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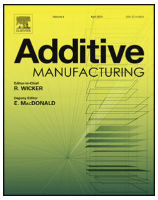

Full Length Article

Hot isostatic pressing of IN718 components manufactured by selective laser melting

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ABSTRACT

Selective laser melting and other additive manufacturing (AM) techniques have recently attracted substantial interest of both researchers and the processing industry. The freedom of design leads to completely new possibilities for constructions and, thus, to entirely new products. In the selective laser melting (SLM) process, the components are produced layer-wise using a laser beam. SLM is a powder bed based AM process and is characterized by the complete melting of the utilized powder material. Employing SLM, complex three-dimensional parts and light weight structures can be produced directly from 3D CAD data. However, although SLM is a very promising technology, there are still challenges to solve. In the present study, a close look is taken at the porosity. Under cyclic loading, pores can act as stress raisers and lead to premature crack initiations, which reduce the fatigue strength of the material. Hot isostatic pressing (HIP) offers the possibility to reduce the porosity. HIP combines high pressure and high temperature to produce materials with superior properties. The influence of the HIP process parameters on the density and microstructure of IN718 SLM components is investigated by means of micro X-ray computed tomography and scanning electron microscopy. The results of the experiments show that the majority of pores can be densified by means of HIP. On the other hand, some pores cannot be densified. The reason for this is seen in entrapped argon gas from the SLM process.

Introduction

The generic term *additive manufacturing* (AM) is an umbrella term for different manufacturing processes in which the components are built up layer-by-layer. Near-net-shape components can be manufactured directly from 3D CAD data and do not require further forming or process planning. So-called powder bed fusion or powder bed laser fabrication processes, such as selective laser melting (SLM), belong to the group of AM processes. In the SLM process, a powder layer (=powder bed) is selectively exposed to a high power laser beam (see Fig. 1). A scanner system moves the focus point of the laser according to the contour of the desired part. The powder is locally full melted, and the powder particles are bonded to each other. After this procedure, the build platform is lowered, and a new powder layer is applied with a recoater system (see Fig. 1). Subsequently, the new powder layer is selectively exposed to the laser. This procedure is repeated until the complete height of the part is obtained. The entire process takes place in an argon-filled chamber to avoid an oxygen and nitrogen contamination of the processed metal. The main advantages of SLM are the wide range of possible geometries (even with undercuts), the high flexibility of metallic feedstock powders, and the realization of inner structures with additional functions. Commonly used SLM powder materials are Ni-based superalloys, Fe-alloys, and Ti-alloys [1–4].

Inconel 718/IN718 (Special Metals Corporation, Huntington, USA) is one Ni-based superalloy commonly employed for high temperature applications [5]. Its superior mechanical properties, such as the high temperature strength and outstanding creep behavior, are mainly based on solid solution strengthening and precipitation strengthening [6,7]. SLM offers new possibilities to manufacture parts from IN718, especially in the aerospace industry, such as internal cooling structures, light weight structures or integrated sensors, which are not featured by conventional production methods (e.g. forming and machining). Thus, researchers, as well as the manufacturing industry are highly interested in this process [14]. IN718 powder can be successfully processed by SLM. Sev-

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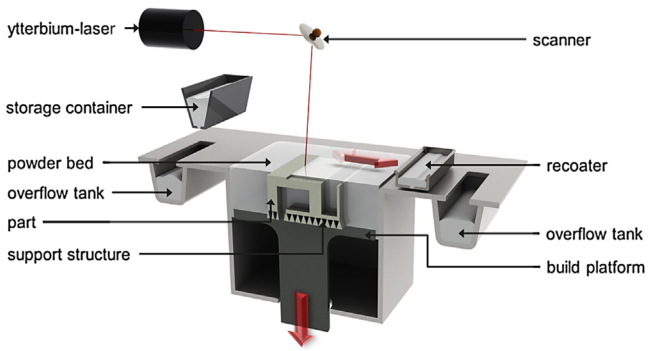

Fig. 1. SLM process sketch (source: DMRC).

eral researchers and institutions have already started to analyze the SLM building process with an IN718 powder feedstock and to investigate the mechanical properties of IN718 components made by SLM [8–13]. In general, the properties of components made by means of SLM are mainly determined by the parameters of the SLM process. For IN718, different columnar dendritic structures and different porosity values were observed, depending on the laser energy density [9,13]. High laser energy density leads to slender and uniformly distributed columnar dendrites and a low porosity [9]. So far, even with optimized parameters, SLM still faces challenges that need to be solved with regard to the quality of parts. One critical point is the poor surface quality immediately after manufacturing by means of SLM [15,16]. The surface roughness of components made by SLM is typically very high and depends on the SLM process characteristics. It is commonly known that a high surface roughness influences the fatigue strength negatively. Another main disadvantage of the SLM process is that completely dense parts cannot be obtained with this process [8,9,14]. Especially under cyclic loading, the remaining pores act as stress raisers and can lead to premature crack initiation, eventually reducing the fatigue strength of the component.

To improve the static and dynamic mechanical properties of SLM-parts, different post-processing methods moved into the focus of numeral investigations. HIP is increasingly attracting attention as a post-processing technique for SLM. HIP is an established technique, which is used for master forming, diffusion welding, compaction, and of course traditional sintering. High pressures and temperatures lead to diffusion and plastic deformation. The main parameters are temperature, pressure, and time [17–19]. Most literature related to IN718, combined with HIP processing is about the master forming of components by means of HIP and does not deal with the post-densification of SLM parts (e.g. [20,21]). Several studies reveal that the internal porosity of laser consolidated, laser deposited, and SLM processed parts made out of different powder materials, is strongly reduced by means of HIP and hence the mechanical properties are enhanced [22–28]. In the experiments of Leuders et al. [27] the fatigue strength (high-cycle fatigue) of Ti6Al4V fatigue samples, produced by SLM and compacted by HIP, was clearly improved. This effect was attributed to the reduction of the pore size and overall porosity, respectively. Some previous studies [23,25] already confirmed the positive effect of HIP post-processing for pure titanium samples. Likewise, CoCr alloy powder, (ASTM F75) processed by SLM and densified with HIP, showed a higher fatigue strength (high-cycle fatigue) compared to the as-built condition and the as-cast material [29]. The closure of all remaining pores and a complete recrystallization of the microstructure were identified as causes for this effect in [29]. Qiu et al. [28] showed for Ti6Al4 V alloys that in addition to the lower porosity, the quasi-static mechanical properties were changed due to heat treatment during the HIP process as well. In the as-built state, the tensile strength is high and the ductility is low due to fine martensitic needles in a typical SLM microstructure. After the HIP process, the tensile strength is reduced and the ductility is enhanced [28]. There exists a detailed study concerning the post-processing of IN718 made by means of selective electron beam melting (SEBM) [30] as well as a brief investigation of the HIP post-processing of IN718 made by means of direct laser deposition (DLD) [31]. The HIP post-processing of IN718 DLD samples reduced the anisotropy and improved the interlayer adhesion [31]. For SEBM microstructural findings were reported and a grain growth after HIP processing was recognized [30]. The investigation of the hardness after HIP showed that the HIP processing reduced the hardness when compared to its state directly after SEBM manufacturing [30]. The porosity before and after HIP processing was not quantified and discussed in both studies.

A fundamental problem not often taken into account is that the SLM process chamber is filled with an inert gas (e.g. argon) during the building processing and it is possible that the protective gas is encapsulated in cavities. Consequently, the complete closure of these pores would be hard to achieve by means of HIP. Furthermore, for an effective compression, the component should have a closed porosity to avoid pressure equalization inside the pores, which would prevent the pores from closing [17–19]. In our own studies [8], the sporadic presence of small pores which were open to the surface was shown in IN718 components, made by means of SLM. Also, it was shown that these pores could not be compacted by means of HIP. Hence, the sample must be encapsulated [8].

Overall, two important effects were identified that are responsible for the mechanical properties after post-processing the SLM components by HIP. The first is the reduction of pores. The second is the carefully controlled heat treatment.

2. Material and methods

For the conducted densification experiments, a simple geometric shape was chosen for the specimens. Flat rectangular specimens (26 mm × 7 mm × 1.5 mm) were processed vertically, using a SLM 250^{HL} machine (SLM Solutions GmbH, Germany) equipped with a 400 W fiber laser and SLM AutoFab software (Marcam Engineering GmbH, Germany). Inconel 718 powder was employed with an average particle size of approximately 30 μm. Fig. 2 shows a SEM image of the IN718 powder used and the particle size distribution. The particle size distribution was measured with a Mastersizer 2000 (Malvern Instruments Ltd, United Kingdom) system. This system uses laser diffraction to measure the size of particles.

Table 1 shows the composition of the IN718 samples used in the experiments. The composition was determined by X-ray fluorescence spectroscopy. This analysis was conducted at the *Revierlabor* (Chemische Laboratorien für Industrie und Umwelt GmbH, Essen, Germany). The results show that the composition listed in Table 1 is within the standard specification. The applied and optimized SLM process parameters are summarized in Table 2. The parameters were optimized to achieve a low porosity. Furthermore, fatigue experiments certified a good fatigue behavior of the samples produced with these parameters [32]. The skin-core strategy was used to produce the samples. Hence, the process parameters of the contour and the volume area differ from each other (Table 2). For the better connection between the skin and core area, beam offset (compensation) for the contour was used. Without this, large pores were found in this area. This fact would lead to a significant higher porosity.

For densification experiments, a HIP facility featuring a maximum temperature of 2000 °C and a maximum gas pressure of 200 MPa was used (QIH-3, Asea/Avure Technologies, Franklin (TN), USA). Argon (ALPHAGAZ 1 ARGON, Air Liquide GmbH, Germany)