Journal of Materials Processing Tech. 255 (2018) 679–688

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

journal homepage: www.elsevier.com/locate/jmatprotec

General investigations on processing tool steel X40CrMoV5-1 with selective laser melting

Julian Krell*, Arne Röttger, Karina Geenen, Werner Theisen

Chair of Materials Technology, Institute for Materials, Ruhr-Universität, Bochum, Germany

ARTICLE INFO

Keywords:
Additive manufacturing
Selective laser melting
Tool steel
Solidification behaviour
Phase transformation
Segregation

ABSTRACT

The X40CrMoV5-1 (H13) hot work tool steel was densified by selective laser melting (SLM) using different laser parameters and preheating temperatures. The porosity and crack densities of the processed specimen were determined, the resulting microstructure characterized, tempering hardness diagrams recorded and the reusability of the powder assessed.

The X40CrMoV5-1 steel showed a good densification behaviour. Relative densities of above 99.5% were obtained. After SLM densification, the specimen showed a fine-grained microstructure, with a cellular arrangement consisting of ferrite and austenite. Although the microstructure did not change with preheating temperature, a decrease in crack density could be observed for higher preheating temperatures. By combining microstructural observations with some simulations, a new model describing the microstructural evolution of SLM-densified X40CrMoV5-1 is suggested. The peak in secondary hardness after tempering SLM-densified X40CrMoV5-1 was observed at higher temperatures compared to the cast reference steel in the same heat treatment condition.

1. Introduction

To save resources, shorten manufacturing times and improve part quality, tools are often specially customized for manufacturing processes. Modern simulation techniques such as FEM allow the optimal tool shape to be determined.

However, with increasing geometrical complexity, producing customized tools using conventional manufacturing processes becomes exceedingly time and energy consuming (or may not even be possible at all). Thus the optimal tool shape, while known, may not be achievable.

One promising solution in this context is additive manufacturing technology. Given that the mechanical demands on tools are usually high, selective laser melting (SLM) is one of the most promising additive manufacturing technologies for manufacturing highly complex tool parts. According to Tolosa et al. materials densified by SLM exhibit tensile strengths equal to or even better than those obtained via conventional manufacturing processes such as casting and forging (Tolosa et al., 2010). As a layer-by-layer powder bed process, SLM provides the possibility of nearly unrestricted freedom in design. *Bremen* for example showed that the production of internal cooling channels with arbitrary orientation inside a tool is possible. This in turn can lead to reduced cycle times and improved part quality (Bremen, 2012).

In recent years SLM has been the focus of extensive research. The processing of a wide variety of materials, including nickel base alloys, aluminium alloys, cobalt base alloys, titanium alloys and of course, iron based steels, has been investigated. Despite the obvious differences, the research has found some commonalities in the microstructure of SLM-processed parts of these different alloy groups. Most of the material, when produced with SLM displays a hierarchical microstructure consisting of different grains at a macro scale, a cellular subgrain structure on the microscale and nano scaled precipitations inside this cellular structure. This was observed by Wang et al. (Wang et al., 2016) and Zhong et al. (Zhong et al., 2016) in stainless steel 316L, by Bai et al. in maraging steel 300 (Bai et al., 2017), by Qian et al. in a Cobalt based dental alloy (Qian et al., 2015), by Thies et al. in SLM processed AlSi10Mg (Thijs et al., 2013), by Mostafa et al. for Ni-base superalloy Inconel 718 (Mostafa et al., 2017), but also for some alloys undergoing a phase transformation in solid state during cooling like the martensitic stainless steel AISI 420 investigated by Krakhmalev et al. (Krakhmalev et al., 2015). The occurance of this subgrain cellular structure is mainly linked to the microsegregation of heavy elements like Mo or Nb, or in the case of AlSi10Mg to the microsegregation of Si and is usually observed to decompose upon annealing. Prashanth and Eckert investigated the formation of this metastable cellular structure and concluded that it is caused by Bernard Maragoni driven instability and particle accumulated structure formation in combination with the

* Corresponding author at: Ruhr-Universität Bochum, Lehrstuhl Werkstofftechnik, Universitätsstr. 150, D 44801 Bochum, Germany.
E-mail address: krell@wtech.rub.de (J. Krell).

https://doi.org/10.1016/j.jmatprotec.2018.01.012
Received 6 June 2017; Received in revised form 19 December 2017; Accepted 16 January 2018
0924-0136/

extreme thermal conditions present during SLM (Prashanth and Eckert, 2017).

Next to these processes, which occur during solidification, the repetitive heat exposure of the already solidified material can be another important factor in the microstructural evolution of selective laser melted material. For materials with high and low temperature allotropes this intrinsic heat treatment can change the microstructure and phase composition of the material. Barriobero-Vila et al. have shown that by using an adapted scanning strategy the amount of unwanted α´ martensite in Ti6Al4V can significantly be reduced by decomposition in the solid state ($\alpha' \rightarrow \alpha + \beta$) (Barriobero-Vila et al., 2017). Whereas Krakhmalev et al. have reported a significant higher amounts of retained austenite in the lower layers of selective laser melted parts of the martensitic stainless steel AISI 430, which they attributed to in-situ carbon partitioning (Krakhmalev et al., 2015).

In order to understand the microstructural evolution of a material during SLM, these process intrinsic aspects have to be considered, as well as the processability of the material and its metallurgical characteristics.

Martensitic hardenable tool steels, like the H13 tool steel investigated in this study, exhibit a complex processing behaviour due to possible phase transformations in the solid state. The associated changes in specific volume during phase transformation in the solid can cause additional stresses, thus promoting crack propagation and distortion.

As one of the first researchers in this field *Over* investigated SLM-densification of tool steels and showed that scanning speed has a decisive influence on attained densities and residual tensions (Over, 2003). The dependence of relative density on scan rate was later also confirmed by Taha et al., who showed that for an ultra-high carbon steel greater densities were achieved with decreasing scan rate (Taha et al., 2012). Kempen et al. showed that the crack density and distortion of tool steels can be reduced by base plate preheating (Kempen et al., 2014). Later, Holzweissig investigated the microstructure of SLM-densified H13 tool steel in more detail and found significant amounts of residual austenite in an otherwise martensitic matrix (Holzweissig et al., 2015). Mertens et al. first investigated the effect of powder bed preheating on microstructure and mechanical properties of H13 tool steel (Mertens et al., 2016). In agreement with the research cited earlier, they reported of a fine cellular microstructure consisting of martensite and retained austenite, which does not significantly change for different preheating temperatures. The mechanical properties of the generated parts and x-ray diffraction suggested, that a preheating temperature of 400 °C led to a different formation of the microstructure and the formation of bainite instead of martensite, indicating that preheating may eliminate the necessity for a strengthening post heat treatment.

However, the effect of preheating around the martensite start temperature has not yet been investigated in detail, as well as the effect of different preheating temperatures on the crack density in H13 tool steel or the effect of preheating on powder reusability. It is the aim of the present study to answer these questions and furthermore, to gain inside into the microstructural evolution of H13 tool steel during SLM.

To comprehensively investigate the densification behaviour, the H13 hot work tool steel was densified via SLM using preheating temperatures in a range from room temperature to 300 °C. In addition, one specimen was processed at a preheating temperature of 300 °C and held at that temperature for two more hours to investigate whether the microstructure can be manipulated using preheating and an isothermal holding strategy ("+2 h"). The microstructure and phases of the densified tool steel specimens were then investigated and characterized using X-ray diffraction (XRD), electron backscatter (EBSD) diffraction and scanning electron microscopy (SEM). The volume fractions and cell size of the different phases were determined by image analysis. In addition, the hardness of the specimen was measured after external tempering treatment at temperatures between 100 and 700 °C, subsequent to the SLM processing. To assess the reusability of the residual powder after processing, the oxygen content, carbon content and the flowability of gas-atomized H13 powder were determined before and after SLM processing.

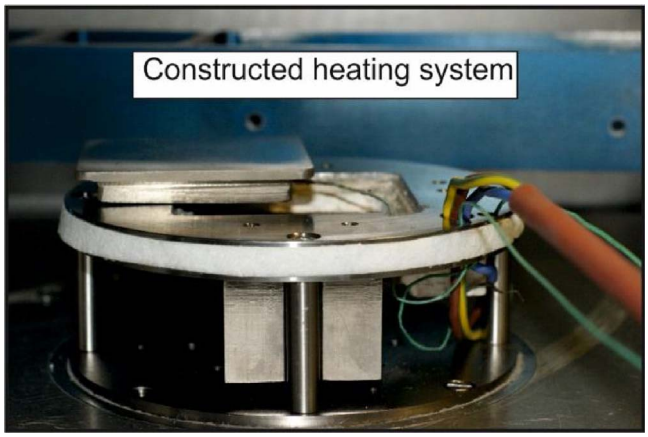

Fig. 1. Heating system installed in the SLM machine to allow preheating temperatures up to 300 °C.

2. Methods

2.1. Selective laser melting

The SLM specimen for this work were produced with the SLM machine Realizer II ^{SLM} from MCP HEK Tooling GmbH (wavelength 1076.5 nm, focal diameter ~90 µm, maximum energy ~100 W). A new base plate heating system was designed and installed into the machine in order to allow preheating temperatures up to 300 °C (Fig. 1). The thermocouple used for controlling the temperature was placed approximately 1 mm under the surface of the base plate´s centre. Preheating the baseplate to 300 °C resulted in temperature of about 285 °C on the top most layer of a specimen with 10mm height. The specimens investigated for this work were tetragonal in shape and 5 × 5 x 10 mm in size (x, y, z = build-up direction). The SLM process was carried out in an argon atmosphere (10mbar outlet pressure, O_2 content less than 0.3 vol%). Based on the results of a previously conducted parameter study with the same machine (Röttger et al., 2016), we decided to use the maximum output power of 100 W, a point distance of 30 µm and layer thickness of 30 µm. The hatch exposure time was then varied between 75 and 150 µs to determine the optimal energy input. These parameters result in a scan velocity between 200 and 400 mm/s. The porosity and crack density of the resulting samples were measured using quantitative image analysis (Section 2.7). The parameter set (100 µs, 30 µm, ~300 mm/s scan velocity) which showed the smallest crack density for a porosity below 0.5% was then used to build up the specimen at preheating temperatures between RT and 300 °C. This parameter set resulted in a specific energy input of 111 J/mm^3. The building time with these parameters and thus, the time at preheating temperature for each set of specimen was about 120 min.

2.2. Powder handling and experiment sequence

The powder used for SLM processing was mechanically sieved from a powder bulk into a fraction of 25–63 µm in a nitrogen atmosphere. After one SLM process, the non-densified powder was sieved, dried (100 °C, 2 h, inert gas) and reused for further processing. The powder was sieved in order to separate any splashes or conglomerated powder particles from it, as these could hamper the flow characteristics of the powder and are known to be rich in oxygen (Röttger et al., 2016). Drying was performed to ensure best comparability in flow time measurements. Drying removes humidity from the powder, which in the