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Thermal Post-Processing of 4140 Alloy Steel Parts Fabricated by Selective Laser Melting (SLM)

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Abstract—Selective laser melting (SLM) additive manufacturing (AM) technology has become an attractive research topic due to its low environmental impact, minimal material waste, and ability to deal with complex geometries. However, the mechanical performance of parts produced using SLM needs to be improved. Enhancing the performance of the fabricated parts is the main goal of different industrial implementations. To achieve this objective by providing a homogeneous microstructure and reducing cracks and porosity within the produced parts is a significant part of this investigation. The heating process for additively produced parts is significant for eliminating porosity, relieving residual stresses, and homogenizing the microstructure. The goal of this experimental investigation is to evaluate the influence of thermal post-processing on the microstructure and mechanical properties of AISI 4140 alloy steel fabricated using an SLM technique. A full characterization of the mechanical properties for the SLM produced sample was conducted and compared to the commercial sample. In addition, microstructure assessments were conducted for the as-built and printed samples. The results revealed that thermal post-processing enhances the mechanical properties of the SLM printed parts. This makes industrial production more feasible and offers a great possibility for applications in many industries like the automobile, aerospace, and machinery industries.

Keywords-Additive manufacturing (AM), selective laser melting (SLM), microstructure, mechanical properties, 4140 steel, heat treatment

I. INTRODUCTION

In the past few years, several metals have been additively fabricated to full density with equivalent or better mechanical properties as compared to counterparts manufactured using conventional methods. The selective laser melting (SLM) process is probably the most rapidly growing additive manufacturing technology due to its ability to produce high precision and high-performance metal parts. Many studies have reported that the mechanical properties of materials produced using SLM are at least comparable to the cast material of the same alloy. Gao et al. [1] stated that SLM additive manufacturing can be a reasonable alternative to many ordinary manufacturing processes. Kruth et al. [2] claimed that it is possible to obtain acceptable mechanical properties and densities using the SLM process. Read et al. [3] reported that samples of an AlSi10Mg alloy fabricated by SLM methods provided better elongation and strength properties than a die-cast Al-alloy with the same chemical composition. Liverani et al. [4] demonstrated that it is possible to produce samples that are close to full density and have a better elongation and final tensile strength in comparison to conventional AISI 316L steel. This study also observed that the laser power has a significant effect on the sample density. Song et al. [5] pointed out that the extreme mechanical strength of samples fabricated by SLM was obviously due to the lower grain size and the high dislocation density associated with the rapid cooling rates. As well, Abe et al. [6] found that the high porosity and large pore size reduced the ductility of the SLM specimens. Another parameter that has a great effect on the grain size of the SLM samples was found to be the volume energy density (ω). Wang et al. [7] also found that the volume energy density significantly influenced the grain size of SLM samples.

The medium carbon AISI 4140 steel alloy is one of the most important steel alloys that is used in the production of many industrial components, such as rotors, shafts and gears, due to its excellent harden-ability, toughness, strength, and wear resistance. Wang et al. [8] used laser powder bed fusion (LPBF) to additively fabricate medium carbon steel 4140 builds. This study found that the 4140 steel builds provided promising mechanical properties and showed potential applications in industries such as automobile, aerospace, and machinery. Damon et al. [9] utilized the LPBF technique to manufacture 4140 alloy steel parts. The resulting additively manufactured 4140 steel showed a mechanical performance comparable to that of the 450^{o}C tempered state of a conventional material.

All additive manufacturing approaches, however, contain internal defects formed during the printing process due to the layer-by-layer nature of the process. These defects, such as porosity and cracks in the material, negatively affect the mechanical properties. To solve this problem, thermal post-processing (post-heat treatment and tempering) of additively fabricated parts is important to eliminate porosity, homogenize the microstructure, and relieve residual stresses. In general, previous studies have not included an analysis of the effects of heat treatment and tempering processes on the microstructural homogeneity and mechanical properties of 4140 alloy steel fabricated under different AM process parameters. Thus, this experimental study presents an evaluation of the microstructural development and mechanical properties of 4140 alloy steel which was fabricated using SLM and received thermal post-processing. It is then compared to as-built.

II. Experimental Procedure

A. Materials

Materials that used in this study are two 4140 alloy steel fabricated by using SLM under different process parameters. These AM samples were heated to 845°C and underwent two different tempering temperatures. The resulting samples were compared to commercial 4140 steel alloy. Steel alloy samples were printed by changing the laser power and the laser scanning speed. Table I represents the design of experiments (DOE) that was followed in this study. The first set of samples, labeled from SPT1 to SPT4, were fabricated using a laser power of 350W and a laser scanning speed of 1000 mm/s, while the second set of samples, labeled from SPT5 to SPT8, were printed using a laser power of 350W and a laser scanning speed of 9000 mm/s. The samples labeled from SS1 to SS4 represent the commercial 4140 steel. Table II shows the chemical composition of the 4140 steel alloy. The heat treatment and tempering processes were carried out in a Thermo Scientific furnace. From each set of samples (W450 @1000 mm/s, W350 @9000 mm/s, and commercial), three specimens were heated at 845°C for 60 min and then quenched with vegetable oil as recommended.

TABLE I. Description of all samples that were used in the experiments.

Sample	Processing Parameters	Thermal Post-processing		
		Heat treatment	*Tempering*	*Condition*
STP1	350W @ 1000 mm/s	-	-	As-built
STP2	350W @ 1000 mm/s	845 °C 60 min	538 °C 45 min	
STP3	350W @ 1000 mm/s	845 °C 60 min	-	
STP4	350W @ 1000 mm/s	845 °C 60 min	316 °C 45 min	
STP5	350W @ 9000 mm/s	-	-	As-built
STP6	350W @ 9000 mm/s	845 °C 60 min	-	
STP7	350W @ 9000 mm/s	845 °C 60 min	538 °C 45 min	
STP8	350W @ 9000 mm/s	845 °C 60 min	316 °C 45 min	
SS1	Commercial	-	-	As-received
SS2	Commercial	845 °C 60 min	-	
SS3	Commercial	845 °C 60 min	538 °C 45 min	
SS4	Commercial	845 °C 60 min	316 °C 45 min	

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TABLE II. Chemical composition of the stock AISI 4140 steel

Cr	Mn	C	Si	Mo	S	P	Fe
0.8	0.75	0.38-0.43	0.2	0.25	0.04	0.035	Bal.

B. Heat Treatment and Microstructural Characterization

One heated specimen from each set was used to investigate the effects of the heat treatment. The second specimen was tempered at 316°C for 45 min and the third was tempered at 538°C for 45 minutes in order to study the effect of tempering on the mechanical properties and the microstructure. Figure 1 describes the thermal post-processing. The microstructural characteristics of 4140 alloy steel were evaluated using a Keyence VHX series digital microscope. Representative samples were cut from the gauge length of the tensile samples and prepared for the polishing process. The polishing processes were performed as recommended by metallographic techniques. To facilitate the study of the microstructural observations, samples were etched using a solution of 2% nitric acid for five to ten seconds. The samples were rinsed with ethanol and deionized water (DI) after etching, and eventually dried. Hardness tests were carried out using a United hardness testing machine. Tensile tests were performed at room temperature on SLM rectangular cross-section samples with a 2.8 mm thickness and an 8.2 mm width using an INSTRON hydraulic testing machine with a 50 KN load. The cross-head separation was set to 1 mm/min. An Extensometer was mounted on each specimen with a rubber band during the tensile tests to achieve a more accurate strength reading. To compare the mechanical properties (hardness, elastic modulus, yield strength, and tensile strength) with a reference value, tensile tests on samples of commercial

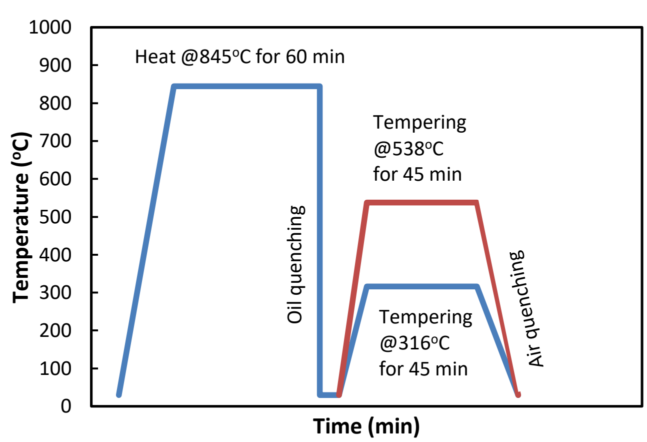

Figure 1. Heat treatment and quenching processes.

4140 steel were also carried out. The mechanical properties of all the samples were estimated in the as-received condition, as well as in the annealed and the tempered condition.

III. RESULTS AND DISCUSSION

A. Mechanical Properties

This section discusses the effects of the thermal post-processing (heat treatment and tempering processes) on the mechanical properties. This includes the hardness, elastic modulus, yield strength, and tensile strength of the printed samples compared to those of the commercial ones. The stress strain curves were used to determine the mechanical properties.

Hardness:

The main reason that metals undergo heat treatment is to improve their mechanical properties such as hardness. The degree of heat treatment and the rates of cooling after the heat treatment (quenching) can significantly change the metallic properties. As seen in Figure 2, the hardness of commercial 4140 steel is notably increased after a heat treatment at 845^{o}C for 60 min compared to as-received. This is due to the formation of a finer pearlite and ferrite microstructure. Among the samples, materials produced via additive manufacturing were observed to display a higher hardness than the stock 4140 steel both with and without the heat treatment/tempering. The reason for this high degree of hardness is the formation of fine martensite and bainite. The martensitic-bainitic microstructure is the result of the micro welding manufacturing and the rapid cooling. The fast melting and solidification with a rapid cooling rate in the laser powder bed process produces a smaller microstructure compared to traditionally produced metals with the same chemical composition [13]. Additionally, for all the samples, the highest value of hardness was observed after a heat treatment and in the absence of any tempering. To summarize, when more ductility is required for additively manufactured parts, tempering them at 538^{o}C would help attain the desired ductility. Furthermore, it was noted that changing the laser power and scanning speed does not significantly affect the hardenability of the SLM printed material. Figure 3 describes the microstructures of samples before and after the heat treatment at 845^{o}C.

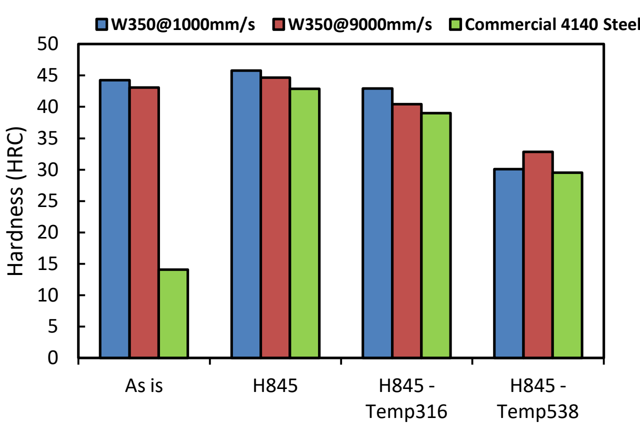

Figure 2. Results of hardness tests (HRC).

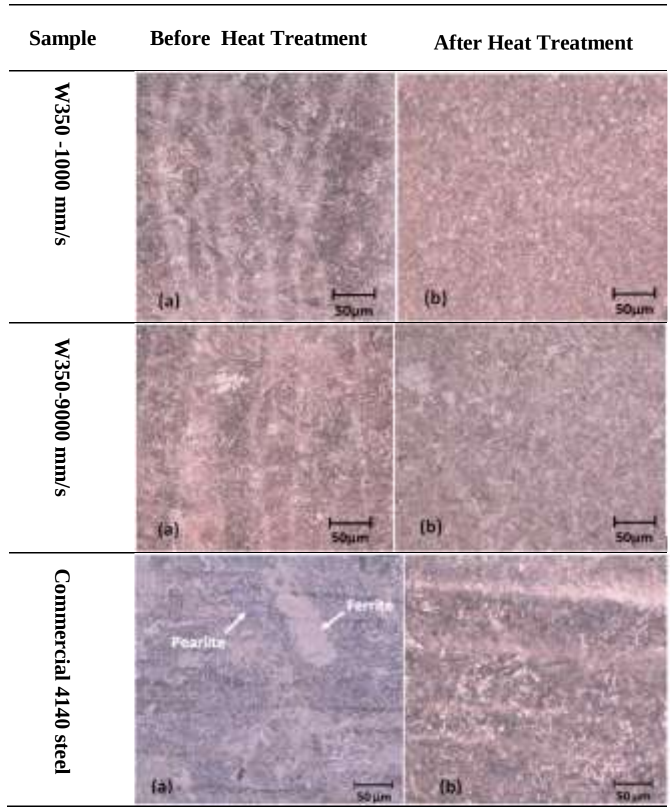

Figure 3. Micrograph images of the microstructure.

Elastic Modulus:

In contrast to the positive effects of heat treatment on the material hardness of all the samples, the effect on the elastic modulus of the samples was varied. After a heat treatment at 845^{o}C for 60 min, the elastic modulus of the SLM printed samples with W350 @1000 mm/s was increased by 13% compared to the as-built condition. In comparison, the elastic modulus of the SLM printed samples with W350 @9000 mm/s and the commercial 4140 steel decreased by 0.95% and 3.5%, respectively, as seen in Figure 4. Furthermore, air quenching and tempering at 316^{o}C for 45 minutes decreased the elastic modulus in all the samples, except for that of the W350 @ 1000 mm/s sample, which increased by 4.6%. Compared to tempering at 316°C, tempering at 538^{o}C for 45 min increased the elastic modulus of W350 @ 9000 mm/s by 25%, while the other samples showed lower elastic modulus value compared to the as-received condition. It should also be stated that no significant differences in the elastic modulus were observed among the SLM printed samples fabricated using different laser powers and laser scanning speeds.

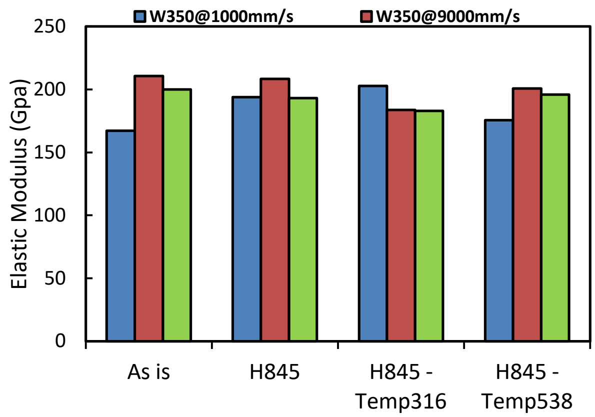

Figure 4. Results of elastic modulus (at room temperature).

Tensile Strength:

The ability of materials to withstand fracture is an important property and is defined by tensile strength. Figure 5 indicates that tempering samples at 316°C after the heat treatment increases the tensile strength of all the AM samples above that of their as-built condition and W350 @1000 mm/s had the highest strength at 1400 MPa. This is because the tempering process relieves the internal stresses in the boundaries by rearranging the atoms, thereby reducing the brittleness and increasing the strength. However, tempering the samples at 538°C reduces the tensile strength of all samples. Raising the tempering temperature decreases the concentration of martensite and increases the ferrite as a result of the carbon diffusion of the atoms into cementite and the movement of the dislocations by thermal assistance. It was also noted that the 4140 steel attained the highest tensile strength after tempering at 316°C (1120 MPa) compared to all the 4140 samples under different heat treatment and tempering operations. To summarize, tempering SLM samples at relatively low temperatures (316°C) is considered a good choice to improve their tensile strength.

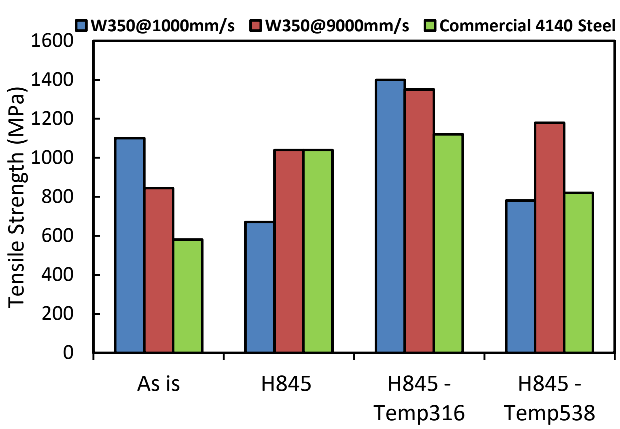

Figure 4. Results of tensile strength.

IV. CONCLUSION

The main results of this study can be summarized as follows:

- No significant differences in the elastic modulus were observed among the SLM printed samples fabricated with different laser powers and laser scanning speeds. The SLM printed samples with a W350 @ 1000 mm/s showed the highest tensile strength in after tempering at 316°C.
- The SLM printed steel could be used in as-built condition due to its good hardness, its elastic modulus, and its suitability for applications that need a high degree of hardness.
- It is possible to improve the mechanical properties of AM parts by a simple heat treatment procedure followed by oil quenching and tempering. This makes industrial production more feasible and offers a great possibility for applications in many industries like the automobile, aerospace, and machinery industries.
- A further investigation of other mechanical properties, such as impact tests, fatigue tests, and physical properties, is planned for a future study.

V. ACKNOWLEDGMENT

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