Mechanical Analysis and Heat Simulation of Laser Welding of 3D-Printed SS316L Stainless Steel

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Abstract— Additive manufacturing is becoming increasingly common in industry fabrications especially for durable and expensive spare parts which cannot be found easily in the local market and also for tailor made parts. For large parts that are not economically and practically 3D printed, due to its size limitation it is sometimes more convenient to join 3D printed parts together to form larger parts. In this paper 3D printed flat plates 3mm thick were prepared by direct laser sintering of SS316L stainless steel powder. Mechanical properties and microstructure were investigated. Elongation and maximum tensile stress of 3D printed flat plates are with 1.3% and 704MPa close to the values 2% and 1241MPa of cold-rolled SS316 parts. The 3D printed flat plates were joined by laser welding. The welded joints were tested for their mechanical properties and microstructure, and simulation of the welding process was performed by ANSYS. For the used welding conditions, the fracture occurred outside the weld zone. The maximum stress of the welded parts is 80% of 3D printed flat plates. The elongation of the welded parts is above 3%.

Key words: Additive Manufacturing, Laser Welding, Laser Simulation

I. INTRODUCTION AND STATE OF ART

Additive manufacturing (or 3D printing) is a form of rapid prototyping technology which allows for the fabrication of three dimensional products via a layer by layer materials buildup method. Its relevance as a mainstream tool for series production has grown significantly over the past 10 years [1]. While 3D printing techniques remain less competitive to conventional (subtractive) manufacturing methods such as milling, grinding, cutting, casting and rolling, in terms of high volume production. It brings along a profound advantage in terms of the possibility of easily fabricating complex geometry components and the customization of components to be deployed to highly specialized engineering applications. Such a technical merit brings 3D printing technologies to an industrial foreground where its application alongside other manufacturing techniques is being explored. There are five most widely applied forms of 3D printing techniques namely Fused Deposition Modeling (FDM), Stereolithography (SLA), Inkjet Printing, Laminated Object Manufacturing (LOM), Selective Laser Melting (SLM) and Selective Laser Sintering (SLS). Each of these methods is unique in the sense that the kinds and forms of materials used as feedstock as well as the approach to materials build-up into a three-dimensional form are different. For metal processing the SLM and SLS methods are most popularly applied. These methods use a laser source to fuse together metallic powder particles in a layer by layer fashion until a dense part is built-up. By altering the beam parameters such as power and flux and also scan strategies such as rate and direction, new and unusual, even non-equilibrium microstructures can be produced; including controlled microstructural architectures which ideally extend the contemporary materials science and engineering paradigm relating structure-properties-processing-performance [2-4]. For 3D printed parts the importance of testing on essentially every part cannot be over stressed especially since 3D printing technology has still not been fully technically assessed and characterized [5]. To understand the technical capabilities of 3D printed parts, the systematic examination and testing of parts need to be conducted. The main tests are carried out using tensile testing, hardness testing and others depending on the application of the product. Among the properties measured are the modulus of elasticity, yield strength, ultimate tensile strength and ductility. The results of these testing can be obtained from the tensile test applied on samples with standard shape and dimensions. Hardness profile tests give an indication about the resistance to surface scratching and wearing of the material [6]. Furthermore, the product size and dimensions of 3D printing are restricted by the size of the platform of each 3D printing machine (typically a surface area no more than 300mm x 500m, and a height of about 600mm), which is not large enough for big parts. One of the ways to produce bigger components via 3D printing and still preserve the economic benefits of the process is to subdivide the component into several parts then to join these parts together. The joining of metallic parts is a key process in technical practice. For instance welding is an essential manufacturing step in the automotive and aerospace industries. It provides both joining and repair value in these industries. These joining processes account for a huge portion of investment in engineering construction. Very few information is however available in the literature on how to use joining techniques on 3D printed parts and the kind of mechanical properties and microstructure induced at the joint zones. Comparison of welded wrought and SLM parts have been studied by Casalino et al. [7] and Järvinen [8]. A schematic drawing showing the concept of a Selective Laser Melting (SLM) process is shown in Fig. 1. The primary goal of this study is to see the influence of the welding process on the weld properties of SS316L stainless steel samples prepared by SLM. Microstructural examination as well as the mechanical test on the welded parts will be correlated to the 3D printing conditions thus allowing for the determination of the optimal conditions for producing good weld joints of the studied materials.

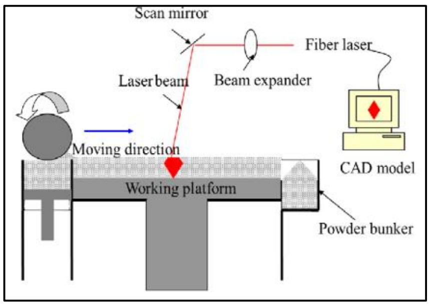

Fig. 1: Schematic diagram of selective laser melting process [9]

II. EXPERIMENTAL PROCEDURE

The preparation of the samples consists of several steps such as 3D printing, welding of the samples and preparation for mechanical testing and microstructure characterization. The specimens were produced from SS316L powder whose chemical composition was determined to contain iron and 16-18% Chromium, 10-14% Nickel, 0.03% Sulfur, 0.04% Phosphorous, 0.03% Carbon, 1% Silicon, 2% Manganese. The apparent density was between 3.5g/cm3 and 5g/cm3. The particle size is determined by 400mesh which translates into a layer size of 50 micrometers. The 3D printing of samples was performed using a Selective Laser Sintering (SLS) Machine available at the department of additive manufacturing at Aachen University of Applied Sciences. The 3D process uses laser for the micro-melting and welding of fine powder particles in stacked layers until the complete part is built. This process depends strongly on the process parameters to get high strength and crack free products. Here, the parameters applied are: laser power 200W, scanning speed 800 mm/min, line overlap 30%, focus diameter 0.15 mm, and layer thickness 50 micrometer. The specimens were built with an orientation angle of 45 degrees relative to the base. The samples were then laser welded. Laser welding was done with CO2-Laser RS6000 Machine from Balliu. Laser welded samples are shown in Fig. 2. The optimum welding conditions to achieve a complete weld penetration without undercuts were found within a welding speed of 1300mm/min, power: 1100 W (35% activation with small opening, shielding and working gas: He 20 l/min, optic: off-axis -parabolic mirror, focal length: 150 mm. Samples for microstructure investigation and mechanical testing were cut at different locations of the steady state of the welded sample. The dimension of the tension specimens is shown in Fig. 3.

Fig. 2: Laser Welded Sample

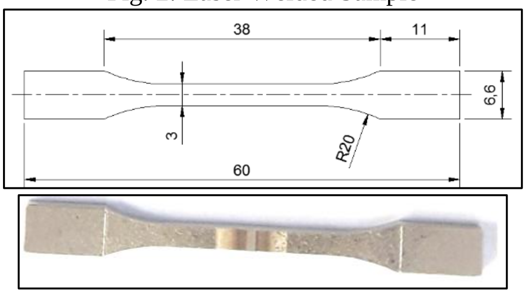

Fig. 3: Flat sample dimensions (upper) and real sample (lower)

III. MICROSTRUCTURE AND MECHANICAL TESTING

After welding, the welds were cut and prepared as metallographic samples to assess the integrity of the weld beads. The result for optimum welding parameters are presented in Fig. 4, which is showing complete weld penetration without undercuts and a convex weld bead. The microstructure of the weld bead showed a complete columnar texture during the recrystallization of the powder compact particles at the center.

Hardness Testing was also performed at two levels; 0.5 mm away from the upper and lower surface across the cross section of the welded sheet as shown in Fig 5. Vickers hardness (HV) was measured every 0.4 mm and a hardness profile was constructed from the measured values. The results of which are shown in Fig. 5 below.

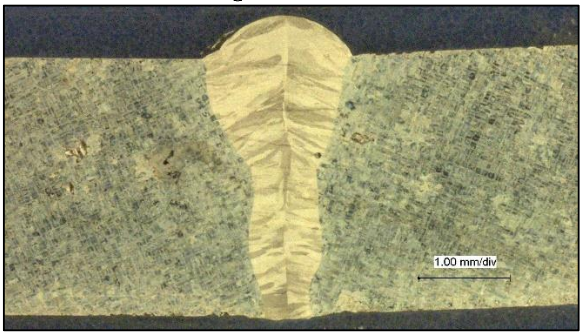

Fig. 4: Laser welded bead cross section in 3mm sheet

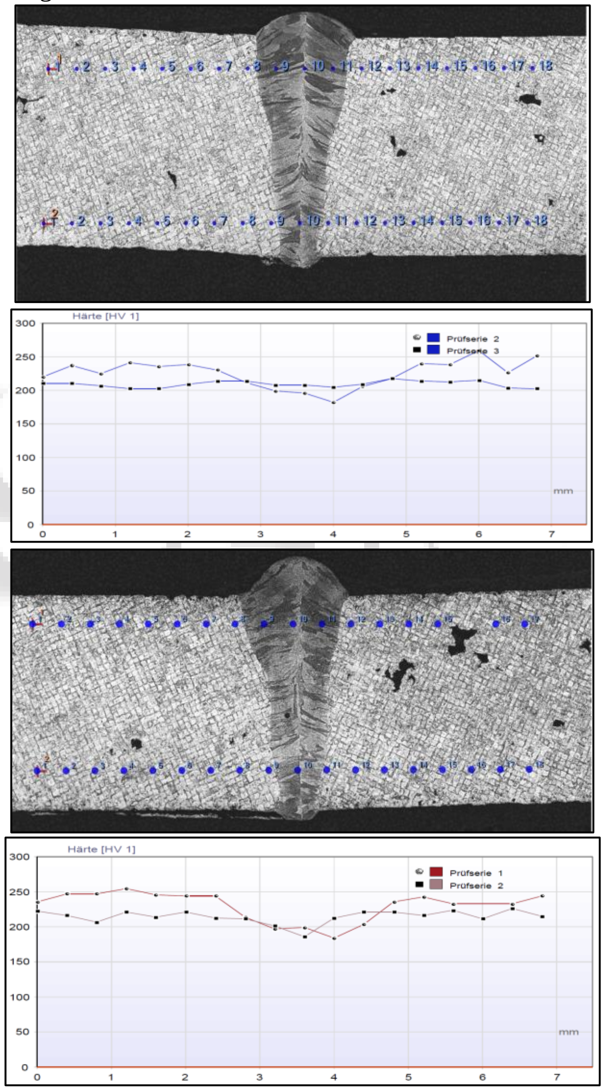

Fig. 5: HV hardness profile for two selected samples

The results have shown that the laser welded samples had almost constant hardness with little drop at the weld region. The hardness of base material ranged between 240-260 HV while that of the weld region ranged between 180 -200 HV.

Tensile tests of laser welded samples were also performed and gave a yield strength of 617±6MPa, a tensile strength of 711±3MPa and a maximum force of 6.40±0.02kN, respectively. Fig. 6 shows the stress strain curves for the tested samples.

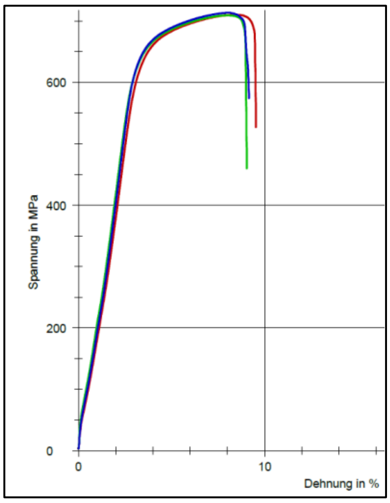

Fig. 6: Tensile testing of laser welded samples

IV. FINITE ELEMENT ANALYSIS SIMULATION

A finite element analysis model was constructed to compute the temperature distribution in the weld region. The model was solved using ANSYS and was based upon the Beer-Lambert equation [10]

$$I(z,t) = (1-R)I_o(t)\frac{e^{-z/\delta}}{\delta} \quad (1)$$

Where I(z, t) is the laser intensity at a depth z from the surface and time t, R is the reflectivity, $I_o(t)$ is the laser intensity at the surface and δ is the penetration depth of CO_2 laser in SS316L taken to be 100 nm [11]. The spot size was measured to be 0.7 mm. Kim et al [12] mention that the reflectivity of stainless steel 316 L is about 0.3 when subjected to CO_2 lasers however more realistic results were achieved with a reflectivity of 0.35.

To verify the temperature distribution results the temperature of the node at the lower surface of the sheet at the midsection was plotted against time as shown in Fig. 7 Clearly that location has reached the melting temperature of the material (1700 K) and even exceeded it to reach about 1800 K which agrees with Fig. 4 that shows that the whole section has melted during the welding.

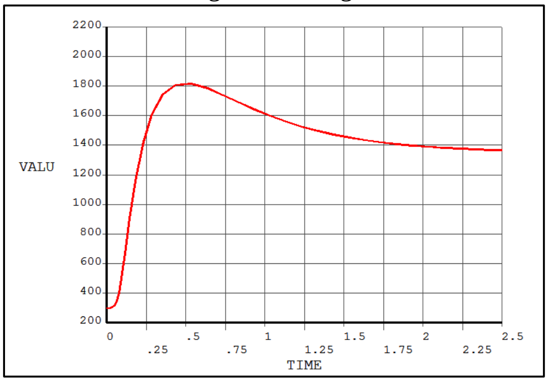

Fig. 7: Temperature at the midsection of the bottom surface as a function of time

At a time of 0.536 seconds the whole depth of the sheet reached the melting temperature. The temperature distribution, shown in Fig. 8 at time t =0.536 s, shows that the area subjected to melting (>1700 K), enclosed by the three highest temperature contours, takes nearly the same shape as the melt area depicted by Fig. 4. Fig. 8 shows a wider melt width near the top surface that gets narrower with depth which agrees with the microstructure results that show new grains being formed in the same area. The columnar grain texture in Fig. 4 also agrees with the temperature contours shown in the Fig. 8 indicating that grain growth occurred in a perpendicular direction to the temperature contours.

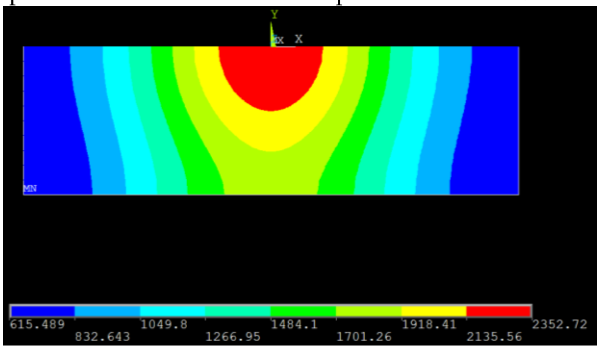

Fig. 8: Temperature distribution at t = 0.536 s.

V. CONCLUSION

This paper describes the influence of the laser welding process on the weld properties of SS316L stainless steel samples prepared by SLM. Microstructural examination as well as the mechanical test on the welded parts were correlated to the 3D printing conditions thus allowing for the determination of the optimal conditions for producing good weld joints of the studied materials. The results of the Vickers hardness and the tensile testing showed both consistency and reproducibility. Microstructure investigations as well as simulation results showed that the laser power (1100W) was sufficient to cause melting through the whole depth of the welded sheets. The melt shape was consistent between the finite element analysis model and the microscopic imaging. The resulting columnar grains and their orientation is thought to be a consequence of the temperature gradient and contours predicted by the model.

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