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Physics Procedia 41 (2013) 843 – 848

Physics Procedia

Lasers in Manufacturing Conference 2013

Microstructure and properties of selective laser melted high hardness tool steel

F. Feuerhahn[a]*, A. Schulz[b], T. Seefeld[a], F. Vollertsen[a]

[a]BIAS - Bremer Institut für angewandte Strahltechnik GmbH, Klagenfurter Str. 2, 28359 Bremen
[b]Stiftung Institut für Werkstofftechnik, Badgasteiner Str. 3, 28359 Bremen

Abstract

A secondary hardening tool steel material X110CrMoVAl 8-2 was successfully processed by selective laser melting (SLM), producing defect free samples of high density. The microstructure appeared irregular after SLM, which was attributed to locally different temper states in consequence of the SLM process pattern. By a subsequent heat treatment, a homogeneous microstructure with ultrafine carbide precipitations and a very high resulting hardness of 765 HV were achieved. The hardness came very close to that of the same material processed by spray forming and forging, whilst the SLM microstructure was significantly finer. Therefore this tool steel material was considered as highly promising for SLM manufacturing of tools, e.g. for micro tooling applications.

Keywords: SLM; Selctive Laser Melting; X110CrMoVAl 8-2; Tool Steel; Heat Treatment; Spray Forming; Microstructure; Hardness

1. Motivation / State of the Art

For more than a decade, selective laser melting (SLM) has been considered a key additive manufacturing technology for rapid prototyping, rapid manufacturing and rapid tooling [1]. It allows for the consolidation of a vast variety of metallic powder materials into dense components of arbitrary 3D geometry [2]. However, only a limited number of suitable materials are available for tooling applications with very high hardness requirements. These materials will often have a limited weldability, which can be challenging in an SLM

* Corresponding author. Tel.: +49-421-218-58107; fax: +49-421-218-58063.
E-mail address: feuerhahn@bias.de.

doi:10.1016/j.phpro.2013.03.157

process [3]. Hardness levels significantly above 58 HRC (ca. 650 HV) are not yet commonly achieved in rapid tooling with available tool steel materials, and there is thus a strong demand for SLM solutions that can provide tools with significantly higher hardness levels.

2. Experimental

A novel tool steel material denominated as X110CrMoVAl 8-2 was investigated. The chemical composition is given in Table 1. Due to its alloy composition this cold work steel is suitable for stamps, dies, shearing blades and other cutting or punching tools according to a comparable commercial cold work steel Böhler K340 [4]. In particular this steel is useful in adhesive wear applications, because of its good wear properties. Another positive property in relation to the area of application is its high pressure resistance combined with its high dimensional stability after heat treatment [5].

Table 1. Chemical composition of the material X110CrMoVAl8-2 (wt.-%)

Fe	C	Cr	Mo	V	Si	Mn	Al	Nb	N
bal.	1.04	7.95	2.12	0.41	1.08	0.22	1.04	0.04	0.013

Gas atomized powder with a particle size <75 µm (available as overspray powder from spray forming (Osprey) experiments [6]) was selective laser melted to produce cube shaped specimen with dimensions of 10×10×10 mm³ on a steel substrate. A Realizer 250 SLM machine with a 200 W IPG single mode fiber laser was employed using the parameter set given in Table 2. The single mode laser was operating in continuous wave mode.

After SLM processing, specimens underwent a heat treatment cycle indicated in Fig. 1, involving stress relieve for 3 h at 500 °C before austenitizing in vacuum at 1080 °C and quenching with 6 bar nitrogen, followed by three tempers for 2 h at 535 °C for secondary hardening. Microstructure and Vickers hardness were investigated before and after hardening and compared to the same material produced by spray forming followed by forging and a similar hardening process [6].

Table 2. Parameters used in the selective laser melting process

Parameter	Sign	Setting	
Laser power	P	150	W
Scanning speed	v	700	mm/s
Hatch distance	a	75	µm
Layer Thickness	Δz	30	µm
Preheating Temperature	T	240	°C

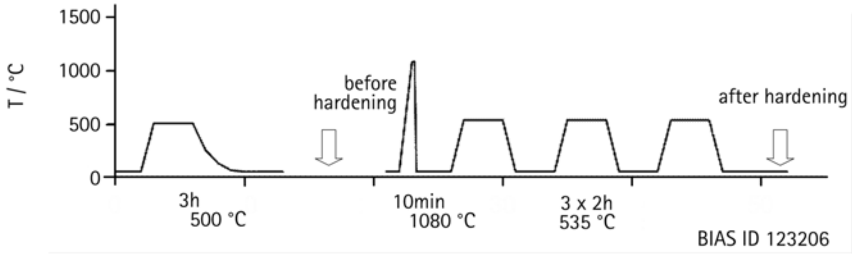

Fig. 1. Heat treatment cycle applied to X110CrMoVAl 8-2 material after selective laser melting

Furthermore, wear resistance and the coefficient of friction were probed with a ball on disc tribometer. A Si_3N_4 ball with a diameter of 10 mm was used.

The applied load was set to 10 N and the angular velocity to 0.5 Hz. The wear resistance were evaluated, using a track length of 10.01 mm, after a testing time of 24 h the total sliding distance was about 864 m.

Temperature and humidity were controlled in a range of 21 °C to 23 °C and 39 % to 41 %, respectively. The worn surfaces of the samples as well as the used Si_3N_4 ball were observed using a Keyence VK9700 laser-scanning confocal microscope.

3. Results and Discussion

A cross section of a specimen after SLM and stress relieve is given in Fig. 2, showing straight side walls and a comparatively uneven top surface. The pattern of layers and lines of the SLM processing is clearly observed at this scale. At higher magnification, each line of the final layer featured a brighter zone next to a darker zone adjacent to the following layer, making a regular microstructural pattern indicating an alternation of temper states due to heat affect from subsequent lines. In the bulk of specimen it can be seen how this was changed into a more irregular pattern by multiple melting and heat influence cycles from subsequent layers.

A detail of this microstructure is provided at higher magnification in Fig. 3a, that supports the finding of different temper states corresponding to the laser melting pattern. It is noteworthy that no cracks and only small pores were observed in the cross section at this magnification. Moreover, very few microscopically visible carbide precipitations were found in this condition of the material [6]. The hardness of this material was 493±3.9 HV10 before hardening.

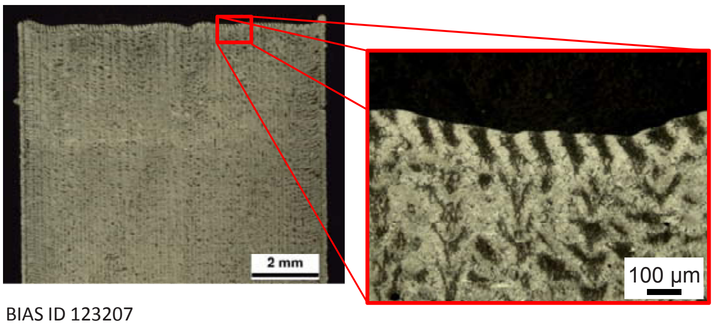

Fig. 2. Cross-section of SLM generated specimen with close-up of the final layers, generated with the parameter settings given in table 2

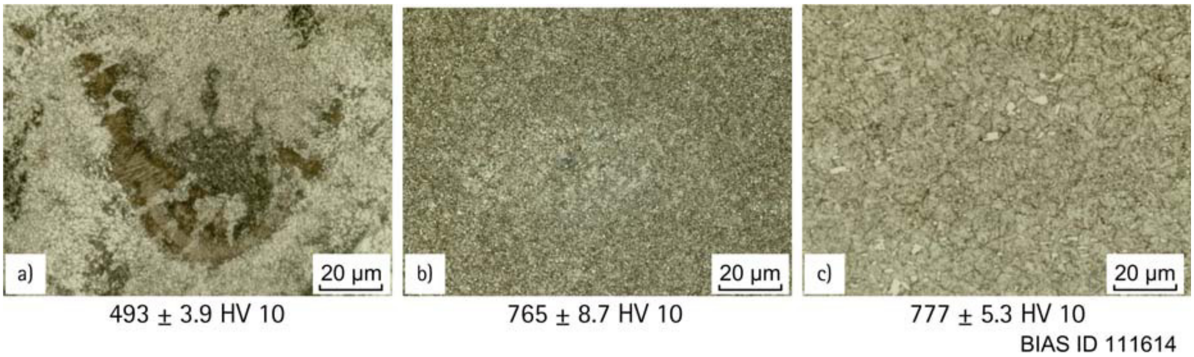

Fig. 3. (a) SLM sample before hardening; (b) SLM sample after hardening; (c) Spray formed and forged sample after hardening

After a full heat treatment cycle, the cross section showed a fine and homogeneous microstructure free of a pattern corresponding to the laser melting scheme (Fig. 3b). A large number of very small carbides were observed, with dimensions of the largest carbides not exceeding 2 µm. The hardness increased to remarkable 765±8.7 HV10.

For comparison, a spray formed and forged tool steel of the same material gained a slightly higher hardness of 777±5.3 HV10 after a similar heat treatment cycle. In the microstructure of this material, however, carbide precipitations were less in number, significantly larger in size, and generally more irregular in shape (Fig. 3c). It should be noted that spray forming is a process known for producing materials with exceptional properties due to their particularly fine and homogeneous microstructures [7]. In view of this, the combination of high hardness and ultrafine microstructure of the SLM material must be considered as highly promising for tooling applications, especially for micro tooling.

Proving the good materials properties of wear resistance, the selective laser melted and heat treated specimens were probed in a tribological test to investigate the wear volume and its coefficient of friction. The specimens were embedded in demotec 20, a cold polymerisate used for metallography preparation. The embedded specimens underwent a cycle of grinding and polishing to ensure the same initial condition to all tested samples. In addition for the observation of the worn surfaces and validation of the wear volume it was necessary to have a polished surface. Fig. 4a shows the worn surface after tribological testing and three close ups of one of the wear marks as well as their profile along the line drawn in the close up figure (Fig.4b). The wear volume was calculated as the median of the measurements at three points along the wear mark. Because of the undefined conditions in the turning points the close ups were set to 2.5 mm; 5 mm and 7.5 mm.

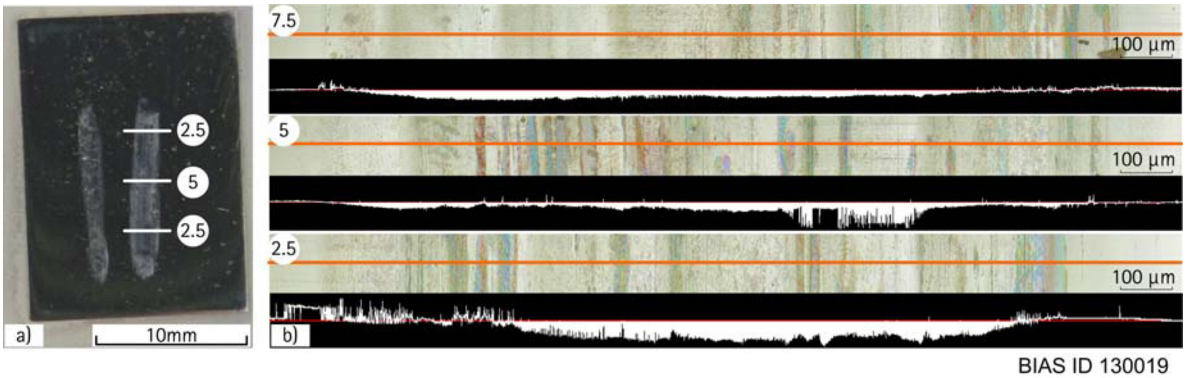

Fig. 4. (a) Representative sample used in the tribological test; (b) close up of the wear mark and the detected profile along the drawn line

For the tribological test six wear marks were set on three identical samples, it was expected to get a homogeneous result for all six wear marks. The obtained results -the coefficient of friction and the wear volume- are plotted in a diagram (Fig. 5). The microscopical evaluation showed that the wear volume was not constant in the small represented range. It is between 420 ×10³ µm³ and 105 ×10³ µm³, most of the specimens exhibited a wear volume of about 200 ×10³ µm³. The median of the detected coefficient of friction was about 0.73. An effect of an increasing coefficient of friction causing an increasing wear volume was not observed. At this point there is no explanation for the two samples which deviate significantly from the mean value of wear volume.

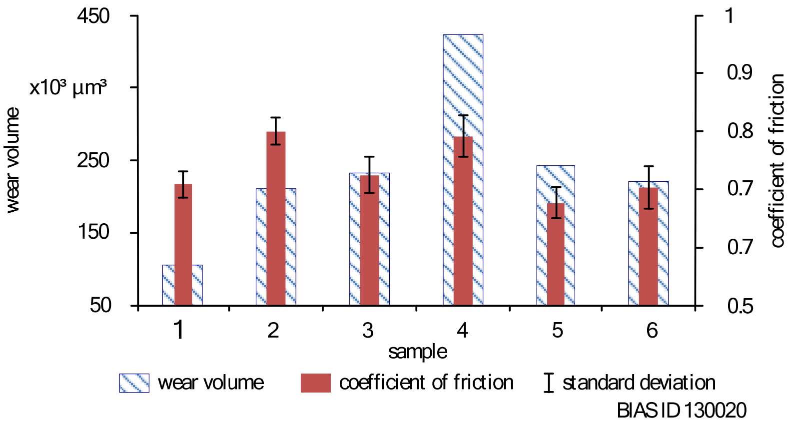

Fig. 5. Wear volume and coefficient of friction of the generated and heat treated samples

The investigated material is considered suitable for all applications where a high degree of dimensional stability and repeat accuracy is essential like in micro tooling applications. Micro rotary swaging is an application in the collaborative research center SFB 747 [8], therefore some tools were selective laser melted. A near net shape SLM generated micro rotary swaging tool is shown in Fig. 6a. After the SLM process and heat treatment the tools were machined by micro milling to make a finishing of the surfaces as shown in Fig. 6b and 6c.

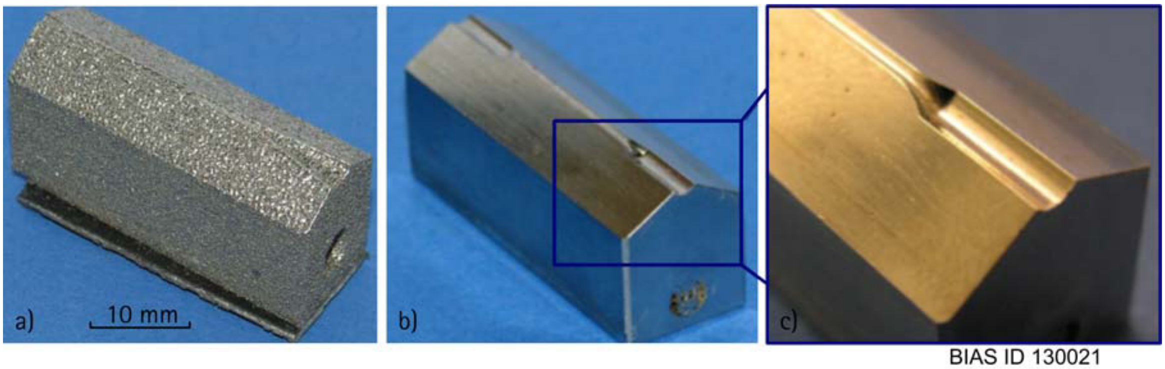

Fig. 6. (a) SLM near net shaped micro rotary swaging tool; (b) Micro rotary swaging tool after micro milling (c) Close up surface detail

Summary

- It was possible to process the X110CrMoVAl 8-2 by selective laser melting, the specimens were microscopical defect free, no cracks and only small voids were observed
- By a subsequent heat treatment, a homogeneous microstructure with ultrafine carbide precipitations and a very high hardness of 765 HV was achieved
- Comparing selective laser melted specimens with specimens processed by spray forming and forging, the SLM generated specimens feature a significantly finer microstructure
- The tribological test showed a scatter of wear volume, this still should be investigated

Acknowledgements

The authors gratefully acknowledge the financial support by DFG (German Research Foundation) for subproject C1 and C6 within the SFB 747 (Collaborative Research Center) ”Mikrokaltumformen” (micro cold forming) which lead to the reported results.

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