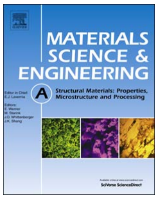
Materials Science & Engineering A 709 (2018) 82–89

Contents lists available at ScienceDirect

Materials Science & Engineering A

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



Microstructure and mechanical properties of stainless steel CX manufactured by Direct Metal Laser Sintering

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ARTICLE INFO

Keywords:
Stainless steel CX
Additive manufacturing
Microstructure
Mechanical properties
Fracture surface

ABSTRACT

In the present paper, the microstructural evolution and tensile properties of additively manufactured stainless steel CX were investigated. Using scanning electron microscope (SEM), several powder particle morphologies were identified in the stainless s steel CX feedstock powder where the spherical morphology was found to be the dominant one. In addition, X-ray diffraction (XRD) technique detected austenite and martensite phases in both stainless steel CX powder and as-built sample, whereas no carbide peak appeared on the XRD patterns. Moreover, lath or needle-like martensite phase was observed in the microstructure of the as-built sample. The level of porosity was very low in the as-built sample, indicating the manufacturing of a nearly fully dense sample. Furthermore, a high ultimate tensile strength together with a good elongation to fracture was obtained for the horizontally-built stainless steel CX sample. Finally, examination of the fracture surfaces after tensile tests confirmed the ductile failure mode of the samples, in which the pull-out of the scan tracks and coalescence of the voids resulted in the tear and final rupture. This study demonstrates the successful additive manufacturing of stainless steel CX with outstanding tensile properties.

1. Introduction

One of the well-known techniques for mass production of plastic parts is injection molding process, which includes several steps, namely injection of molten plastics, packing, cooling and ejection process [1]. Among the steps of injection molding, cooling plays an important role that influences the productivity and quality of the final molded parts [2,3]. A complex cooling system, which is able to induce a uniform thermal distribution, may decrease the shrinkage and warping defects in the parts and consequently, increase the productivity rate without compromising part quality [4–6].

Another important issue in injection molding is the material properties, which is used for production of the injection molds. Stainless steels are usually recommended for long service injection molding due to their superior mechanical properties and good corrosion resistance to water, vapor, salts and carbonates [7,8]. The corrosion properties of the stainless steels that are currently used in injection molding can decrease under elevated temperatures, so that introducing cooling channels in the dies can decrease the service temperature and maintain the corrosion properties. However, the main barrier against the industrial application of stainless steels (and other steels) as an injection mold material with complex cooling channels is the lack of an appropriate conventional manufacturing process, which does not require further welding [8]. Furthermore, application and exploring of new alloys with higher strength and corrosion resistance as a mold material is another challenge in injection molding.

Selective Laser Melting (SLM), which is also known as Direct Metal Laser Sintering (DMLS) [9], is a promising technology to additively manufacture metals and alloys. In SLM, a thin layer of a feedstock powder material is spread on the building platform. A high power laser melts the powder at specified points defined by a 3D model. After melting of certain points in the powder layer, the platform is moved down and a new powder layer is spread on it. This process is repeated until the successive individual powder layers are welded together and final part is built [10,11]. SLM technique has shown promising improvements in recent years to offer lower shape restrictions and geometrical complexity giving rise to manufacturing of more complicated parts for reduced lead times [12,13]. However, this technique is still in research and development phase and need continuous advancements to offer competitive surface roughness and dimensional accuracy to compete with conventional machining. To date, some research works have been published on the SLM fabrication of the injection molds using stainless and tool steel powders [14–17]. However, their main focus is on the feasibility and SLM process parameters optimization and unfortunately, microstructural evolution and mechanical properties of the fabricated parts have not been adequately addressed.

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http://dx.doi.org/10.1016/j.msea.2017.10.045
Received 23 August 2017; Received in revised form 12 October 2017; Accepted 13 October 2017
Available online 16 October 2017
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Currently, P20 mold steel, which is a low alloy tool steel with hardness as high as 30 HRC is used for applications, where there is a need for moderate strength, such as zinc die-casting. H13 tool steel, which is a chromium-molybdenum hot work steel, with hardness as high as 57 HRC is used for applications, where high strength along in elevated temperatures are needed such as aluminum die-casting. Grade 420 stainless steel is a high carbon steel with minimum 12% chromium, which possess excellent corrosion properties along with hardness as high as 50 HRC; thus, it is used in corrosive plastic and rubber injection molding applications, where there is a need for high corrosion properties and strength.

One of the biggest challenges with 3D printing of steels and stainless steels is that alloys with high content of carbon can not be printed appropriately due to presence of many cracks and subsurface pores during the printing process. Therefore, steels and stainless steels powders with similar properties yet lower carbon contents have been introduced by metal 3D printing companies to replace these very versatile alloys in the tool and die industry. Maraging steel is intended to replace P20 in not heat-treated form (33–35 HRC) and H13 in heat-treated form (53–57 HRC). At the same time, stainless steel CX is proposed to replace stainless steel grade 420 due to its superior strength and corrosion resistivity.

The biggest advantages of additive manufacturing for tool and die industry is the ability to introduce cooling channels inside the die inserts in order to cool the hot spots during service and increase the fatigue life of these parts. The introduced cooling cannels can be curvilinear channels that are impossible to manufacture using conventional methods without further welding procedures. The introduction of cooling channels to 3D printed maraging steels and stainless steel CX using Direct Metal Laser Sintering has been tested successfully in Europe and recently in North America.

Stainless steel CX is a newly developed tooling grade steel powder with very low carbon content and more than 11% chromium. Stainless steel CX possesses excellent corrosion resistance, high hardness (51 HRC), and outstanding mechanical strength enabling it to be a strong candidate for injection molding tools and extrusion dies for corrosive plastics and rubbers [18]. Additionally, the feedstock powder of high corrosion and wear resistant stainless steel CX has been recently produced and announced by EOS GmbH and can be used in DMLS machines. Therefore, this alloy can be considered as the first choice for several industrial applications, such as molding tool, where strength and corrosion resistance are of high importance. There are also other potential applications for additively manufactured stainless steel CX parts including marine, shipbuilding, subsea oil and gas, oceanography, energy, offshore technologies, and defence, where there is a need for a metal with high strength and good corrosion properties. It is noted that, the focus of this work is to successfully 3D print this new alloy, stainless steel CX, with the least porosity level and acceptable mechanical properties and hardness values.

Since the stainless steel CX powder and related DMLS process are very new, there is no information in the open literature regarding the microstructure and mechanical properties of the parts using this alloy fabricated by DMLS technique. Therefore, the microstructural evolution and mechanical behavior of DMLS-stainless steel CX are investigated for the first time in the present paper. This manuscript is the first scientific paper on the mechanical and microstructural characteristics of stainless steel CX built with optimum process parameters.

2. Experimental procedure

2.1. Materials and DMLS process

Table 1
Chemical composition of the stainless steel CX feedstock powder [18].

Element	Fe	Cr	Ni	Mo	Al	Mn	Si	C
Weight (%)	Balance	11–13	8.4–10	1.1–1.7	1.2–2	0.40	0.40	0.05

Table 2
DMLS process parameters used in the present research.

Laser type	Laser power (W)	Scanning speed (mm/s)	Hatching distance (μm)	Layer thickness (μm)
Yb-fibre	258.7	1066.7	100	30

Two types of samples, namely cube (15 × 15 × 15 mm) and cylindrical (12 cm in length and 12 mm in diameter), were built using stainless steel CX powder with nominal chemical composition shown in Table 1. It is noted that, the chemical composition of stainless steel CX is almost the same as UDDEHOLM CORRAX® precipitation hardening stainless mold steel. An EOS M290 machine located at Additive Metal Manufacturing Company in Concord, ON, Canada, was employed to conduct DMLS process. The DMLS process parameters, including laser power, scan speed, layer thickness, and layer thickness, used in this research are the ones already developed by EOS GmbH to achieve the least porosity and best mechanical properties provided in Table 2. It is noted that, the lower volumetric energy density used to melt this alloy during the DMLS process in comparison with stainless steel 17-4PH and stainless steel 316L can be due to the presence of different alloying content, mainly Nickel. It should be noted that, cylindrical samples were built in horizontal direction. The stripe scanning strategy, where the laser beam is rotated 67 degrees between successive layers, was used during the DMLS process. Moreover, the building platform temperature was increased and kept at 80 °C during the DMLS process to minimize the residual stresses in the samples.

2.2. Microstructural properties

Zeta-20 optical microscope (OM) and Jeol 6400 scanning electron microscope (SEM) were used to study the morphology of the stainless steel CX feedstock powder, cross-sectional microstructure of the powder, as-built cube sample, and features on the fracture surfaces after tensile test. Both powder and cube samples that were used for cross-sectional microstructure study were polished using conventional metallography methods to a 1 μm finish. Polished surfaces were then etched for 45 s using Kalling's reagent (5 g $CuCl_2$, 100 ml Hydrochloric acid and 100 ml Ethanol).

Phase composition of the feedstock powder and as-built cube samples was determined by X-ray diffraction (XRD) technique using a Bruker D8 Diffractometer with Co-Kα radiation ($\lambda = 0.178886$ nm), a step size of 0.02°, and a step time of one second over a 2θ range of 5–80° at 40 kV and 30 mA.

To estimate the stainless steel CX powder particle size, mapping technique was used. Using SEM, several series of pictures at different magnifications were taken from the powder particles and analyzed by ImageJ software [19], and the average particle size (APS) was calculated. Moreover, to measure the porosity percentage of the as-built cube sample, about thirty OM images were taken from its mirror-like surfaces after polishing and then using ImageJ software, the mean value of porosity percentage of the sample was reported.

2.3. Mechanical properties

A CLARK – Model CRM12 Rockwell hardness testing machine with a diamond indenter under 150 kg load was used to measure the hardness of the as-built cube samples. The hardness measurements were done both on the top surface of the samples, parallel to the build direction, and on the faces of the sample, perpendicular to the build direction. The hardness measurements were performed 10 times both on the top and sides of the samples to ensure repeatability of the procedures. The

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