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Effect of process parameters on the Selective Laser Melting (SLM) of tungsten

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ABSTRACT

Selective Laser Melting (SLM) is a promising technique for the fabrication of complex net shaped parts of many metals. However, the high melting temperature of tungsten makes fabricating complex parts via SLM difficult. A study was undertaken to understand the effect of process parameters like hatch spacing and scan speed on the densification of tungsten by the SLM technique. Experiments were conducted at hatch spacing of 15 and 30 μm and scan speeds in the range 200–1400 mm/s. A constant laser power of 90 W and a powder layer thickness of 30 μm were used. Rectangular cuboids of 7.8 ± 1.4 mm × 10.1 ± 0.1 mm × 10.1 ± 0.04 mm were printed using various process parameters and analyzed for densification. The densification of tungsten was found to increase with an increase in energy density. A maximum density of 75% theoretical was achieved at energy density of 1000 J/mm^3.

1. Introduction

Tungsten, due to its inherent characteristics like high melting point, good thermal conductivity, high hardness, and oxidation resistance, is used in many critical components across a wide range of applications in electronics, medicine, defense, etc. [1]. The production of tungsten in industrial scale is carried out exclusively by powder metallurgy. The pressed powder is sintered and generally deformed (forged, rolled, drawn, etc.) under high temperature to produce mill products (billets, bars, plates, etc.). In some cases, tungsten parts are produced by hot isostatic pressing. Metal injection molding (MIM) is used for the production of small components with complex shapes [2–5]. In general, pressing and sintering of W is not used to manufacture near-net shape parts because of the high temperatures required for sintering (2100 °C–2600 °C). W is difficult to machine, making the manufacture of complex shapes expensive.

The Selective Laser Melting (SLM) technique is gaining popularity for manufacturing complex net shaped parts of many materials. The SLM technique uses laser as the energy source and powder as the starting raw material. The part is manufactured layer-by-layer by melting the powder. Several studies have been reported in the literature discussing the SLM processing of metals like Fe, steel, Ti alloys, Cu alloys, Al alloys etc. [6–12]. A good understanding of the effect of process conditions like laser power, hatch spacing, scan speed, and energy density on the densification of the powder has been gained from these studies. However, very few studies have been reported dealing with SLM processing of high melting temperature metals like W, Ta, Mo etc. [13–16].

SLM processing of W is complex and challenging due to its high melting point and high thermal conductivity. Understanding the effect of process parameters like laser power, hatch spacing, and scan speed on the densification of W powder is crucial for fabricating parts with high mechanical properties. A study was undertaken to understand the effect of process parameters like hatch spacing and scan speed on the densification of tungsten by the SLM technique. It was found that the resulting density is inversely proportional to hatch spacing and scan speed, with scan speed being the dominant factor.

2. Experimental procedures

W powder of average size 30 μm was used as starting material in the study. The physical properties of the W powder are shown in Table 1. The morphology of the powder is shown in Fig. 1. SLM experiments in the study were carried out using a Concept Laser machine (Model: Mlab Cusing R). Experiments were conducted at hatch spacings of 15 and 30 μm and scan speeds in the range 200–1400 mm/s. A constant laser power of 90 W and a powder layer thickness of 30 μm were used in the study. Rectangular cuboids of 7.8 ± 1.4 mm × 10.1 ± 0.1 mm × 10.1 ± 0.04 mm were printed at various process parameters and analyzed for densification. The samples were built on a steel base

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Table 1
Physical properties of the W powder used in the present study.

Property	Value
Bulk density (g/cm^3)	8.25
Tap density (g/cm^3)	10.64
Hall flow (s/50 g)	11
Carney flow (s/50 g)	7.4
BET (m^2/g)	0.02

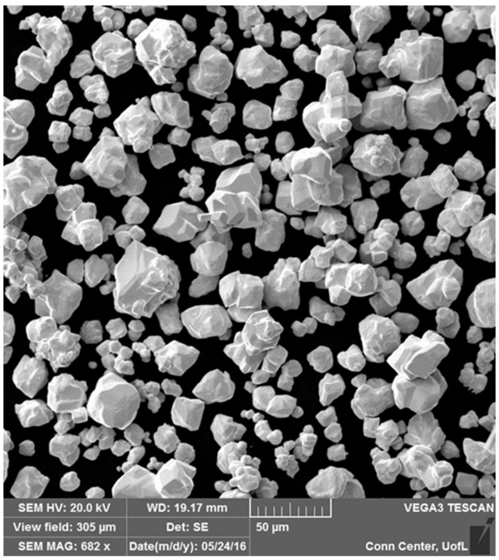

Fig. 1. Morphology of the W powder.

Table 2
Summary of the experimental.

Laser power (W)	Scan speed (mm/s)	Layer thickness (µm)	Hatch spacing (µm)
90	200	30	30
90	400	30	30
90	600	30	30
90	800	30	30
90	1000	30	30
90	1200	30	30
90	1400	30	30
90	200	30	15
90	400	30	15
90	600	30	15
90	800	30	15
90	1000	30	15
90	1200	30	15
90	1400	30	15

plate. After printing, the samples were sectioned from the base plate. The density of the samples was estimated based on the weight and dimension of the samples. A summary of the experimental conditions used in the present study is shown in Table 2. The samples with hatch spacing of 30 µm were carried out in the first build and the samples with hatch spacing of 15 µm were carried out in the second build. The statistical analysis of the results was carried out with the software Minitab version 17.

3. Results and discussion

The final density of the samples processed under different conditions is shown in Table 3. Densities in the range of 59–75% theoretical were obtained. The densities were similar to those reported by Zhou et al. [15] and Zhang et al. [16].

Table 3
Final density of the W samples processed at different conditions.

Laser power (W)	Scan speed (mm/s)	Layer thickness (µm)	Hatch spacing (µm)	Energy density (J/mm^3)	Final density (g/cm3)	% Theoretical density
90	200	30	30	500	12.71	66%
90	400	30	30	250	13.45	70%
90	600	30	30	166.7	12.60	65%
90	800	30	30	125	12.51	65%
90	1000	30	30	100	12.04	62%
90	1200	30	30	83.3	11.75	61%
90	1400	30	30	71.4	11.34	59%
90	200	30	15	1000	14.38	75%
90	400	30	15	500	13.44	70%
90	600	30	15	333.3	12.81	66%
90	800	30	15	250	12.56	65%
90	1000	30	15	200	12.46	65%
90	1200	30	15	166.7	11.60	60%
90	1400	30	15	142.9	12.07	63%

The main effects plot showing the influence of scan speed and hatch spacing is shown in Fig. 2. The data clearly shows an increase in densification of tungsten with a decrease in scan speed and hatch spacing. A similar influence of scan speed on the densification of tungsten was reported in a study by Zhang et al. [16].

Response surface regression analysis was carried out for the data shown in Table 3 to quantify the effect of scan speed and hatch spacing on the densification of W. The results from the analysis are shown in Table 4. The P-value for the scan speed was less than 0.05 indicating a major influence on the densification of the W. The P-value of hatch spacing was 0.057 and is slightly above 0.05 suggesting a lower influence on densification of W samples compared to hatch spacing. The analysis also shows that scan speed is the dominant factor, contributing to 75.7% of the variation in densification, while hatch spacing contributed only 7.1%.

The contour plot showing the influence of scan speed and hatch spacing on the final density of W is shown in Fig. 3. The contour plot clearly shows the dominant effect of scan speed on the density of W samples as compared to hatch spacing. At any scan speed, the density of the W was fairly constant with change in hatch spacing. The high density of W was obtained at low scan speed and hatch spacing. The high thermal conductivity of W might be the reason for the lack of significant effect of hatch spacing on densification.

The energy density (E) for the experiments carried out in the present study was estimated based on Eq. (1).

$$E = \frac{P}{h^{*}v^{*}t} \tag{1}$$

where P is laser power, h is hatch spacing, v is scan speed and t is powder layer thickness. The densification of tungsten samples was found to increase with an increase in energy density Fig. 4. A maximum density of 75% theoretical was obtained at an energy density of 1000 J/mm^2.

The SEM micrographs of the sample processed at scan speed of 1200 mm/s and hatch spacing of 15 µm is shown in Fig. 5. The SEM micrographs clearly show balling phenomena of W powders during SLM processing. W balling was reported in a prior study by Zhou et al. [15]. The balling phenomenon occurs primarily due to incomplete wetting and spreading of W melt droplets exposed to the laser. The solidification time of molten tungsten droplets is very short due to the high thermal conductivity of tungsten. The solidification time is much shorter than the spreading time, resulting in molten W droplets that solidify without completing the spreading process. The low power used in the study (90 W) is not sufficient to completely melt the W powder and reduce the viscosity of the partially melted W droplets. The low