equation (2).

$$KHN = f(P,L) = \frac{P}{C_p L^2} \qquad \text{Eq. (2)}$$

Where:

P – load (kgf)

C_p – correction factor related to the shape of indenter, ideally 0.070279

L – length of indentation along its axis (mm)

The measurement uncertainty is given by equation (3).

$$e_M = \sqrt{\left[\frac{\partial f(P,L)}{\partial L}\Delta L\right]^2 + \left[\frac{\partial f(P,L)}{\partial P}\Delta P\right]^2} \qquad \text{Eq. (3)}$$

Where:

ΔL – measurement error of the indentation length (0.5um [8])

ΔP – manufacturing error of the micro-hardness test machine load (0.00075g)

To draw the whole uncertainty for the micro-hardness test, the standard deviation σ derived from different measurements is combined with the measurement uncertainty by equation (4).

$$E = \sqrt{(\sigma)^2 + (e_M)^2} \qquad \text{Eq. (4)}$$

3. Results and Discussions

3.1 Aggressive Milling

Examined with different loads, the Vickers micro-hardness of the milled surface is listed in Table 2. Deeper work hardening effect was made at higher cutting speed: the sample cut with 0.1mm/tooth has a work hardened layer of about 6μm thick, the hardening layer of sample cut with 0.025mm/tooth is less than 3μm, the hardening layer of the other two are about 4μm thick. The cross-sectional micrograph confirmed this estimated result: Figure 6 showed that a plastically deformed layer less than 10μm was formed underneath the milled surface. This kind of bended grains were observed beneath the whole milled surface. The Knoop micro-hardness test results on the cross section were plotted as Figure 7.

Table 2. Estimation of work hardened layer thickness with micro-hardness test

(Original deposition hardness: 403±24.8)

Cutting Speed	VHN100	VHN200	VHN300	VHN400
0.025mm/tooth	415±18.9	410±22.6	408±30.4	405±27.9
0.050mm/tooth	428±25.9	423±40.7	412±19.8	407±28.3
0.075mm/tooth	430±33.5	424±31.7	413±21.2	409±32.1
0.100mm/tooth	431±27.2	426±32.5	417±33.8	410±35.6
Indentation Depth	3μm	4μm	5μm	6μm

Limited by the size of indentation, the micro-hardness of the work hardened layer cannot be examined from this direction. Moreover, the fact can be found that the hardness of the subsurface within 50μm below the milled surface was lower than that of base material. This softening effect was probably due to the recovery of the material as a result of high milling temperature produced and retained at this layer. From this plot, no significant work hardened layer was observed. Therefore, the deepest work hardening effect the aggressive milling can achieve on DMD part is less than 10μm.

3.2 High Pressure Burnishing

Figure 8 shows plots of the micro-hardness for the samples burnished without roller's rotation. With the higher burnishing pressure, not only the higher hardness value was recorded, but the thickness of hardened layer markedly increased as well. In other words, the greatest work hardening was found to take place on the sample rolled under 9KN pressure. The highest hardness value (KHN165) was recorded at 250μm beneath the surface and the hardened layer thickness is around 600μm. On the other hand, the hardened layer thickness of the sample rolled under 3KN is around 140μm and the highest hardness value (KHN144) was recorded at 125μm beneath the surface. Figure 9 shows the disturbed microstructure from the center of the burnishing track, and Figure 10 is the micrograph of unaffected zone. It is observed that the disturbance of microstructure was gradually reduced from the center to the edge of the affected zone. The softening effect within the 25μm beneath the surface can also be explained by the recovery as a result of the heat caused by the friction between the tool and the work piece.

The micro-hardness for the rotationally burnished samples is shown in Figure 11. Similarly, the highest hardness recorded and the thickness of hardened layer increase with the burnishing pressure. Compared to the former experiment, this burnishing process is able to reach higher hardness and form thicker work hardened layer. The highest hardness value recorded is KHN180. Except for the one rolled under 3KN pressure, samples were work hardened deeper than 1000μm beneath the surface. Figure 12 shows the microstructure from the deformed zone. In comparison with Figure 9, it depicts that the microstructure was severely disturbed by the burnishing process. The original lamellar α phase cannot be observed from the center of the affected zone and gradually appeared on the edge of this zone.

In summary, the plastic deformation was created on the work piece surface with the burnishing process, so the recrystallized layer can be formed with proper subsequent heat treatment. Furthermore, the near surface work hardened layer (~500-1000μm thickness) has beneficial effect on the fatigue life of Ti-6Al-4V at both ambient temperature and elevated temperature (450˚C) due to its effect of reducing the plastic strain amplitude and thus lessening the driving force for fatigue damage [9]. Therefore, these burnishing processes are capable of improving the fatigue strength of DMD parts effectively.

3.3 Surface Roughness

Surface roughness was measured before and after these surface treatments. The results for aggressively milled samples were listed in Table 3. It is clear to see that the higher the cutting speed is, the higher the surface roughness is. The highest cutting speed (0.1mm/tooth) led to an increase of measured surface roughness by more than 50%. However, the surface is still much finer than the deposited surface. The surfaces of burnished samples were compared with the originally machined surface in Figure 13. While the rotational burnishing made the surface coarser, the non-rotational burnishing made the surface finer than the mildly milled surface. It is well known that the lower surface roughness improves the fatigue strength due to the lower chance of fatigue crack initiation [10,11]. Therefore, in terms of surface finish issue, the non-rotational burnishing process improved the fatigue life further and even the aggressive milling can help to some extent.

Table 3. Surface roughness of aggressively milled samples

Samples	0.025mm/tooth	0.050mm/tooth	0.075mm/tooth	0.100mm/tooth	Original
R_z (μm)	0.49	0.64	0.72	0.98	0.40

4. Conclusions and Future Work

The enhanced fatigue resistance at ambient and elevated temperature was found to be associated with the near surface work hardened layer [9], so the three surface treatments including aggressive milling, non-rotational burnishing and rotational burnishing are able to improve the fatigue life as a result of inducing work hardened layer to the work piece surface. The rotational burnishing induced the highest degree of work hardening, and the depth influenced is more than 1000μm. The work hardening thickness of non-rotational burnishing is about 600μm, and that of aggressive milling is less than 10μm. On the other hand, compared to the other two processes, the non-rotational burnishing led to a finer surface finish which is another factor of increasing the fatigue resistance. The advantage of aggressive milling is that it doesn't require any pre-processes, whereas the work pieces need to be machined before the burnishing processes. Fatigue tests will be implemented to investigate the specific effect of fatigue strength improvement induced by these three surface treatments. All these surface treatments result in plastic deformation that is the first key step for recrystallization, and the work pieces will be heat treated at the recrystallization temperature to verify that the layer with refined bi-modal microstructure could be created.

5. Acknowledgements

This research was supported by the National Science Foundation Grant Number DMI-9871185, the grant from the U.S. Air Force Research Laboratory contract # FA8650-04-C-5704, and UMR Intelligent Systems Center. Their support is greatly appreciated.

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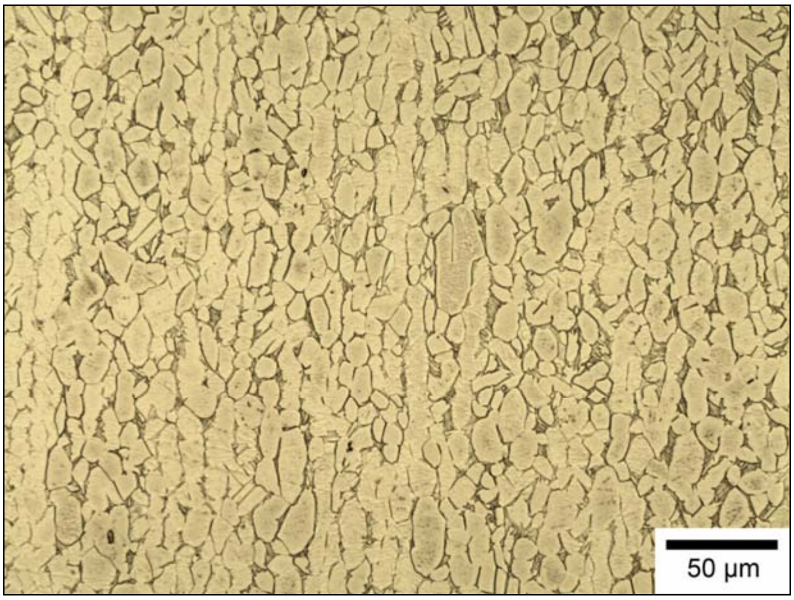

Figure 1. Bi-modal microstructure of the substrate

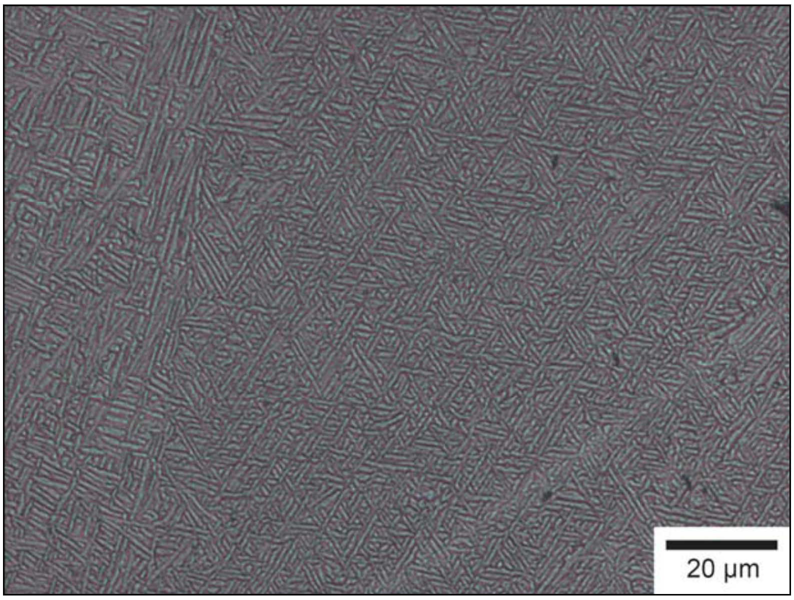

Figure 2. Basketweave α grains of the deposition

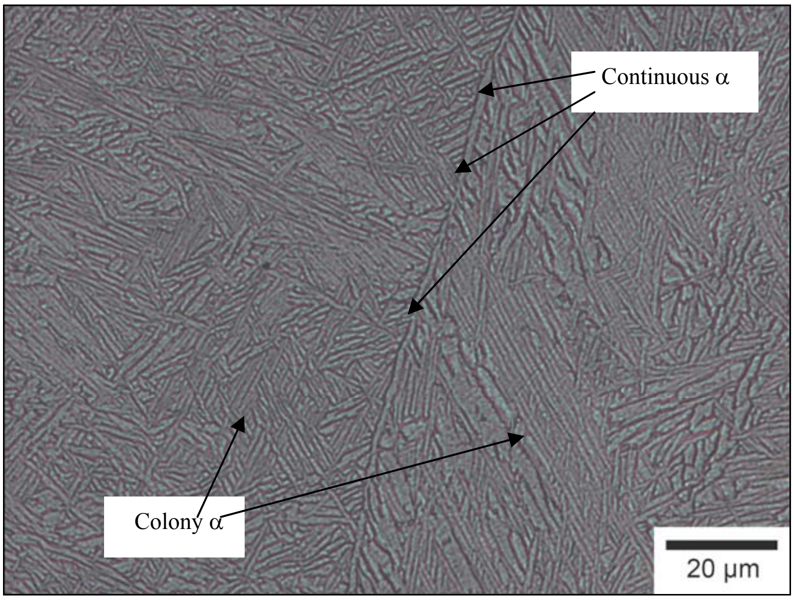

Figure 3. Colony and continuous α grains of the deposition

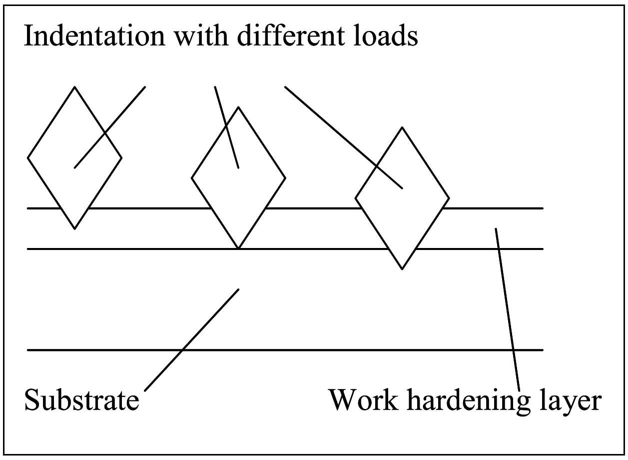

Figure 4. Scheme of the work hardened layer thickness estimation

Figure 5. Burnishing tool setup

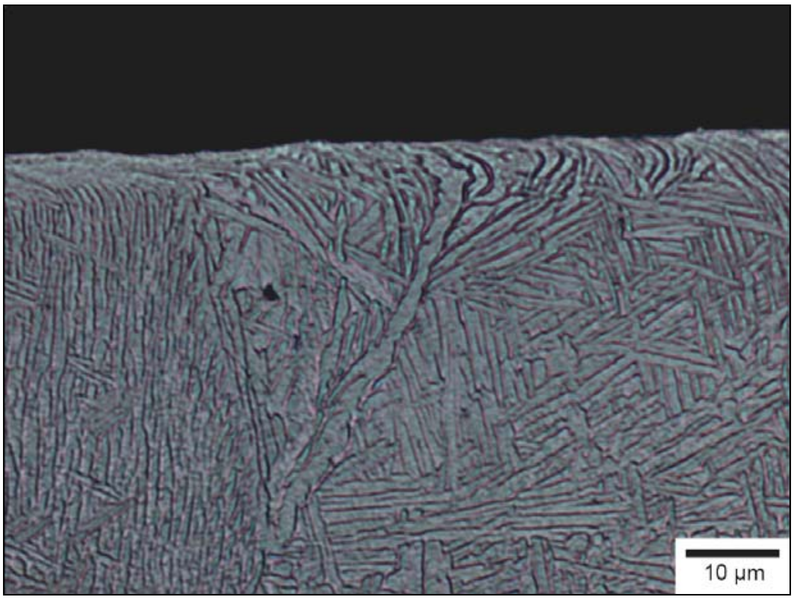

Figure 6. Micrograph of milled surface cutting at 0.004in/tooth

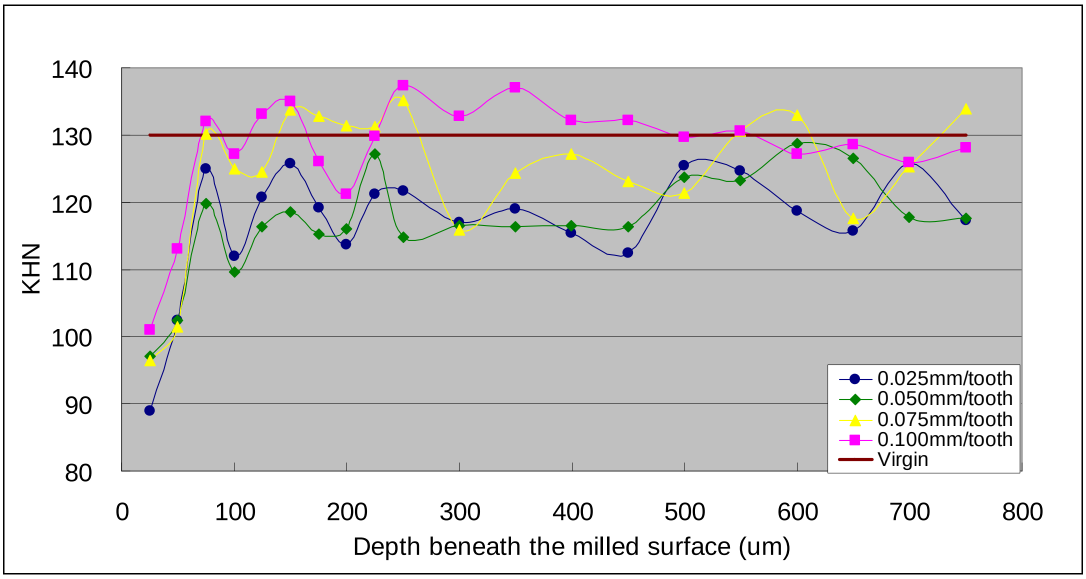

Figure 7. Micro-hardness values beneath aggressively milled surface

(Uncertainty 8.3~13.8)

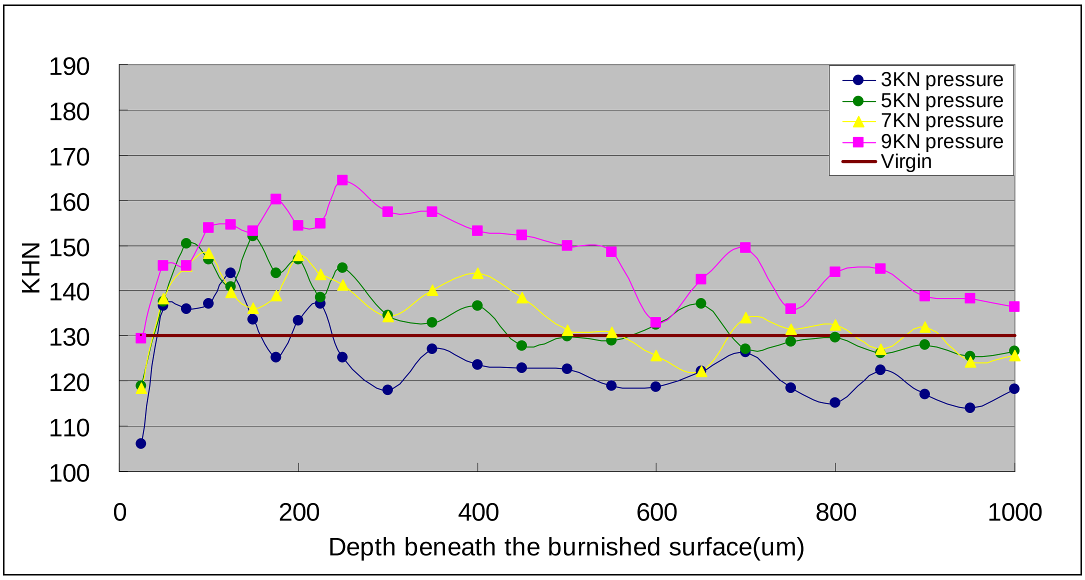

Figure 8. Micro-hardness values beneath non-rotationally burnished surface

(Uncertainty 7.4~15.1)

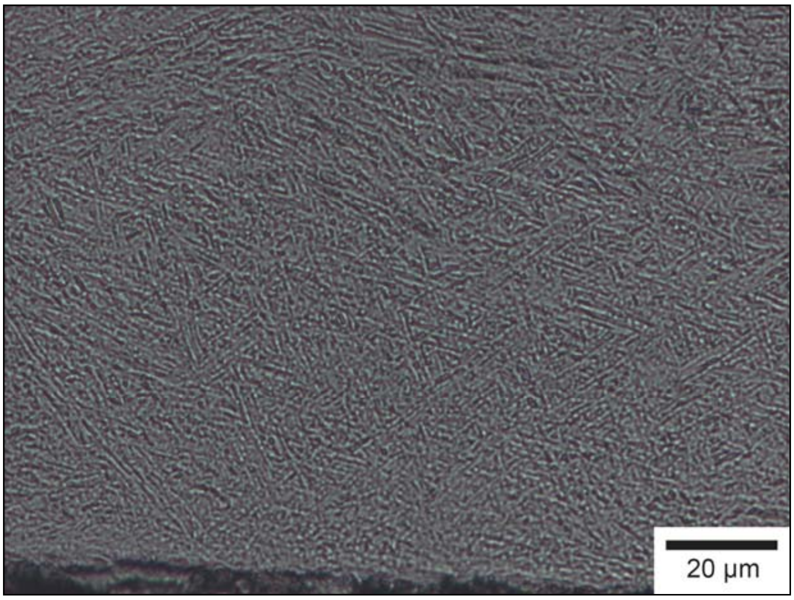

Figure 9. Micrograph of the surface non-rotationally burnished under 9KN pressure

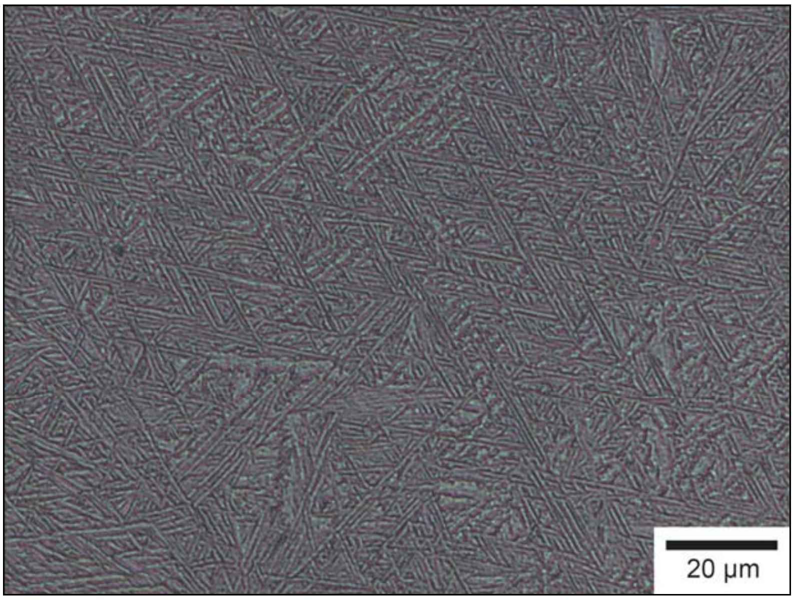

Figure 10. Lamellar α+β microstructure from the unaffected zone of burnished samples

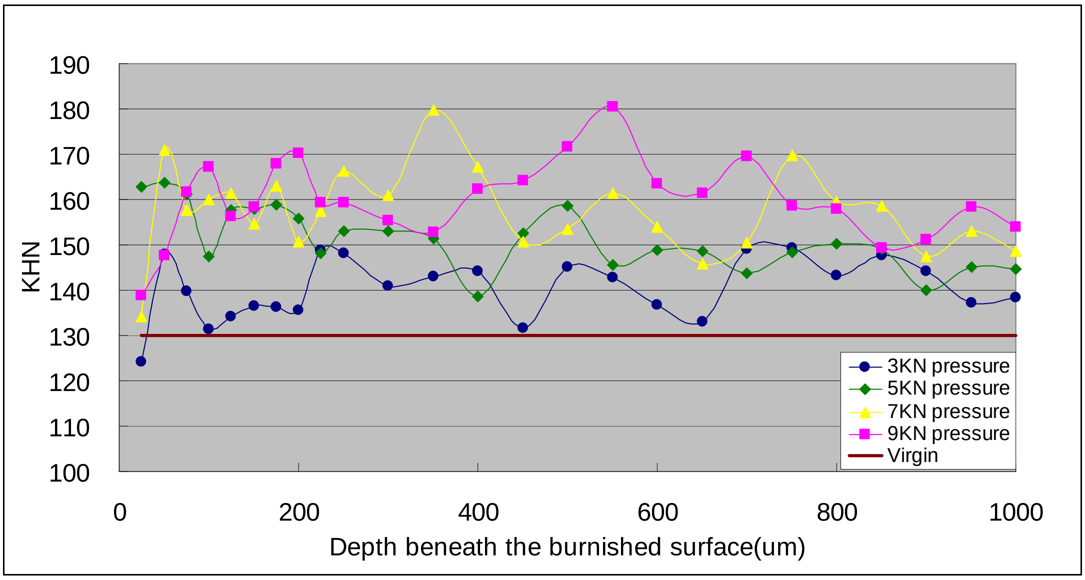

Figure 11. Micro-hardness values beneath rotationally burnished surface (Uncertainty 8.2~14.8)

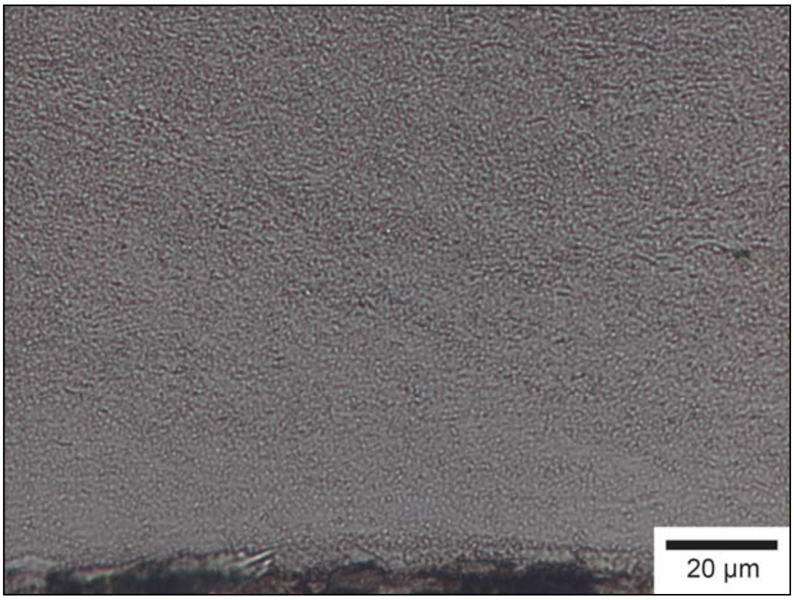

Figure 12. Micrograph of the surface rotationally burnished under 9KN pressure

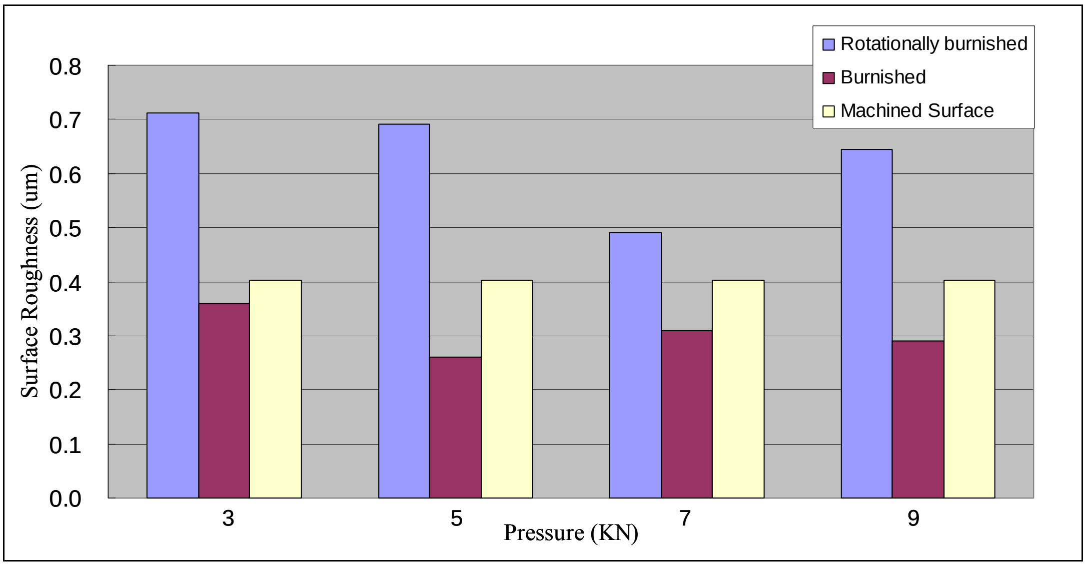

Figure 13. Surface roughness of burnished samples

PAPER II

EVALUATION OF MECHANICAL PROPERTIES AND MICROSTRUCTURE FOR LASER DEPOSITION PROCESS AND WELDING PROCESS

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Abstract

Laser Aided Manufacturing Process (LAMP) can be applied to repair steel die/molds which are currently repaired using traditional welding process in industry. In order to fully understand the advantages of laser deposition repair process over traditional welded-repair process, the mechanical properties such as tensile strength and hardness of H13 tool steel samples produced by these two processes were investigated. The microstructure and fracture surface of the samples were analyzed using optical microscope and SEM (Scanning Electron Microscope). Moreover, depositions on substrates with different shapes were studied to evaluate the performance of LAMP on damaged parts with complicated geometric shape.

Keywords: Laser deposition, Microstructure, H13 tool steel, Repair

1. Introduction

A laser-based die repair system [1] is being developed in the Laser Aided Manufacturing Process (LAMP) lab of University of Missouri-Rolla. For die casting, the primary failure mechanism of steel molds is abrasive wear [2]. If a repaired die can provide a similar life to a new one, then it is much more cost-effective to repair it than manufacturing a new die. Currently, the most common used repair process in industry is fusion welding. However, welding has some significant disadvantages, such as the randomicity of manual process which affects the reliability and quality of the repair very much. On the other hand, the LAMP system automatically complete the repair process with the hybrid laser metal deposition and machining process, and thus, the performance of the repaired part is reliable.

This paper concentrates on characterizing laser deposition process compared to the TIG welding. The same substrates were separated into two groups, one group was TIG welded, the other laser deposited. Tensile tests and hardness tests [3] were performed. A fracture analysis and microstructure comparisons were conducted on the samples after mechanical testing. Due to the faster cooling rate, the average hardness of deposited samples is higher than that of welded samples. The fracture surface analysis shows that the deposited samples retain some ductility, indicating that the hardness can be improved via heat treatment.

Moreover, in order to test this hybrid system’s ability of repairing on the uneven surface, substrates with different height steps were machined with a wire EDM. After deposited on these substrates, samples were sectioned and polished to check if there is any defect and map out the type and position of defects.

2. Material and Experiment

2.1 Material

All the substrate material, the powder for deposition and the filler for TIG welding are H13 tool steel, which is a common used material for the die/molds in industry. Table 1 shows the nominal composition of H13 tool steel.

Table 1. The main composition of H13 tool steel

Element	C	Cr	V	Mo	Si	Mn	Ni	Fe
Composition (%)	0.4	5.2	1	1.5	1	0.4	0.3	Balance

2.2 Laser-based Repair System Framework

The LAMP system mainly consists of a 5-axis CNC machining center, a 1.0 KW Diode laser, a powder feeder system from Bay State Surface Technologies Inc, and a real–time control system from National Instruments. During the depositing, the substrate is fixed on the fixture of the 5-axis CNC. The nozzle through which the laser and metal powder is transmitted is mounted on a vertical linear axis fixed to z-axis of the CNC. The laser is focused on a small area of the substrate and create a melting pool, and the metal powder is delivered by the powder feeder system into the melting pool to create the deposition. The x, y and z table positions and velocities are regulated via the CNC machining center controller according to the program generated from the CAD model [4]. This hybrid repair system employs 5-axis positioning system which includes of 3 linear axis and 2 rotating axis. The advantage of it over conventional 3-axis positioning system is that it does not require the support material to build overhang features for 3D parts and allows both the deposition and machining in a single set-up for a part even with intricate or hidden features.

2.3 Experimental Procedure

The procedure for the comparison between these two processes is outlined below.

1) H13 tool steel was deposited on 18mm cube substrates to 36mm height with the hybrid repair process. The parameters for the process are listed in Table 2. The size of the samples was decided by tensile test procedure.

Table 2. Parameters of hybrid repair process

Laser Power	Thickness per Deposition Layer	Nozzle Travel Speed	Powder Feed Rate	Heat Treatment
700W	0.5mm	381 mm/min	12 g/min	no

2) H13 tool steel was deposited on the same substrates to the same height with the TIG welding process. This process was completed by Spartan Light Metals Inc. The only difference between procedure used in this project and normal practice is the height of the welding is higher than that used in practice. There is no heat treatment for these samples.
3) The samples were cut into tensile "dog bone" shapes with a wire EDM.
4) The tensile test was performed on an Instron 4469 UTM (Universal Testing Machine).
5) The hardness was measured with reference to position within the deposition/welding.
6) The fracture surface was observed with Scanning Electron Microscope (SEM).
7) The samples were polished, etched with 2% atal, and then observed for the microstructure with optical microscope.

The procedure for the study about substrates with steps is outlined below.

1) The substrates were cut with wire EDM. And the steps are 0.01mm, 0.05mm, and 0.1mm.
2) H13 tool steel was deposited on these substrates with the same parameters listed in Table 2.
3) The samples were cut through to show the area of step.
4) The samples were polished, etched with 2% atal, observed for the microstructure.

3. Results and Discussions

3.1 Fracture Surface Analysis

Figure 1 is a SEM image of the fracture surface of a specimen which was laser deposited. And figure 2 shows the fracture surface of welding sample. These images were acquired on a Hitachi S570 SEM under the following conditions: Magnification 40X, Accelerating Voltage 30KV, Working Distance 20mm, Spot Size 4 [5].

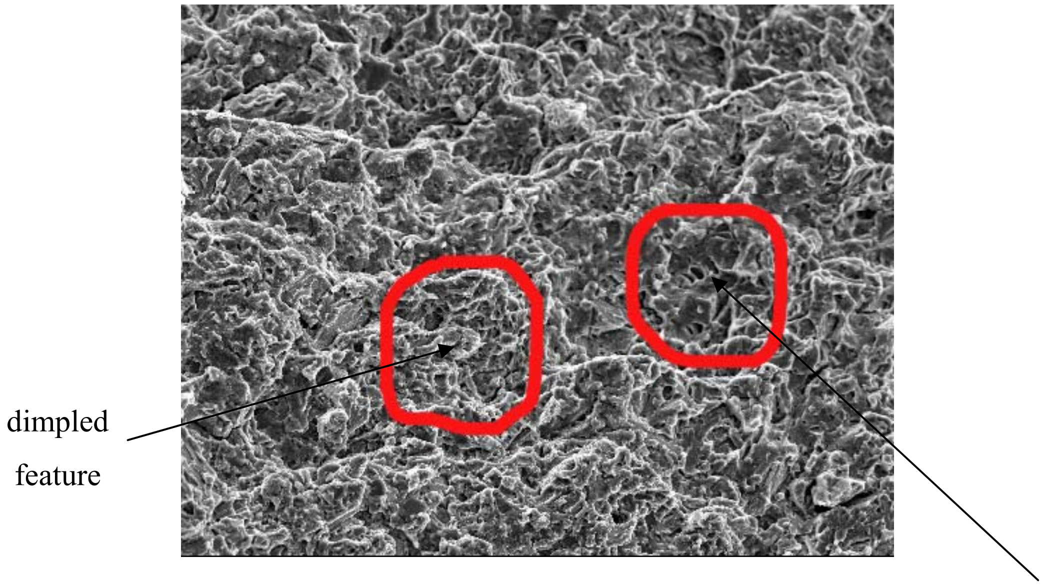

Figure 1. Fracture surface of laser deposition sample (300X)

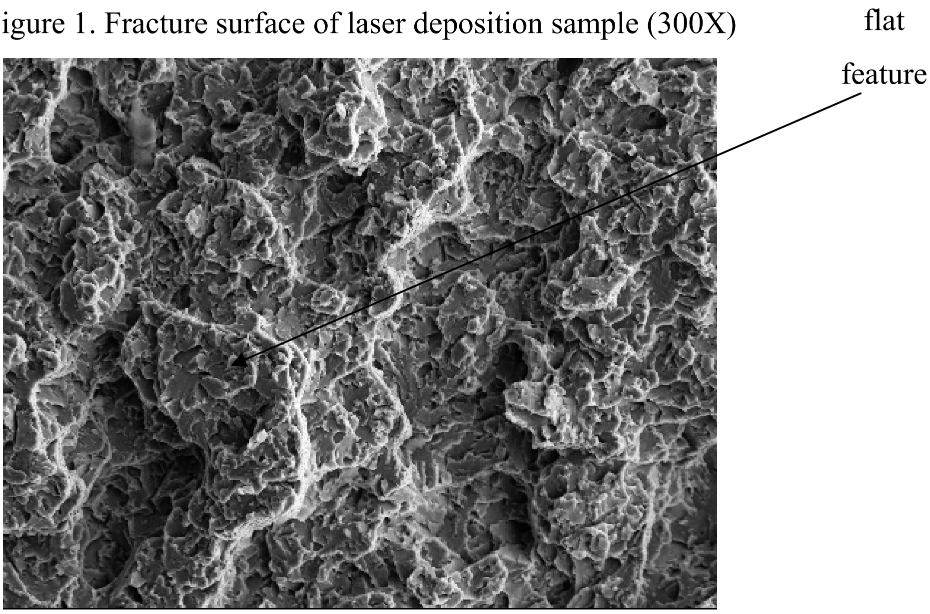

Figure 2. Fracture surface of welding sample (300X)

From Figure 1, it can be observed that there are both dimpled features and flat features on the fracture surface of laser deposition sample. Figure 2 shows only flat features for the welding sample. The dimpled features represent ductile fracture, while flat features represent brittle fracture [6]. Therefore, these two images indicate that the laser deposition sample still has some ductility and its hardness can be improved through heat treatment, while the welding sample has little ductility.

3.2 Microstructure Comparison

Figure 3 shows the microstructure of laser deposition sample. The microstructure changes gradually from equiaxed structure to dendritic structure over the first four layers and becomes constant with all of the following layers which are showed as one image because all of them are the same.

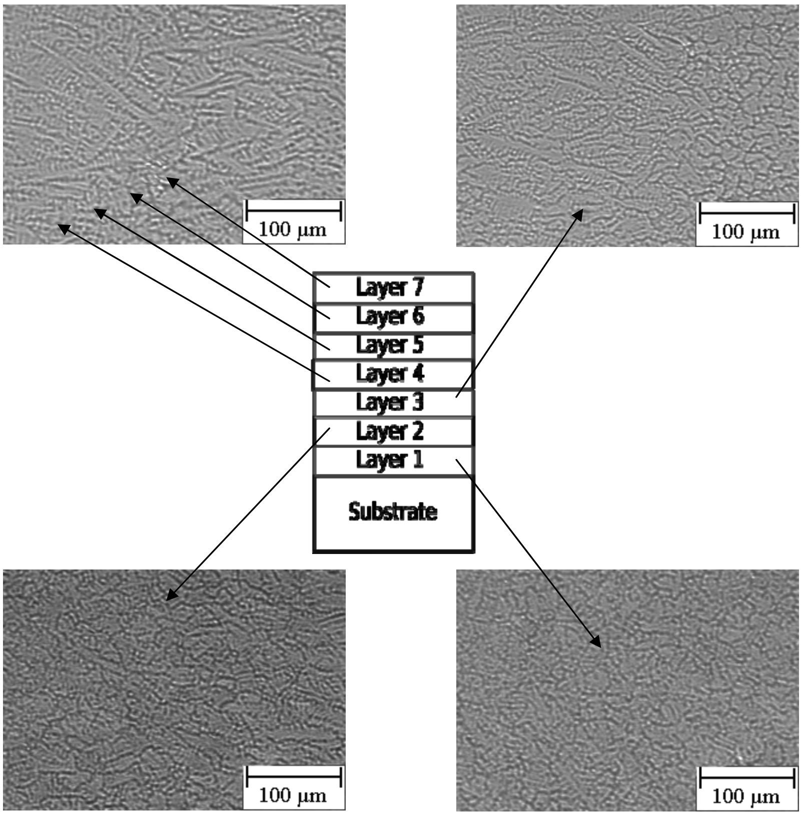

Figure 3. The microstructure sketch of laser deposition sample

Moreover, the microstructure is very uniform across the width of the substrate. Because the microstructure is related with mechanical properties of samples, this uniform microstructure is desirable for reliability and performance in production situations [7].

Figure 4 shows the microstructure of welding sample. The first layer is a regular columnar structure across the width of the substrate, but the microstructure changes rapidly with depth. And later layers become non-uniform across the width and change significantly with positions.

This non-uniform microstructure is caused by different cooling rate at different areas. The nature of the manual arc welding process induces some randomness into the weld. This makes the reproducibility and performance of the repair unsatisfactory.

3.3 Comparison between Deposition on Substrates with Different Steps

Figure 5 shows the interfacial area of the sample deposited on the substrate with 0.1mm step. The dark area is the substrate, and the grey area is the deposition. The big crack between deposition and substrate clearly indicates that these two sections were not bonded well and this is a failure deposition.

In the same way, figure 6 and figure 7 show the interfacial area of the sample deposited on the substrate with 0.05mm and 0.01 steps, respectively. The crack observed from figure 6 elucidates the deposition on this type of substrate is still not success, while figure 7 shows that the step is melted away and there is no defect found from the bonding.

It can be concluded that this hybrid repair system is able to successfully deposit on the uneven substrate whose height difference is smaller than 0.01mm. With the substrate whose height difference is bigger than 0.05mm, the tool track and deposit parameters need to be adjusted to make a good deposition. Some more works are needed to explore deposit ability on the substrates with step height from 0.01mm to 0.05mm.

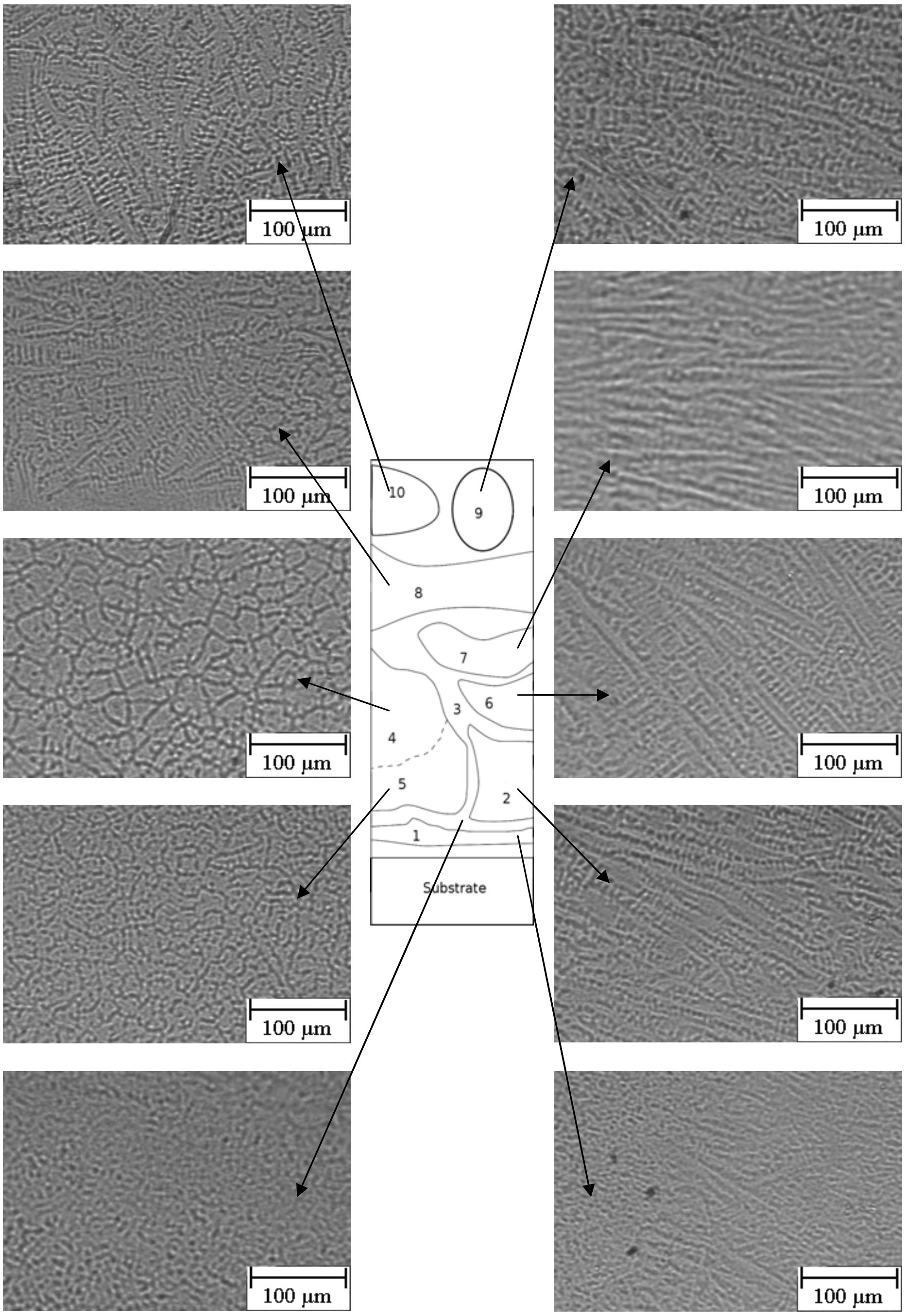

Figure 4. The microstructure sketch of welding sample

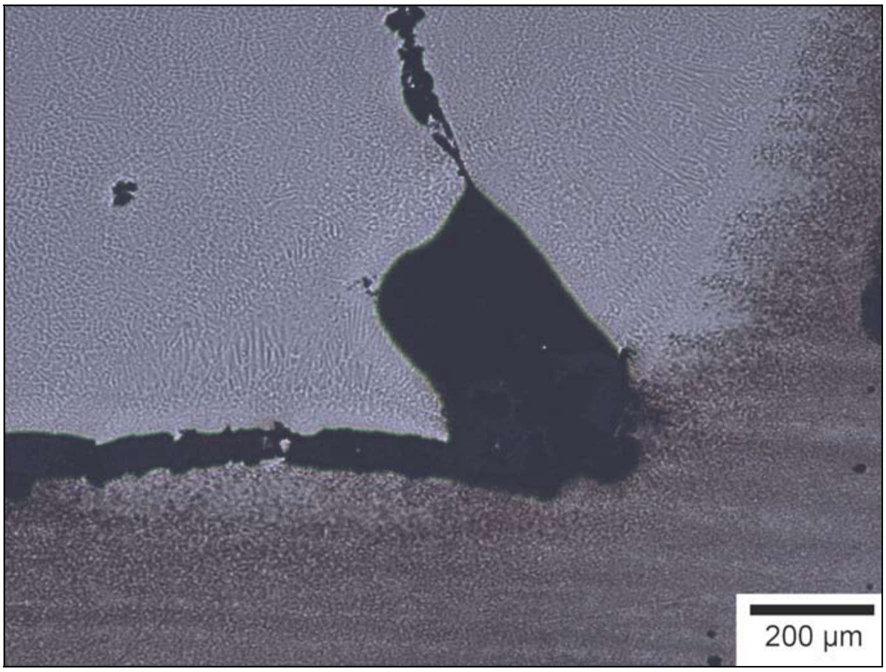

Figure 5. Sample deposited on the substrate with 0.1mm step

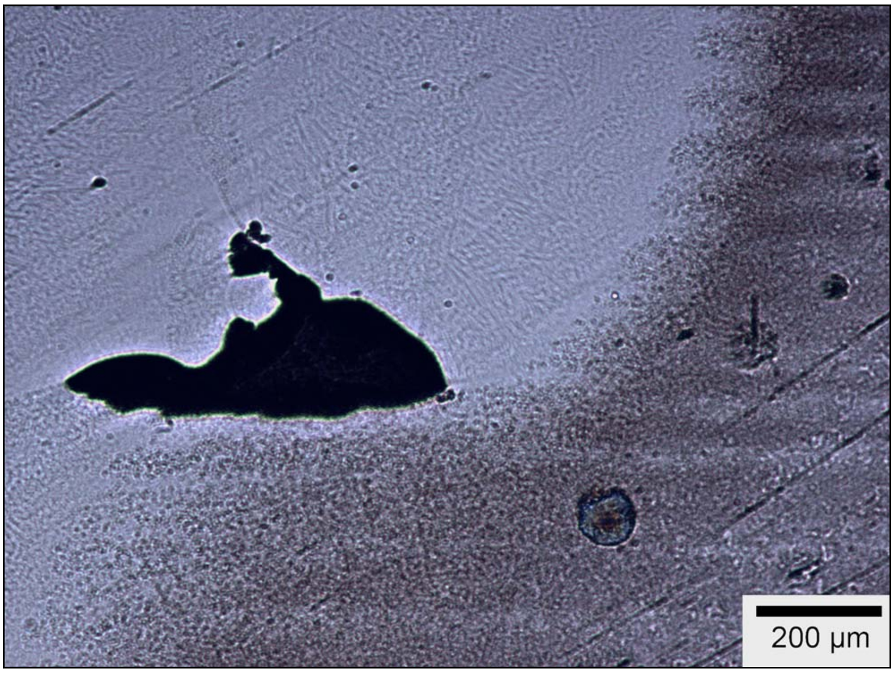

Figure 6. Sample deposited on the substrate with 0.05mm step

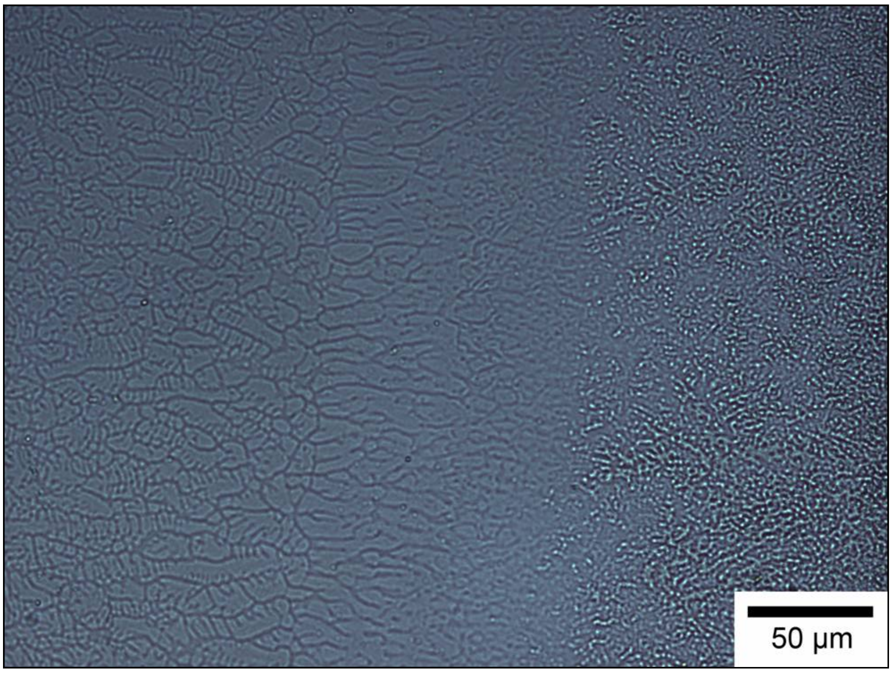

Figure 7. Sample deposited on the substrate with 0.01mm step

3.4 Hardness and Tensile Strength

The Rockwell C-Scale hardness was measured for deposition and welding samples. In addition, because of the different cooling rate, the hardness changes with depth. Therefore, the hardness is listed with different heights which were measured from the interface to the cladding section and with 5mm interval.

From the results showed in Table 3, it is clear that the average hardness of laser deposition samples is higher than that of welding samples, however, the hardness of position 2 deposition is the lowest. The hardness of material can be approximately transferred to its tensile strength [8] and the sample will be broken from its weakest section, i.e. deposition sample will be broken from position 2 and welding sample broken from position 1. Thus, the tensile strength for the samples can be estimated as Table 4 listed.

Table 3. Hardness of deposition and welding sample (HRC)

	Deposition	Welding
Position 1	53.7	43.0
Position 2	40.0	48.1
Position 3	56.2	44.5
Average	50.0	45.2

Table 4. Tensile strength estimated from hardness (ksi)

	Deposition	Welding
Tensile Strength (Approx.)	184.0	201.6

For the weakest section, the deposition sample is weaker than welding sample, and that is why its fracture surface can present more ductile feature. In this way, more works such as adjusting the laser deposition process and applying an effective heat treatment are needed to improve the mechanical properties of this section.

4. Conclusions

The hybrid laser metal deposition and machining process can be used to repair casting dies. And the microstructure of laser deposition sample is much more uniform in both the thickness and width directions than that of TIG welding sample. This indicates that more uniform mechanical properties are possible with the laser deposit process. The average hardness of deposition sample is higher than that of welding sample, but the fact that deposition is weaker at the weakest area will lead to a lower tensile strength. This problem could be solved by transferring the ductility to the hardness via heat treatment and optimizing the deposit process. So far, the hybrid repair system can deposit on the uneven surface whose height difference is smaller than 0.01mm, and the process needs to be adjusted if the height difference is larger than 0.05mm.

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