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Laser Directed Energy Deposition (LDED) in the dental prosthetic industry

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Abstract

Laser Directed Energy Deposition (DED) using CoCrW alloys is a promising technology for the dental prosthetic industry. CoCrW alloys are widely used in the dental field due to their high strength and biocompatibility. The use of a focused laser beam in DED allows for precise and material efficient fabrication of the metallic structure of the dental prostheses such as crowns and bridges. This comparison has been performed with the currently employed techniques: lost wax casting, milling from disk and Selective Laser Melting (SLM) techniques. The material obtained via LDED the material obtained via DED performs similarly to the best performing traditional technique, possessing nearly twice modulus of toughness of the other materials. Finally, we can conclude that the LDED material competes directly with the material quality of the milling technique, but with an increased material efficiency.

Keywords: Co-Cr alloy; laser directed energy deposition (LDED); additive manufacturing; dental restorations; casting; milling; selective laser melting (SLM)

1. Introduction

Over the past century, dental restorations have gained significant popularity. Initially, gold and its alloys were widely used (Knosp, Holliday and Corti, 2003). However, due to the high cost associated with gold, alternative non-precious metallic alloys such as Co-Cr or Ni-Cr have become more prevalent. It is worth noting that Ni-based alloys are gradually being phased out due to their toxicity concerns (Denkhaus and Salnikow, 2002). Consequently, Co-Cr alloys have emerged as the preferred choice in the dental restoration industry today. This preference is primarily attributed to their enhanced biocompatibility (Steinemann and Perren, 1984) and superior resistance against corrosion (Helsen and Jürgen Breme, 1998).

Co-based alloys have found extensive use in various industries, including aeronautics, petrochemicals, and medicine (Davis, 2001).

In dentistry, traditionally, the casting technique using the lost wax method has been widely used for metallic structure production (Kim et al., 2016). However, milling techniques have gained popularity due to their ability to enhance precision and ensure consistent homogeneity within the inner material (Nesse et al., 2015). Despite the advantages of milling, the cost of Co-Cr alloys and the low material efficiency associated with milling technique for personalized small parts, such as dental prostheses, have prompted research into alternative manufacturing approaches. In recent years, additive manufacturing (AM) techniques have emerged as a promising solution for Co-Cr alloys (Karpuschewski et al., 2013; Yap et al., 2015; Barro et al., 2020). Among these techniques, laser-directed energy deposition (LDED) stands out. LDED involves melting a substrate using a laser beam and supplying a second material in real time, typically in powder form, to create clad tracks. By stacking multiple layers of these clad tracks based on a three-dimensional CAD model, the final dental prosthesis is generated (Arias-González et al., 2020).

Laser Directed Energy Deposition (LDED), belongs to the Directed Energy Deposition (DED) family of additive manufacturing techniques that utilize lasers as an energy source. By directing the laser beam onto a sacrificial substrate, a molten pool is formed, which is then supplemented with material injection (typically in powdered form fluidized by a carrier gas (Huang et al., 2019). Through the relative movement between the laser processing head and the workpiece, material deposition is achieved by overlapping the clad tracks, ultimately resulting in the fabrication of the desired part through the addition of subsequent layers. Initially, LDED, better known simply as laser cladding, was primarily utilized for generating various types of coatings, including titanium (Arias-González et al., 2021), and Co-based alloys (Janaki Ram, Esplin and Stucker, 2008). In recent years, this technique has been increasingly employed for additive manufacturing of functional metal parts (Schmidt et al., 2017; Barro et al., 2021).

LDED can be defined as a near net shape process, and the two-step manufacturing methodology used in Selective Laser Melting (SLM) can also be applied to LDED to meet the intricate details and tolerance requirements of dental prostheses (Bai, Chaudhari and Wang, 2020). Moreover, LDED has the potential to combine the benefits of freeform generation and material efficiency from additive manufacturing processes like SLM, along with the high material performance offered by CAD/CAM milling techniques, when producing dental restorations. However, it is crucial to ensure compliance with existing ISO standards for dental materials.

Therefore, the aim of this study is to evaluate the microstructural and mechanical properties of the Co-Cr obtained through LDED technique following the ISO regulations for dental materials, and comparing it with conventional techniques like casting and CAD/CAM milling, as well as modern techniques such as SLM (already implemented in the dental industry).

2. Materials and methods

The samples employed in this study were manufactured using four different techniques: lost wax casting, Laser Directed Energy Deposition (LDED), milling from commercial disk, and Selective Laser Melting (SLM). For the casting (CAST) specimens, Heraenium Pw alloy ingots were melted with a casting torch and casted using a centrifugal casting machine. LDED specimens were produced using a proprietary LDED manufacturing device equipped with a high-power near-infrared continuous wave laser, using Co-Cr Starbond Easy Powder 30+ as the precursor material. These specimens were then machined to their final dimensions using a commercial CAD/CAM milling system, with a 90° angle between the direction of tensile tests and the building direction. Milled specimens were obtained by milling Co-Cr Kera® dental discs using a CAD/CAM milling machine, with a 90° angle between the tensile test direction and the axial disc direction. SLM specimens were generated using an EOS M 270 machine, utilizing a high-power near-infrared continuous wave laser as the energy source, and Co-Cr EOS SP2 powder as the material. Similar to LDED specimens, the angle between the tensile test direction and the building direction was set to 90°.

Microstructural analysis was conducted on one specimen from each process using a Philips XL30 scanning electron microscope (FEI Technologies Inc.).

Tensile mechanical tests were performed in accordance with the ISO 22674:2016 standard. Six samples were generated for each technique and marked for elongation measurements. A LFV 25 tensile test machine (Walter + Bai AG) equipped with an extensometer (3542-010M-020-ST, Epsilon Technology Corporation) was utilized, with a stroke motion set at 1.5 mm/min. After fracture, the separated tensile samples were reassembled, and the distance between the marks was measured.

Data analysis and statistical comparison of the mechanical data were conducted using two-way ANOVA followed by the Tukey HSD test with a significance level of 0.05.

3. Results and discussion

Microstructural analyses (Figure 1) revealed distinct microstructures and segregation behaviors among the samples obtained from different techniques. CAST specimens exhibited a typical dendritic matrix with noticeable segregation. LDED samples displayed columnar grains with reduced intergranular segregation. Mill samples consisted of equiaxial grains with segregations aligned along the disc axis. SLM samples showcased small cellular grains with uniform segregation distribution throughout the material.

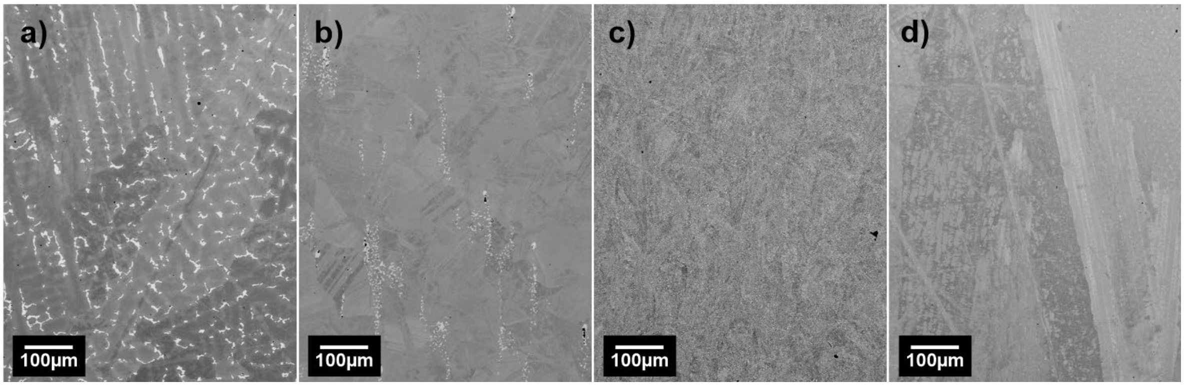

Fig. 1. SEM micrographs displaying a longitudinal section of each fabrication technique: (a) casting; (b) milling from disk; (c) SLM; and (d) LDED.

Mechanically, CAST alloys exhibited similar behavior to LDED and MILL alloys in terms of yield strength, microhardness, and Young's modulus, but showed a significant reduction in ultimate tensile strength and elongation after fracture. This can be attributed to the presence of evenly distributed large segregations, large grain size, and internal casting porosities. LDED alloys demonstrated excellent mechanical behavior comparable to MILL alloys, with no significant differences in yield strength, ultimate tensile strength, Young's modulus, or elongation after fracture with substantial plastic deformation. SLM alloys exhibited higher yield strength and ultimate tensile strength, but with reduced elongation and increased hardness, indicating brittleness. The tensile load angle with respect to the building direction and residual stresses in SLM parts contributed to their brittle behavior. Modulus of toughness analysis revealed that LDED and MILL alloys absorbed nearly twice the energy until fracture compared to other techniques.

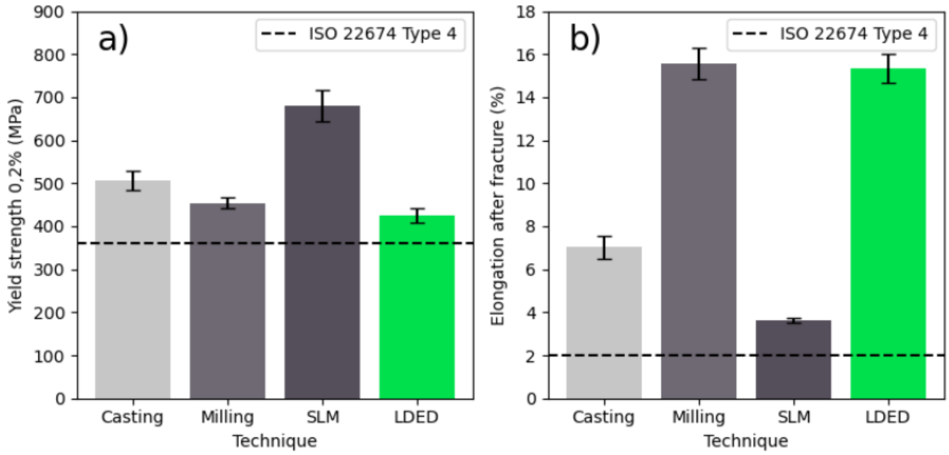

Fig. 2. Yield strength 0,2% (a) and Elongation after fracture; (b) of all materials obtained by casting, milling from disk, SLM and LDED.

Regarding ISO standards requirements, it has been demonstrated that the materials produced by LDED, as well as the other materials, complied with the type 4 specifications of the ISO 22674 standard for dental materials, which is the recommended category for dental fixed restorations. It is noteworthy that LDED material presented similar behavior to the milled discs. Both materials outperformed those obtained through casting and SLM, exhibiting nearly twice (Figure 3) the energy absorbed before rupture and significantly higher elongation after fracture in comparison to the materials obtained by casting and SLM.

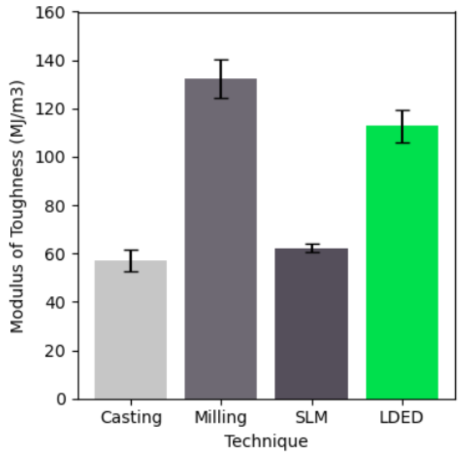

Fig. 3. Modulus of toughness of all materials obtained by casting, milling from disk, SLM and LDED.

4. Conclusion

LDED, as an additive manufacturing technique, offers significant potential for implementation in the restorative dental industry, delivering excellent overall performance. This manufacturing process combines the best aspects of other high-quality techniques already implemented in the industry, incorporating the superior mechanical properties of milling disks and the freeform generation and material efficiency capabilities of additive manufacturing processes like SLM. As a result, LDED stands as a competitive option that merges the advantages of both approaches.

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