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PRELIMINARY INVESTIGATION ON SLM OF ASTM A131 EH36 HIGH TENSILE STRENGTH STEEL FOR SHIPBUILDING APPLICATIONS

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ABSTRACT: In this preliminary investigation of selective laser melting (SLM) of EH36 high tensile strength steel, a 175 W Yb:YAG laser in continuous wave mode was used to produce EH36 test specimens. The laser beam profile follows the Gaussian distribution and has a wavelength of 1.064 μm , with a focal diameter of 81 μm . The powder layer thickness was set at 50 μm . The stainless steel substrate plate was preheated to 100 °C. The scanning speeds were varied from 260 mm/s to 880 mm/s, and hatch spacing were varied from 0.08 mm to 0.12 mm, to obtain the various energy densities. The highest density value of 7.64 g/cm³ was obtained at an energy density of 92 J/mm³ using parameters of 0.12 mm hatch spacing, powder at 175W, 50 μm layer thickness and 320 mm/s laser scanning speed. Compared to the relative density of the compacted supplied powder (7.83 g/cm³), the results translated to 97.57% fully dense part. Micrographs were obtained using light optical microscopy, which showed slight porosities in the SLM built part. X-ray diffraction and scanning electron microscopy revealed BCC phases and martensitic microstructure respectively.

INTRODUCTION

Background

Selective laser melting (SLM) is a layer by layer additive manufacturing (AM) process that enables the fabrication of complex geometric shapes in part design and production[1]. The working concept of SLM is as follows – thin layers (20 to 100 μm) of fine metal powder are evenly distributed using a coating mechanism onto a substrate plate. This takes place inside a chamber filled with inert gas, either argon or nitrogen with oxygen contents of less than 0.05%. Each distributed layer of powder is fused by selectively applying the laser energy to the powder according to the 2D sliced data, by directing focused laser beam. The laser energy is intense enough to obtain full melting of the particles to form solid metal, thus achieving metallurgical bonding. The process is repeated layer after layer until the part is complete.[2]

SLM is one of the AM processes capable of producing functional components from materials having mechanical properties superior to those of bulk materials and comparable to forged properties. Process parameters and building patterns can be optimised to achieve desirable grain structure and properties[3, 4]. It is widely used in industries including dental, biomedical, automotive, oil and gas and aerospace[5-10]. Driven by the demand from these industries, metals including Titanium (such as CP, 6Al-4V, Si-C, Al-C, Ni), Steel (such as SS316L, SS17-4 PH, H13 tool steel, M2 high speed steel), Aluminium (pure and alloys such as Mg, Si), Inconel (such as 718, 939) and Cobalt Chrome (eg CoCrMo) are researched on and proven to work with SLM[11-25].

Objective

SLM is often used as a rapid manufacturing technique due to its potential in several manufacturing applications [26]. This creates an opportunity for the application of SLM in the shipbuilding

industry, where steelwork and manufacturing forms a significant amount of the work processes[27, 28]. As such, the main objective of this study is to conduct a preliminary investigation of ASTM A131 EH36 high tensile strength steel used in shipbuilding applications. In this study, critical SLM process parameters such as hatch spacing and scanning speed are investigated to produce benchmark parts with high density and properties comparable to conventionally produced EH36 parts. Microstructural analysis will also be carried out to investigate the effects of varying process parameters. The results will facilitate future studies on SLM of shipbuilding steel.

EXPERIMENTAL

Material

The ASTM A131 EH36 high tensile strength steel powder used in this investigation was supplied by Sandvik Osprey Limited (UK) produced by gas atomisation process using Nitrogen as the atomisation gas. According to the data sheet provided by Sandvik Osprey, 95.8% of the particle ranges between particle sizes of 20 µm to 53 µm, while 2.2% is less than 20 µm. Powder tests were carried out and the results are shown in Table 1. The particle size distribution is carried out by an independent test body and the results are shown below. The results also indicated that the mean diameter of particles was 47 µm.

Table 1 - Powder test results

Powder Tests		Particle Size Distribution	
Tap Density	5.1 g/cc	D10	28 µm
Hall Flow	27.6 sec/50g	D50	44 µm
		D90	49 µm

Figure 1 - SEM image of powder particles

Table 2 – Elemental composition of powder

Element	Osprey %	ASTM A131 %
Manganese, Mn	1.14	0.9-1.6
Chromium, Cr	0.36	0.2 (max)
Silicon, Si	0.24	0.1-0.5
Nickel, Ni	0.11	0.4 (max)
Carbon, C	0.15	0.18 (max)
Vanadium, V	0.11	0.05-0.1
Niobium, Nb	0.03	0.02-0.05
Molybdenum, Mo	0.02	0.08 (max)
Aluminum, Al	0.02	0.015 (min)
Copper, Cu	0.05	0.35 (max)
Phosphorous, P	0.06	0.035 (max)
Titanium, Ti	<0.01	0.02 (max)
Sulphur, S	0.007	0.035 (max)
Calcium, Ca	0.003	0.005 (max)
Iron, Fe	Balance	Balance

Table 2 shows the composition of the EH36 powder in weight percentage provided by Osprey (based on results from the independent test body) compared with the elemental composition specified in ASTM A131 standard.

Figure 1 shows a scanning electron microscopy (SEM) image of the particles provided by Osprey. From the image, it can be observed that the particles are mostly spherical in shape, except for a small percentage of irregularities which did not cause any deposition issues in this study.

SLM Machine and Process Parameters

In the investigation work, a SLM™ Solutions 250 HL selective laser melting (SLM) machine was used. A 400 W Yb:YAG laser (operating at 175W) in continuous wave mode was used to produce EH36 test specimens. The laser beam profile follows the Gaussian distribution and has a wavelength of 1.064 nm, with a focal diameter of 81 µm. The powder layer thickness was set at 50 µm. The stainless steel substrate plate was preheated to 100 °C to reduce the thermal gradients and thermal stresses experienced by the specimens during the SLM process. Energy density, which was investigated to directly impact the properties of steel parts, is a key factor in the SLM

process[29].The scanning speeds were varied from 260 mm/s to 880 mm/s,and hatch spacing were varied from 0.08 mm to 0.12 mm, to obtain the various energy densities.The volume based energy density E (J/mm³) is defined in Equation (1), where P is laser power (W), v is scan speed (mm/s), h is hatch spacing (mm) and t is layer thickness (mm).

$$E = \frac{P}{v \times h \times t} \quad (1)$$

Based on Equation (1), a set of parameters were obtained for energy densities ranging from 50 J/mm³ to 111 J/mm³. The parameters are detailed in Table 3, where the values in the table refer to laser scanning speed values in mm/s.

Table 3 - SLM process parameters

Energy (J/mm ³)	Layer Thickness:50 μ m				
	Hatch Spacing (mm)				
	0.08	0.09	0.1	0.11	0.12
111	390	350	310	290	260
105	422	376	336	312	280
99	454	402	362	334	300
92	486	428	388	356	320
86	518	454	414	378	340
81	550	480	440	400	360
75	616	540	492	448	404
69	682	600	544	496	448
62	748	660	596	544	492
56	814	720	648	592	536
50	880	780	700	640	580

Table 4 - Results from density test

Energy (J/mm ³)	Layer Thickness:50 μ m				
	Hatch Spacing (mm)				
	0.08	0.09	0.1	0.11	0.12
111	7.178	7.519	7.433	7.489	7.535
105	7.374	7.512	7.528	7.46	7.594
99	7.489	7.483	7.526	7.56	7.573
92	7.476	7.477	7.466	7.528	7.64
86	7.419	7.486	7.494	7.48	7.525
81	7.385	7.465	7.469	7.43	7.401
75	7.503	7.419	7.456	7.434	7.42
69	7.523	7.516	7.482	7.473	7.47
62	7.511	7.537	7.378	7.332	7.361
56	7.47	7.468	7.278	7.391	7.365
50	7.471	7.273	7.014	7.075	6.982

RESULTS

The completed specimens were observed to have no visible cracks, distortion or surface porosities as illustrated in Figure 2. They were then put through several analysis to determine the integrity of the specimens – density test, x-ray diffraction, light optical microscopy and scanning electron microscopy.

Density Test

Density tests were carried out for the SLM built specimens in accordance to ASTM B962 – 13: Standard Test Methods for Density of Compacted or Sintered Powder Metallurgy (PM) Products Using Archimedes' Principle. Masses of each specimen in air (m_a) and water (m_w) were measured independently on an electronic balance with ± 1 mg accuracy. The measured values were then inserted into Equation (2) to obtain specimen density ρ_s , where ρ_w is the density of water (1 g/cm³).

$$\rho_s = \frac{m_a}{m_a - m_w} \times \rho_w \quad (2)$$

The results of the tests are shown in Table 4, where table values represent density values in g/cm³. The highest density value of 7.64 g/cm³ was obtained at an energy density of 92 J/mm³ using parameters of 0.12 mm hatch spacing, powder at 175W, 50 μ m layer thickness and 320 mm/s laser scanning speed. Compared to the relative density of the compacted supplied powder (7.83 g/cm³), the results translated to 97.57% fully dense part. Graph of SLM built part density vs energy density (Figure 3) was plotted based on the results to identify the effects of the parameters on part density. It was observed that increasing energy density generally improves part density, but there were only two peaks which represented optimal energy density values. At the points with higher density, it was observed that hatch spacing were generally higher and scan speeds were generally lower.

Figure 2 - SLM built test specimens

Figure 3 - Graph of SLM built part density vs energy density

Figure 4 - XRD of EH36 (a) powder sample, (b) SLM built specimen

Figure 5 - (a) Image of unetched SLM built specimen showing slight porosities, (b) etched sample showing grain boundary and porosity indicating incomplete melting of powder particle

X-Ray Diffraction

The x-ray diffraction (XRD) of the sample powder and SLM built specimen were compared. The XRD results showed body centered cubic (BCC) phases in both the sample powder and SLM built specimen. Comparing the results shown in Figure 4, BCC peak positions for both sample powder and SLM built specimen are similar, indicating no change in phases after the SLM process.

Light Optical Microscopy

Figure 5 shows the micrographs of the SLM built specimen taken with light optical microscopy (LOM). Slight porosities could be observed, which were consistent to the density test results discussed earlier. The specimen was then etched using 3% nital and observed under LOM. The micrographs revealed distinct grain boundaries and acicular martensitic microstructure, which was consistent with previous works conducted on SLM of steel [20].

Figure 6 - SEM images of SLM built specimen showing (a) fine grains (Zone A) vs coarse grains (Zone B), (b) acicular martensitic structure

Scanning Electron Microscopy

The SLM built specimen was then observed under scanning electron microscopy (SEM). Figure 6 shows the micrographs obtained. In Figure 6a, 2 distinct zones were observed, where Zone A shows finer grains and Zone B shows coarser grains. This indicated a possible laser melt track along Zone A, where the higher energy intensity in the middle of the melt produced finer grain structure. Figure 6b shows the acicular martensitic structure in the SLM built specimen.

DISCUSSION

In this preliminary investigation of SLM of EH36 high tensile strength steel, parts were successfully produced with SLM without any cracks. The density results obtained in this investigation showed that parts with more than 97% of relative density could be fabricated. From the XRD results, there was no phase change before and after the SLM process. The micrographs also showed the formation of acicular martensitic structure in the SLM built parts.

CONCLUSION

In conclusion, it was found that SLM is capable of producing EH36 high tensile strength steel parts with a relative density of more than 97%. This study also indicated the possibility of producing higher density EH36 parts as the energy density could be increased further. This lays the foundation work for future work of SLM of EH36, which includes using additional techniques to improve part density (eg re-melting), performing tests (eg hardness test, tensile test) to determine the mechanical properties of the SLM built parts, and post processing such as heat treatment to improve or recover mechanical properties such as ductility of as-built SLM parts.

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