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Effect of adding support structures for overhanging part on fatigue strength in selective laser melting

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ABSTRACT

Selective laser melting (SLM) technology was recently introduced to fabricate dental prostheses. However, the fatigue strength of clasps in removable partial dentures prepared by SLM still requires improvement. In this study, we attempted to improve the fatigue strength of clasps by adding support structures for overhanging parts, which can generally be manufactured at an angle to be self-supporting. The results show that the fatigue strength of the supported specimens was more than twice that of unsupported specimens. Electron back-scattered diffraction analysis revealed that the supported specimens exhibited lower kernel average misorientation values than the unsupported specimens, which suggested that the support structure reduced the residual strain during the SLM process and helped to prevent micro-cracks led by thermal distortion. In addition, the supported specimens cooled more rapidly, thereby forming a finer grain size compared to that of the unsupported specimens, which contributed to improving the fatigue strength. The results of this study suggest that the fatigue strength of overhanging parts can be improved by intentionally adding support structures.

1. Introduction

Selective laser melting (SLM) is an additive manufacturing (AM) technology that enables semi-automatically directly producing complex-shaped three-dimensional (3D) parts using laser power by melting metal powders layer by layer according to computer-aided design (CAD) data (Strano et al., 2013a, 2013b; Vayre et al., 2012). SLM technology provides significant geometric design freedom; therefore, complex components that are difficult-to-impossible to fabricate through subtractive methods can be created with minimal material waste (Strano et al., 2013a, 2013b; Vayre et al., 2012). Currently, SLM is widely used to fabricate dental prostheses such as dental implants, crowns, and bridges (Koutsoukis et al., 2015; Patzelt et al., 2015). In addition, its geometric design freedom, a major advantage of SLM technology, is expected to be exploited to fabricate more complex prostheses such as the metal framework of removable partial dentures (RPDs), which consist of complex parts such as major and minor connectors, rests, clasps, and denture bases (Kajima et al., 2016; Nakata et al., 2017). Recently, several researchers reported that RPD frameworks produced by SLM were comparable to conventional frameworks in terms of accuracy, quality of fit, and function and exhibited good mechanical properties and biocompatibility, as well as superior corrosion resistance (Jevremović et al., 2012; Takaichi et al., 2013; Williams et al., 2006). Therefore, SLM is a potential process for fabricating RPD frameworks in the era of digital dentistry.

Clasps are a key component of RPD frameworks that wrap around certain teeth and serve to retain and stabilize the RPD (Phoenix et al., 2008). Clasps undergo repeated flexure caused by RPD insertion and

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removal (Carr and Brown, 2011; Mahmoud et al., 2005; Yeung et al., 2002). Due to such stresses, the permanent deformation and fatigue fractures of clasps have been reported as complications of RPDs in some studies (Behr et al., 2012; Saito et al., 2002). In particular, Saito et al. (2002) reported that the incidence of complications of RPDs was about 50% during a follow-up over 2–4 years, and these failures were mainly fractures and deformations of clasps. Therefore, clasps require high fatigue strength. Several authors have reported the mechanical properties and fatigue strength of SLM clasps (Kajima et al., 2016; Nakata et al., 2017; Yager et al., 2015). One of these studies showed that clasps manufactured by SLM and conventional casting exhibited comparable mechanical properties such as yield strength and yield point (Yager et al., 2015). Other researchers found that after 10,000 insertion/removal cycles, SLM clasps exhibited a lower decrease in the retentive forces than those of conventionally cast specimens, which suggested that SLM clasps could have a higher fatigue strength (Nakata et al., 2017). However, we reported that clasps prepared by SLM exhibited significant anisotropy in their fatigue strength, and in some build directions, the fatigue lives of SLM specimens were significantly shorter than conventionally cast specimens (Kajima et al., 2016). In addition, other researchers have also reported that standard specimens prepared by SLM showed lower fatigue strength than specimens prepared by conventional techniques (Edwards and Ramulu, 2014; Mower and Long, 2016; Riemer et al., 2014). Therefore, the fatigue strength of SLM builds should be improved.

Although the fatigue behavior of SLM builds is not fully understood, their low fatigue strength may be due to residual tensile stress, remaining porosity, and thermal distortion during forming, which may lead to micro-cracks and promote crack propagation (Aboulkhair et al., 2016; Edwards and Ramulu, 2014; Kasperovich and Hausmann, 2015; Mower and Long, 2016; Riemer et al., 2014). Some researchers have reported that a post-heat-treatment could effectively reduce residual stress and improve the fatigue strength (Aboulkhair et al., 2016; Kasperovich and Hausmann, 2015). In particular, hot isostatic pressing is an effective heat treatment for removing internal pores and cracks, and relieving residual stress (Kasperovich and Hausmann, 2015). However, this post-heat-treatment cannot eliminate surface-connected pores and cracks; therefore, a promising new approach to further improve the fatigue strength is required (Aydinöz et al., 2016; Tillmann et al., 2015).

During the construction of overhanging parts by SLM, external support structures are necessary to fix the part to the building platform (Calignano, 2014; Gan and Wong, 2016; Hussein et al., 2013a; Strano et al., 2013a, 2013b; Wang et al., 2013). However, the presence of support structures increases both the time required to manufacture the part and the complexity of post-processing operations (Calignano, 2014; Gan and Wong, 2016; Hussein et al., 2013a; Strano et al., 2013a, 2013b; Wang et al., 2013). Therefore, many researchers have attempted to minimize or eliminate support structures, focusing on the relationship between the inclined angle of overhanging parts and the dimensional accuracy of SLM builds (Calignano, 2014; Hussein et al., 2013a; Strano et al., 2013a, 2013b; Wang et al., 2013). These reports suggest that a compromise is required between the dimensional accuracy of SLM builds and reducing the amount of support, and for angles greater than 40–45° (i.e., the angle between the horizontal plane and a certain surface), SLM builds can be manufactured without a support structure (i.e., self-supporting), although this angle would change depending on the processing parameters and the type of metal powder (Calignano, 2014; Hussein et al., 2013a; Thomas and Bibb, 2008). On the other hand, previous reports have demonstrated the role of support structures in conducting excess heat away from the part and preventing warping, collapse, and cracks resulting from thermal stresses (Hussein et al., 2013b; Liu et al., 2016); thus, adding structures to support overhanging parts that do not require support in principle could positively affect the fatigue strength of SLM builds. However, few studies have investigated the influence of support structures on mechanical properties of SLM builds.

Table 1
Chemical compositions of the Co–Cr–Mo alloy powder (MP1).

	Co	Cr	Mo	Si	Mn	Fe	C	Ni
MP1	60–65	26–30	5–7	< 1.0	< 1.0	< 0.75	< 0.16	< 0.1

The study aimed to evaluate the effect of intentionally adding support structures to overhanging parts on the fatigue strength of clasps whose angle does not require additional support in principle and to compare the results with those of self-supporting clasps. This study contributes to optimizing support design for biomaterials fabricated by SLM, wherein fatigue fracture is critical, considering not only efficiency but also functional aspects.

2. Materials and methods

2.1. Specimen preparation

Commercially available Co–Cr–Mo alloy powders (MP1, EOS, Krailling, Germany) were used in this study. The chemical compositions of the powders as given by the manufacturer are shown in Table 1. Clasp-shaped specimens were prepared using an SLM machine equipped with a fiber laser (EOSINT M280, EOS, Krailling, Germany). The SLM machine was operated using the standard deposition parameters for MP1 under a nitrogen atmosphere. The shape of the specimens, designed according to a previous study (Kajima et al., 2016; Mahmoud et al., 2005), is shown in Fig. 1. The specimen consists of a clasp arm and plate, with the plate serving as an attachment for fixing the clasp to the fatigue-testing machine (MMT-250N, Shimadzu Corp, Kyoto, Japan). The clasp arm originated from the plate with a radius of curvature of 5 mm and a central angle of 137.5°. The width and thickness at the tip of the clasp arm pattern were 0.82 mm and 0.656 mm, respectively, while those at the joint linking the arm and the plate were 1.3 mm and 1.04 mm, respectively. A sphere (0.6 mm diameter) was designed at the tip to provide a point at which to apply a force (Kajima et al., 2016). In order to investigate the effect of the presence of a support structure on the fatigue strength, one group consisted of specimens with a support structure for overhanging parts of clasp arm (denoted by "supported specimens") and the other group consisted of unsupported specimens (denoted by "unsupported specimens") ($n = 6$ for each group) (Fig. 1a). The support structures were designed as blocks that could easily be removed from the specimens without damage. All specimens were prepared with the longitudinal axes inclined from the horizontal plane by 45°, as shown in Fig. 1b, because clasps with this angle can generally be manufactured to be self-supporting (Calignano, 2014; Hussein et al., 2013a; Thomas and Bibb, 2008).

2.2. Surface roughness and microstructure analysis

Prior to fatigue testing, the surface roughness and microstructure were analyzed. The surface roughness (R_a) of the inner surface of all clasp arms was analyzed using a 3D laser measuring microscope (OLS4000, OLYMPUS, Tokyo, Japan). Each sample was measured three times, and the mean value for R_a was calculated. Next, a sample was randomly selected from each group in order to analyze the microstructure. The clasp arm of each of these samples was cut perpendicular to the tangential line at sites between 45° and 80° from the clasp shoulder because in the failed specimens in our previous study, fractures were located between these angles (Kajima et al., 2016). The specimens were polished with waterproof emery paper (up to 1000 grit) and 9 μm diamond and a 0.04 μm colloidal silica suspension, followed by electro-polishing in a solution of H_2SO_4/CH_3OH (5:95) at 15 V and 268–273 K. Some of the microstructures were observed using electron