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Regular Article

Microstructure, mechanical behavior, and wear properties of FeCrMoVC steel prepared by selective laser melting and casting

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Tool steels are known for their marked wear resistance as well as hardness, strength, and adequate toughness. By an appropriate alloy design and manufacturing process, the microstructure and related properties of tool steels can be tailored and adjusted within a large range. Thereby, as-cast steels may show an enhanced wear resistance and strength compared to heat-treated steels resulting in a longer tool life [1]. However, the impact toughness of high-alloyed cast tool steels is in general lower compared to deformed steels due to the coarse carbide network along the primary grain boundaries and has, therefore, to be enhanced [2]. By appropriate grain refinement an increase in toughness and strength can be obtained.

Selective laser melting (SLM) presents an additive manufacturing technology enabling a significant refinement of the grains and microstructural constituents due to very high solidification rates within the process. The investigated Fe85Cr4Mo8V1C1 (wt%) tool steel is generally prepared by special casting conditions involving high cooling rates and pure casting conditions leading to a high compression strength and hardness already in the cast state [3]. Hence, SLM should be suitable for processing of FeCrMoVC.

Various authors report a significantly different mechanical and wear behavior of SLM fabricated samples compared to their cast equivalents. For aluminum alloys [4,5], titanium alloys [6,7], CoCr alloys [8,9], and tool steels [10] an increase of the wear resistance of SLM produced parts was observed. However, no general increase of wear resistance with increasing material strength properties or hardness was observed [11]. Hence, further studies are necessary to fully understand the influence of the SLM process on the mechanical and wear properties.

All SLM experiments were carried out with Fe85Cr4Mo8V1C1 (wt%) gas atomized powder with a particle size distribution of 15 to 63 μm on a SLM 250 HL device (SLM Solutions) equipped with a 400 W Yb:YAG laser. Thereby, no significant deviation between the nominal composition, the powder composition, SLM part composition, and the cast composition could be detected by chemical analysis. The production process of the cast samples was described in [12]. Using a copper mold, high cooling rates can be achieved in the casting process leading to homogeneous properties over the whole casting sample. As reference, 1.2379 (X155CrVMo12-1) steel (Marks) was used.

The microstructure of the samples and the wear surfaces were investigated by scanning electron microscopy (SEM; Leo 1530 Gemini). For this purpose, all samples were deep-etched with a solution of $FeCl_3$, nitric acid, and hydrochloric acid. Phase identification, determination of the phase contents and valuation of the grain size was conducted by X-ray diffraction and Rietveld analysis (XRD; STOE Stadi P, Mo $K_{\alpha 1}$ radiation).

Quasi-static room temperature compression tests were performed with at least seven samples (Ø3 mm × 6 mm), using a constant strain rate of 10^{-3} s^{-1} to study the deformation and failure behavior (Model 8562, Instron). The Rockwell macrohardness was determined using a hardness tester (CV Instruments) applying a force of 1471.1 N with a holding time of 4 s (10 indentations). To study the wear behavior, pin-

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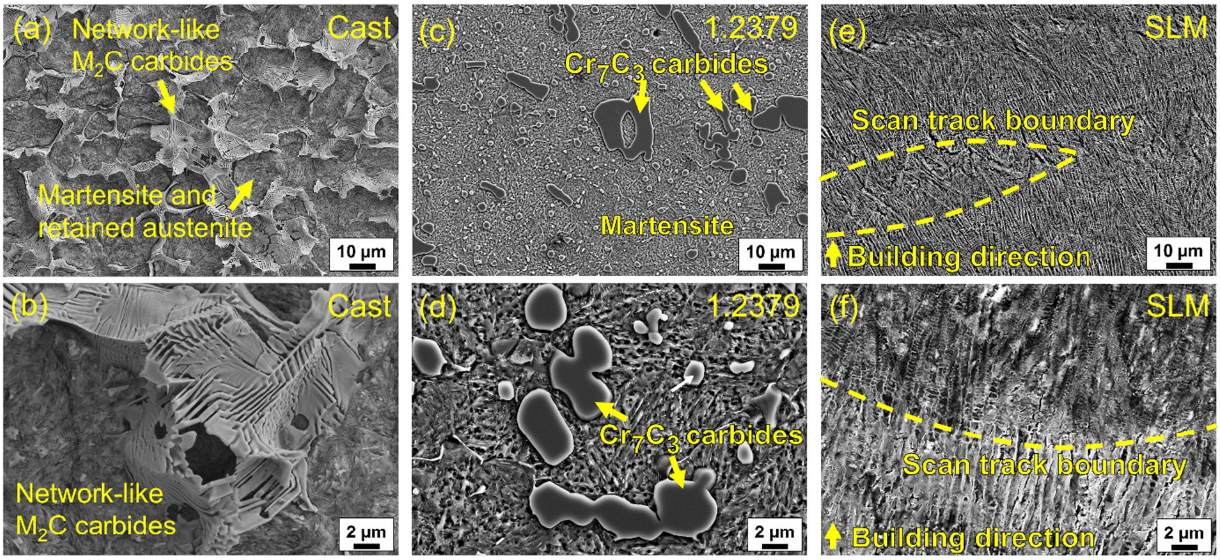

Fig. 1. SEM images (secondary electron mode) of deep-etched samples highlighting the carbide morphology. Cast state of the FeCrMoVC alloy (a, b), 1.2379 steel used as reference material (c, d), SLM sample of the FeCrMoVC alloy (e, f).

on-disk tests were conducted according to DIN EN 1071-13 with a Tribometer (T500, Nanovea) using five pins made from the tested alloys (Ø6 mm × 30 mm) and a ceramic SiC P120 grinding wheel. A force of 20 N was applied and the tests were carried out for a measuring distance of 37.7 m. The surface roughness of the wear surfaces was measured according to DIN EN ISO 4287 using a FRT MicroProf with a measuring length of 5 mm at five positions on the cylindrical surface of the samples.

Fig. 1 presents SEM images of the deep etched microstructure of the investigated FeCrMoVC modifications and the reference material. The arrangement of the carbides is exposed.

The cast sample of the FeCrMoVC alloy consists of martensite (71 wt%), retained austenite (24 wt%), as well as Mo-rich M_2C (M = Mo, V, Cr) carbides (3 wt%), and V-rich MC (M = V, Mo) carbides (2 wt%) [13]. These complex carbides form a fine network-like structure as displayed in Fig. 1a,b.

Fig. 1c,d shows a SEM image of the reference steel (1.2379) which is composed of martensite (64 wt%), retained austenite (3 wt%), and dense isolated clusters of Cr_7C_3 carbides (33 wt%).

The FeCrMoVC SLM sample consists of martensite (73 wt%), retained austenite (15 wt%), carbides of the M_2C type (M = Mo, V, Cr) (6 wt%), and MC (M = V, Mo) (6 wt%). The carbide network has an elongated cell structure (Fig. 1f) and is orientated in building direction. In comparison to the cast sample, the carbides are refined and homogeneously distributed. The refinement is caused by the high cooling rates in the SLM process (10^5 K/s) which is around one thousand times higher than in the present casting process (10 K/s) [3,13]. Furthermore, the grain size in SLM processed FeCrMoVC (<200 nm) is decreased compared to the cast state (<1 µm).

A summary of the mechanical properties of the tested alloys is given in Table 1. The cast FeCrMoVC has a hardness of 59 ± 0.5 HRC, resulting from the high martensite content as well as the M_2C and MC carbides. Moreover, the engineering compression strength is around 3500 MPa combined with a fracture strain of 17 ± 1%. In comparison, the 1.2379 steel shows a hardness of 60.9 ± 0.7 HRC due to the higher martensite content and the much higher carbide content. Nevertheless, the difference of the average hardness is only around 1 HRC despite the 33 wt% Cr_7C_3 carbides in the 1.2379 compared to 5 wt% carbides in the cast sample. This is explained by the lower microhardness of the M_7C_3 carbides compared to M_2C and MC carbides [14]. The compression strength of the 1.2379 steel is 3190 ± 177 MPa, whereby the fracture strain amounts 23.5 ± 3%. The higher average compression strength of the cast FeCrMoVC sample mainly results from the network-like carbide structure and the deformation-induced transformation of retained austenite into martensite [12]. However, the network-like structure of the M_2C carbides in the cast sample provides fracture sites [2], which leads to a reduced fracture strain compared to the 1.2379 steel.

The SLM sample has a significantly increased hardness of 64.6 ± 0.3 HRC compared to the cast sample, an increased compression strength of 5326 ± 171 MPa, and a fracture strain of 15.6 ± 1%. This behavior is due to the refined microstructure of the SLM sample and the homogeneous dispersion of alloying elements and carbides leading to a Hall-Petch-type strengthening [3]. Furthermore, the combined carbide plus martensite content is increased which provides high hardness but causes embrittlement and, consequently, lowers the fracture strain.

The results of the wear tests are given in Table 1, respectively. The SLM samples show a significantly higher wear resistance compared to the cast FeCrMoVC samples and the 1.2379 reference steel. Fig. 2 displays height mappings and SEM images of the wear surfaces. With decreasing wear rate a decrease of the roughness of the wear surface is observed which results from the decreasing depth of the scratches. The depth of the scratches is strongly influenced by the morphology and properties of the phase constituents of the tested materials. With increasing hardness of the phases, a decreasing penetration depth of the abrasive SiC-particles of the grinding wheel was observed, leading to less material removal. Microcutting and microploughing are the

Table 1
Mechanical properties (engineering stress-strain values) of SLM processed FeCrMoVC, cast FeCrMoVC, and 1.2379 reference steel.

	Hardness (HRC)	Wear rate (mm^3/Nm)	Compression strength (MPa)	Fracture strain (%)
1.2379	60.9 ± 0.7	0.06039 ± 0.0037	3190 ± 177	23.5 ± 3
Cast FeCrMoVC	59 ± 0.5	0.08379 ± 0.01112	3536 ± 143	17 ± 1
SLM FeCrMoVC	64.6 ± 0.3	0.04506 ± 0.00295	5326 ± 171	15.6 ± 1