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선택적 레이저 용융 방법으로 제작한 치과용 코발트 크롬 합금에 대한 문헌고찰

Dental Co-Cr alloys fabricated by selective laser melting: A review article

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Cobalt-chromium alloys are used to fabricate various dental prostheses, and have advantages of low cost and excellent mechanical properties compared to other alloys. Recently, selective laser melting, which is an additive manufacturing method, has been used to overcome the disadvantages of the conventional fabrication method. A local rapid heating and cooling process of selective laser melting induces fine microstructures, grain refinement, and reduction of porosities of the alloys. Therefore, it can improve mechanical properties compared to the alloys fabricated by the conventional method. On the other hand, layering process and rapid heating and cooling cause accumulation of a large amount of residual stresses that can adversely affect the mechanical properties. A heat treatment for removing residual stresses through recovery and recrystallization process caused complicated changes in mechanical properties induced by phase transformation, precipitate and homogenization of the microstructures. The purpose of this review was to compare the manufacturing methods of Co-Cr alloys and to investigate the characteristics of Co-Cr alloys fabricated by selective laser melting. (J Korean Acad Prosthodont 2021;59:248-60)

Keywords
Cobalt-chromium; Heat treatment; Mechanical property; Microstructure; Selective laser melting

Introduction

Cobalt-chromium (Co-Cr) alloys have emerged as promising alternatives to the precious metal alloys for the fabrication of various prostheses owing to their

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low cost and satisfactory material properties, such as high strength, elastic modulus, corrosion resistance, and biocompatibility. Generally, metal frameworks of dental prostheses are fabricated using the casting technique; however, the complicated laboratory processes, porosities, and solidification shrinkage associated with this technique have gradually decreased the application of this method. With the development of computer-aided design and computer-aided manufacturing (CAD-CAM) system, CAD-CAM milling has emerged as an alternative method for the fabrication of dental prostheses. This method addresses the problems related to the complicated laboratory processes and processing time of the casting process; however, material wastage and the high wear and consumption rates of the milling tools limit the application of this method. The limitations of these conventional methods are overcome by the use of the additive manufacturing (AM) process, which has emerged as an effective method for the fabrication of dental prostheses. Among the several powder bed fusion (PBF) AM processes, selective laser melting (SLM) has been successfully applied for the fabrication of dental prostheses.[1] SLM processes are characterized by a rapid local heating and cooling process, which improves the mechanical properties of the SLM Co-Cr alloys via the solid solution strengthening effect, secondary phase strengthening effect, grain refinement, and the reduction of porosities.[2] However, a post-treatment (heat treatment) process is required to reduce the accumulated residual stresses caused by the layering process and the rapid heating and cooling in the SLM Co-Cr alloys. Heat treatment reduces the residual stresses of the SLM Co-Cr alloys not only by a recovery and recrystallization process but also by a phase transformation, which changes the behavior of the precipitates and the homogenization of the microstructures. Consequently, heat treatment leads to complex changes in the mechanical properties of the SLM Co-Cr alloys. In this literature review, various fabrication processes of Co-Cr alloys are compared, and the general characteristics of Co-Cr alloys and SLM Co-Cr alloys, and the effects of heat treatment on the SLM Co-Cr alloys were investigated.

Manufacturing method of dental Co-Cr alloys

Traditionally, the metal frameworks of prostheses are fabricated by a casting technique which is based on the lost-wax technique.[2] These prostheses were commonly fabricated using precious metal alloys such as gold alloys; however these alloys were gradually replaced with cheaper, nonprecious metal alloys such as nickel Ni-Cr and Co-Cr alloys, which exhibit relatively superior mechanical properties.[3] Although Ni-Cr alloys were often used in the past, the risk of Ni-induced allergic reactions and the carcinogenic effect of beryllium have restricted their further application.[4,5] Consequently, Co-Cr alloys have emerged as promising nonprecious alloys for the fabrication of prostheses for patients allergic to Ni.[6] In addition, compared to the precious alloys, Co-Cr alloys are relatively inexpensive and exhibit favorable material properties such as high strength, corrosion resistance, tarnish resistance, and biocompatibility.[3,4,6]

The fabrication of Co-Cr alloys via the casting technique is a relatively complex procedure involving waxing, investing, burnout, casting, finishing, and polishing. In addition, defects such as porosity and shrinkage are induced in the alloy during the casting process.[7] Furthermore, among dental alloys that are commonly used, except the titanium alloy, Co-Cr alloys have the highest range of melting points. This poses restrictions on the possible extent of their manipulation in a dental laboratory. Moreover, owing to their high strength and low ductility, it is difficult to finish and polish Co-Cr alloys.[2,8]

Recently, efforts have been devoted to fabricate Co-Cr alloys using the CAD-CAM system with the aim of reducing the processing time, while also reducing laboratory processes-related errors. The CAD-CAM system includes a subtractive manufacturing unit such as, milling and AM unit such as, PBF.[5,7,9,10] During the CAD-CAM milling process, blocks of the materials are cut using a rotary diamond bur. The generation of defects and porosities during this process may be minimized by employing Co-Cr alloy blocks fabricated via a standardized industrial process.[3,7] However, owing to the rigidity of the 'solid' Co-Cr alloy blocks, it is difficult to achieve the CAD-CAM milling of these blocks; therefore, the dry milling of 'soft' Co-Cr alloy blocks has been introduced as an alternative method.[11] During dry milling, a block containing a mixture of a combustible organic binder and the alloy powders are milled, and the milled structure is sintered in a high temperature furnace under argon atmosphere at approximately 1300°C until the block is fully densified.[5] Dry milling enables the fabrication of dental restorations using a CAD-CAM device that is generally available in dental laboratories and reduces the processing time and cost.[2] However, several factors limit the further application of subtractive manufacturing for the fabrication of dental prostheses such as high wastage of raw materials, short life time of milling tools owing to abrasive wears, increased abrasion on equipment, and high maintenance costs.[5,10,12]

AM is an alternative method for the fabrication of dental prostheses and involves the use of powder- or liquid-based materials to fabricate solid structures.[12] PBF is the most common AM method for the fabrication of metals in the field of dentistry and is largely divided into selective laser sintering (SLS) and SLM.[1,9] SLS involves the incomplete sintering of powder particles within a specific area using the energy intensity per unit area of laser irradiation.[13] However, during the partial sintering of the powders by lasers, voids are generated between the powders owing to the balling phenomenon, thus negatively affecting the strength and metal-ceramic bond strength of the fabricated structure.[13,14] SLM is commonly used to fabricate metal frameworks because it shortens the time required for the manufacturing process, thus reducing the manufacturing labor and cost. SLM has attracted attention for the fabrication of desired parts owing to its minimal material use and waste and the ability to recycle the residual alloy powders.[10] SLM involves the use of a high-energy laser such as a CO_2 laser or a fiber laser to melt the alloy powders.[7] For the SLM fabrication of dental parts, first, CAD is employed to obtain the three-dimensional data of the complex shapes of dental prostheses, and divide the shape into several horizontal or vertical layers, after which the data are sent to the laser sintering machine.[10] Subsequently, fine alloy powders, which are used as the raw materials, are applied to the powder bed. The alloy powders are intensively irradiated and heated using a high-energy laser. The alloy powders are rapidly melted and cooled locally to build up several layers, and this process is repeated until the designed structure in the CAD file is completely formed.[7,10] SLM can completely melt alloy powders to fabricate a complicated, dense structure with almost no pores.

Microstructures and mechanical properties of cast Co-Cr alloys

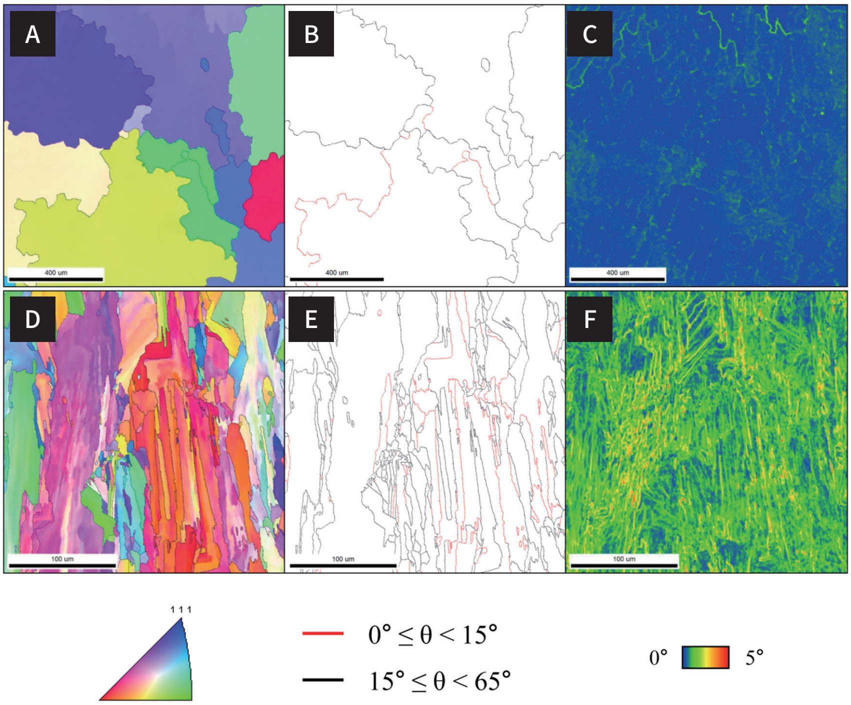
Cast Co-Cr alloys, which are the most clinically used Co-Cr alloys and are used as a control group in experiments on SLM Co-Cr alloys, have the following characteristics. Cast Co-Cr alloys are composed of a face-centered cubic (FCC) lattice, γ phase and hexagonal close packed (HCP) lattice, and ε phase, and are thermodynamically stable at high and low temperatures.[9] A slow FCC to HCP transformation in Co-Cr alloys leads to a metastable FCC phase at room temperature, which is related to the properties of Co-Cr alloys such as high strength, fatigue strength, and stress absorption.[2,9,15-17] In addition, intermetallic compounds and carbides are usually precipitated at the grain boundaries (GBs) and interdendritic spaces of Co-Cr alloys.[8] Although these precipitates contribute to the reinforcement mechanism,[18] the inhomogeneous distribution, shapes, and sizes of the precipitates can reduce the ductility and fatigue strength of cast Co-Co alloys.[16] The cast Co-Cr alloys typically possess coarse grains; however, the strength of these alloys increases with an increase in the cooling rate and a decrease in the grain size.[17] Electron backscatter diffraction (EBSD) can be employed to analyze the microstructures of alloys, including the grain size and distribution, GB, and strain by misorientation. Fig. 1 shows the EBSD data of the cast Co-Cr and SLM Co-Cr alloys. As shown in the image, the cast Co-Cr alloys exhibit equiaxed coarse grains (Fig. 1A, B). The color differences of the grains in the image indicate a difference in the crystal orientation.

A major limitation of the cast Co-Cr alloys is their inherent porosities,[16] which are formed due to solidification and shrinkage during the casting process.[4,18] Cast Co-Cr alloys form typical dendritic structures owing to their low cooling and solidification rates and negative temperature gradient.[19] During the formation of these dendritic structures, the interdendritic regions separate from the melt so that the resultant shrinkage in the solidified alloy is not from the melt, thus leading to the formation of interdendritic micropores (Fig. 2A).[4] Generally, the porous parts of a metal framework undergo drastic changes in the cross-section thickness.[20] These changes affect the tensile strength and ductility of the alloy, thus leading to unexpected fractures in the frameworks of removable partial dentures such as clasps. The generation of internal pores on the surface of the alloy after the adjustment of the prostheses can adversely affect the mechanical strength of the prostheses or reduce the bond strength at the metal-ceramic bonding site owing to the formation of pores at the metal-ceramic bonding site. In addition, the formation of a second phase, which is usually a molybdenum (Mo)-rich phase, is commonly observed in the interdendritic regions, as indicated by the relatively white area in Fig. 2A. The dispersion of the second phase increases the brittleness of the alloy by removing Mo from the solid solution, thus negatively affecting the mechanical properties of the alloy and increasing the vulnerability of the alloy to various types of corrosion such as crevice corrosion and pitting corrosion.

Microstructures and mechanical properties of SLM Co-Cr alloys

The SLM process is characterized by a rapid local heating and cooling of the material. During this process, a

Fig. 1. EBSD data of cast Co-Cr and SLM Co-Cr alloys. (A) Inverse pole figure (IPF) map, (B) Grain boundary (GB) map, and (C) Kernel average misorientation (KAM) map of cast Co-Cr alloy, (D) GB map, (E) GB map, (F) KAM map of SLM Co-Cr alloy.



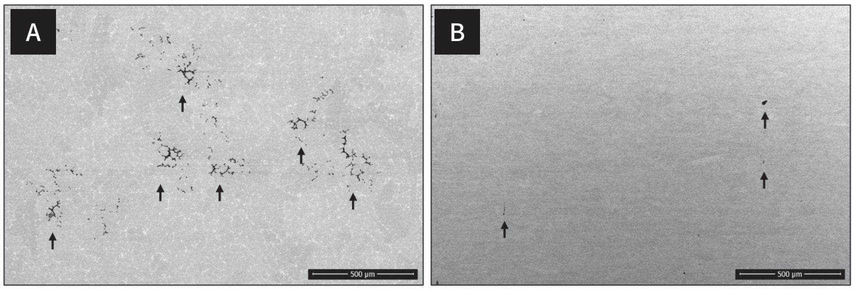


Fig. 2. Backscattered electron (BSE) images of polished Co-Cr alloys. Black arrows indicate microporosities.
(A) Cast Co-Cr, (B) SLM Co-Cr.

high-energy laser beam is used to irradiate the alloy powders, which absorb the energy through bulk coupling or powder coupling.[21] Consequently, high temperatures and cooling rates are generated within the molten pool.[22] In a Co-Cr binary system, the FCC phase has low energy, G, whereas the HCP phase is thermodynamically stable at room temperature.[15] However, in SLM Co-Cr alloys, most of the FCC phase is maintained at room temperature owing to the rapid cooling process. Consequently, the solid solution limit of the alloying elements increases, thus reducing the precipitate and dendritic segregation, while maintaining oversaturation. This leads to the solid solution strengthening effect and second phase strengthening effect.[19] Therefore, SLM Co-Cr alloys exhibit higher strength, hardness, and ductility than the cast Co-Cr alloys owing to the higher FCC phase fractions and solid solution limits of SLM Co-Cr alloys.[8,23]

The grain size of the SLM Co-Cr alloys is closely related to the nucleation rate (I) and is determined by the degree of undercooling (ΔT).[19] Owing to the larger ΔT produced by the SLM technique than that produced by the casting technique, SLM Co-Cr alloys possess a finer grain size and higher strength and hardness compared to cast Co-Cr alloys.[2] For example, Santos *et al.*[24] observed column grains with a mean size of 55 µm (length) and 22 µm (height) in SLM Co-Cr alloys. The improvement in the mechanical properties of SLM C-Cr alloys owing to a reduced grain size can be expressed in terms of the Hall-Petch (H-P) relationship and can be calculated using Equation 1:[25]

$$\Delta\sigma_{cr} = kD^{-1/2}, \quad (1)$$

where D is the mean grain size, and k is the slope of the H-P relationship line that measures the relative extent of the strength contribution. Grain refinement strengthening is an important factor of SLM that improves the mechanical properties of the alloys, enhancing not only the strength but also the ductility and toughness of the alloys.[19] GBs act as a hindrance to crack propagation. With a decrease in the gran size, the GB area increases, thus enhancing the effect of grain refinement strengthening and further improving the mechanical properties of the alloys.[26] In addition, because the primary dendrite spacing in the fine microstructures of the SLM Co-Cr alloys are significantly smaller (2.5 µm) compared to that of the cast Co-Cr alloys, grain refinement strengthening reduces the slip length in the alloy, thus improving the strength of the alloy (Fig. 2B).[27] As shown in Fig. 1, the GB area of SLM Co-Cr alloy (Fig. 1D, E) is larger than that of cast Co-Cr alloy (Fig. 1A, B).

There are several SLM factors that affect the properties of the final product including the choice of powders, building direction or orientation, and processing parameters. The building direction, which is the acute angle between the longitudinal axis of a sample and the building platform, affects the microstructures, texture, and residual stresses of the final product (Fig. 3A).[7] Thermal fluctuations that occur during the SLM manufacturing process have the most significant effect on the building direction of the formed grains, which generally grow from the building platform with lower temperatures to the upper surface with higher temperatures.[28] In addition, the building direction affects the arrangement of precipitates.[7] Several studies have reported on molten pool boundaries (MPBs), which are characteristically observed in SLM alloys,[6,8,28-30] and significantly affect their mechanical properties (Fig. 3B). The number and angle of MPBs vary depending on the building direction and can therefore affect the anisotropy of the mechanical properties.[31-33] As the number of layers at 0° and 45° are higher than those at 90°, a larger number of MPBs are formed. With an increase in the number of layers, the likelihood of defects or porosity also increases, thus resulting in a mechanical anisotropy.[33] In addition, the ductile deformation of SLM alloys results from grain slipping and MPBs. Owing to the relatively weak bond strength of MPBs compared to that of GBs, slipping occurs preferentially along the MPBs.[30] Kajima *et al*.[31] compared the anisotropy of the fatigue strength after setting the building direction of a clasp to 0°, 45°, and 90°. They found that the SLM Co-Cr alloys exhibited higher yield and tensile strengths compared to the cast Co-Cr alloys for all directions and attributed this to the microstructures of the SLM Co-Cr alloys, which were formed by rapid cooling. However, they also observed a mechanical anisotropy in the SLM Co-Cr alloys and a lower fatigue strength when the clasps were set parallel to the building direction. In addition, they reported that because fractures tend to be parallel to the MPBs, cracks would easily advance along the MPBs.

During the SLM process, unique microstructures similar to 'fish scales' appear based on the molten pool and layer stacks of each laser path.[34] Under high magnification, fine microstructures are observed as "fish scales," and numerous columnar grains growing perpendicular to the circular arch-shaped MPBs are also observed.[8,15,31,34] Additionally, large interlocked elongated grains with different directions are observed in the dendritic structures, and the 'weld line' and the three-dimensional texture of these grains, which is similar to those of common weaved fabrics can improve the damage tolerance of the alloy.[30] The columnar-cellular growth of grains is associated with the direction of heat flow.[35,36] Fine cellular- or columnar-dendritic structures act as obstacles to dislocation motions and may increase the tensile strength of the SLM Co-Cr alloys.[8]

The microstructures and mechanical properties of SLM alloys are affected by the SLM process parameters such as the laser power, scanning velocity, hatch spacing, laser beam size, and layer thickness, which are associated with the melting energy and the penetration depth of energy in the alloy powders, which consequently affect the density of the molten alloy.[37] Takaichi *et al*.[8] reported that the porosities of SLM Co-Cr alloys could be reduced by optimizing the process parameters, which include the laser power, hatch spacing, scanning speed, and layer thickness. The laser energy density (LED) of the SLM pro-

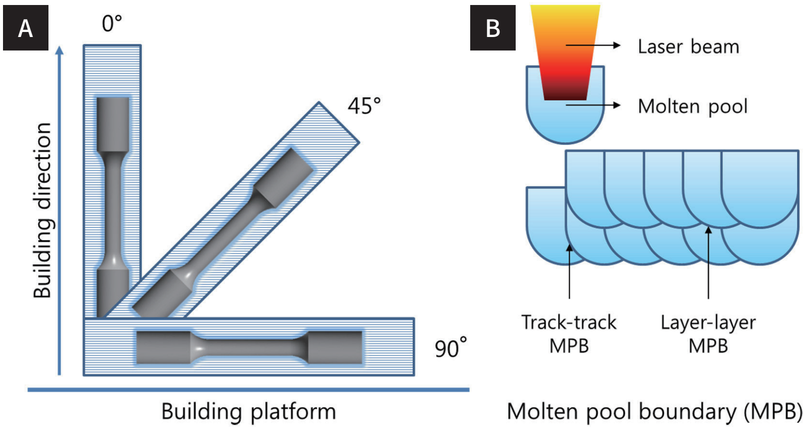


Fig. 3. Schematic diagram of the layers fabricated by SLM.
(A) Anisotropy based on the different building direction, (B) Molten pool boundary (MPB).

cess can be calculated using four major variables: laser power P (W), scanning velocity V (mm/s), hatch spacing H (mm), and layer thickness D (mm), as shown in Equation 2.[38]

$$\mathrm{LED} = \frac{P}{VHD}\ (\mathrm{J/mm^3}) \qquad (2)$$

Takaichi *et al*.[8] examined the correlation between the LED and porosities in SLM Co-Cr alloys and reported that porous structures develop at a LED of <150 J/mm^3. In addition, Qian *et al*.[30] reported that the tensile strength increases at an LED of 118 J/mm^3 than that at an LED of 63 J/mm^3. Additionally, Tonelli *et al*.[39] reported a lack of fusion and presence of large amounts of internal porosities at an LED of <100 Jmm^3 and keyhole collapse at an LED of >200 J/mm^3. Furthermore, studies have reported that optimum mechanical properties are obtained at LED values of 150 - 200 J/mm^3. Owing to the negative effect of high porosities on the mechanical properties of the SLM Co-Cr alloys, achieving a near-full density at an adequate LED is important.[39] As shown in the backscattered electron (BSE) images, a small amount of porosity can be observed in the SLM Co-Cr alloys compared to the cast Co-Cr alloys (Fig. 2B).

As the kernel average misorientation (KAM) value principally indicates the microscopic lattice distortion, the distribution of residual stresses can be indirectly measured using the KAM method. As shown in Fig. 1C, the KAM value of the SLM Co-Cr alloy (Fig. 1F) is higher than that of the cast Co-Cr alloy, indicating a high distribution of residual stresses in the SLM Co-Cr alloy. The accumulation of such a large amount of residual stresses could be attributed to the rapid heating and cooling of the SLM, which may adversely affect the mechanical properties.[25,38,40] In addition, owing to the layer-by-layer additive process of SLM, a significant temperature difference exists between the previously printed layer and the newly deposited layer, and this difference is one of the factors that cause residual stresses.[38] The temperature gradient mechanism and cool-down mechanism based on the expansion behaviors of a material during heating or cooling can be used to explain the generation of residual stresses (Fig. 4).[40] For example, under the assumption that the materials are sufficiently melted and metallurgical connections occur between the layers, strain accommodation occurs in the material and residual stresses are formed. In a laser-based process, a very high cooling rate of the order of 10^3 - 10^8 K/s forms a steep thermal gradient, resulting in high residual stresses, which are close to the yield strength of the material.[38] When the residual stresses exceed the yield strength, heat is retained in the material in the form of residual stresses even after the complete removal of heat. Consequently, this leads to distortions such as bending, warping, pore formation, cracking, delamination, and plastic deformation, thus compromising the mechanical properties.[41] Furthermore, premature fractures can occur even under

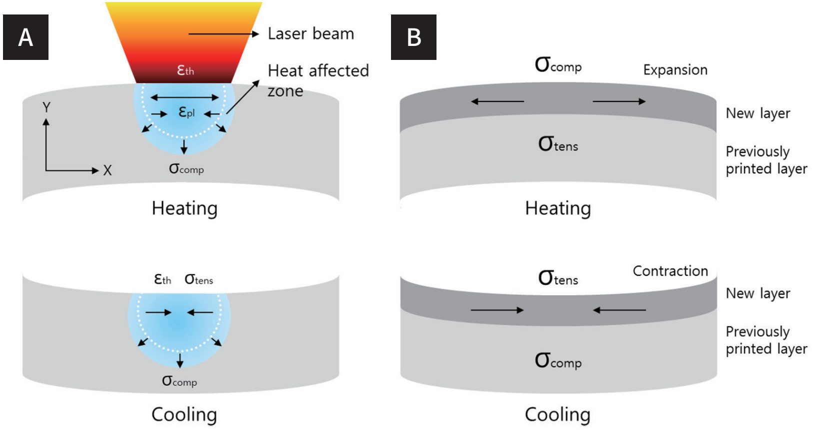


Fig. 4. Temperature gradient mechanism suggested by Simson *et al*.[40]
(A) Residual stress based on heating and cooling (ε_{th}: thermal elongation, ε_{pl}: plastic elongation, σ_{comp}: compressive stress, σ_{tens}: tensile stress), (B) Residual stress at the solid layer connection.

low cycle loads owing to the reduced fatigue strength. Consequently, these problems restrict the immediate application of the components after their fabrication. Thus, methods such as the preheating of powders and the baseplate, island scanning strategy, re-scanning, and heat treatment have been introduced to reduce the residual stress of SLM Co-Cr alloys.[38,41] Among these methods, heat treatment is the most economic and effective method for removing residual stresses.[15] Heat treatment enables the complete removal of the residual stresses in the alloy, while ensuring the formation of homogeneous microstructures, thus improving the mechanical properties of the alloys.[42]

The microstructural differences that affect the mechanical properties of cast Co-Cr alloys and SLM Co-Cr alloys are summarized in Table 1.

Effect of heat treatment on the microstructures and mechanical properties of SLM Co-Cr alloys

Depending on the heat treatment conditions, alloys undergo recovery, recrystallization, and growth, and consequently, grain changes. During deformation, energy is primarily stored in the material in the form of dislocations, which are considered as the crystallographic defect sites.[43] During the recovery process, grains reduce stored energy by removing defects such as dislocations within the crystal structure or rearranging dislocations. The internal strain energy is removed as atoms move from the higher stress areas to lower stress areas. While heat treatment must be performed at sufficiently high temperatures that permit atomic mobility, it should be performed for a short period, in order to prevent undesired recrystallization and grain growth, which are associated with strength loss.[44] Kajima *et al*.[45] and Takaichi *et al*.[32] reported that the recovery process of SLM Co-Cr alloys occurs after heat treatment at 1050°C or less for 6 h, and recrystallization occurred after heat treatment at 1150°C for 6 h. In contrast, some other studies have reported that recrystallization occur in SLM Co-Cr alloy after heat treatment at 1150°C for 1 h[33,45] or at 1220°C.[46] This indicates that an appropriate temperature is more important for the reduction of the residual stresses by the recrystallization process than the heat treatment time. Moreover, as the strength and hardness decrease with an increase in grain size,[15,47] further studies are needed to control the degree of recrystallization and growth.

Heat treatment also affects the FCC → HCP phase transformation, and the changes in the mechanical properties of SLM Co-Cr alloys primarily depend on the changes in the phase fraction of the brittle HCP phase.[15,45,48] With a reduction in the HCP phase after heat treatment, the strength and hardness decreases, thus increasing the ductility. Additionally, heat treatment affects the behavior of the precipitate and the homogenization of the microstructures. As precipitates exhibit a secondary phase strengthening effect, a decrease in the precipitates after heat treatment leads to a decrease in the strength and hardness of the SLM Co-Cr alloy.[15,48] In addition, the homogenization of the microstructures and the reduction of mechanically weak MPBs after heat

Table 1. Microstructural differences influencing mechanical properties between cast Co-Cr alloys and SLM Co-Cr alloys

	Cast Co-Cr	SLM Co-Cr (as-built)	References
Phase fraction	FCC + HCP, dual phase	High FCC, low HCP	2,8,9,15-17
Precipitate	High content, large size	Low content, small size	4,8,9,17,19
Grain size	Coarse	Fine	2,17,19,27
Porosity	High	Low	4,8,16,18,30,39
Residual stress	Low	High	24,38,40

treatment reduces the anisotropy of mechanical properties and increases the fatigue strength.[32,33,46,49] Therefore, a heat treatment that can properly control the required mechanical properties should be considered. The changes in the mechanical properties of SLM Co-Cr alloys based on heat treatment are summarized in Table 2.

In summary, during heat treatment, residual stresses are removed through the recovery and recrystallization processes, and the heat treatment temperature has a more significant effect on the efficiency of the heat treatment than the heat treatment time. In addition, heat treatment affects the FCC → HCP phase transformation, the behavior of the precipitates, and the homogenization of microstructures. The mechanical properties of SLM Co-Cr alloys are closely related to the FCC → HCP phase transformation, and the strength and hardness of the alloy increase with an increase in the phase fraction of the HCP phases, whereas the ductility decreases with an increase in the HCP phase. In addition, the strength and hardness decrease with a reduction in the amount of precipitates. Furthermore, the homogenization of the microstructures including the MPBs reduces the anisotropy of mechanical properties and increases the fatigue strength of SLM Co-Cr alloys.

Conclusion

In summary, Co-Cr alloys are commonly used to fabricate dental prostheses owing to their cost-effectiveness and excellent mechanical properties. SLM overcomes the limitations of existing manufacturing methods for the fabrication of dental prostheses using Co-Cr alloys. The rapid local heating and cooling in the SLM process results in the formation of fine microstructures, grain

Table 2. Mechanical properties of Co-Cr alloys fabricated by SLM and subsequently heat treated

Reference	Heat treatment	Building orientation	Mechanical properties			
			Ultimate tensile strength (MPa)	0.2% Yield strength (MPa)	Vickers Hardness (HV)	Elongation (%)
Kajima *et al.* 2018	As-built	Longitudinal	1173 ± 25	839 ± 32	477 ± 9	12.3 ± 2.8
	750°C, 1h*		1097 ± 11	953 ± 16	498 ± 2	3 ± 0.5
	900°C, 1h		1071 ± 14	793 ± 25	495 ± 10	5.8 ± 0.9
	1050°C, 1h		1075 ± 11	738 ± 4	428 ± 9	11.4 ± 0.7
	1150°C, 1h		1007 ± 32	614 ± 11	365 ± 11	16.3 ± 1.4
Wei *et al.* 2020	As-built	Longitudinal	1142 ± 21	672 ± 24	-	8.0 ± 0.2
	750°C, 1h		1279 ± 16	1019 ± 33	-	4.1 ± 0.3
	850°C, 1h		1463 ± 19	1258 ± 27	-	1.7 ± 0.2
	950°C, 1h		1228 ± 21	973 ± 14	-	1.6 ± 0.2
	1050°C, 1h		1189 ± 20	754 ± 19	-	10.1 ± 0.3
	1150°C, 1h		920 ± 14	516 ± 18	-	12.2 ± 0.4
Zhou *et al.* 2020	As-built	Longitudinal	1113 ± 25	795 ± 11	-	9.8 ± 2.8
	As-built PF**-treated		1325 ± 11	1080 ± 14	-	3.2 ± 0.9
	850°C, 1h PF-treated		1366 ± 32	1056 ± 16	543.7	4.33 ± 2.59
	950°C, 1h PF-treated		1410 ± 11	914 ± 25	557.9	6.05 ± 0.53
	1050°C, 1h PF-treated		1458 ± 14	956 ± 11	537.6	7.73 ± 0.97
	1150°C, 1h PF-treated		1296 ± 11	816 ± 4	402.6	12.20 ± 0.77

* h: hour
** PF: Porcelain firing schedules including degassing and oxidation, opaque porcelain, body porcelain, enamel porcelain

refinement, and the reduction of the porosities in the alloys. Thus, SLM Co-Cr alloys exhibit better mechanical properties such as strength, hardness, and ductility compared to cast Co-Cr alloys. However, the layering process and rapid heating and cooling cause the formation of inhomogeneous microstructures and the accumulation of a large amount of residual stresses, which negatively affect the mechanical properties of SLM Co-Cr alloys. Generally, heat treatment is employed to homogenize the microstructures and remove residual stresses in SLM Co-Cr alloys through recovery and recrystallization processes., heat treatment affects the phase transformation and the behavior of the precipitates, resulting in complex changes in the mechanical properties including strength, hardness, and ductility.

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선택적 레이저 용융 방법으로 제작한 치과용 코발트 크롬 합금에 대한 문헌고찰

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코발트-크롬 합금은 다양한 치과보철물 제작에 이용되고 있고, 다른 합금에 비해 저렴한 가격과 우수한 기계적 특성이 장점이다. 최근, 기존 제작 방식의 단점을 극복하기 위해 적층제조 방식인 선택적 레이저 용융 방법이 보철물 제작에 이용되고 있다. 선택적 레이저 용융 방법의 공정 중 급속 가열과 냉각 과정은 제작된 합금의 미세구조와 결정립을 미세화하고, 기포를 감소시켜 기존 제작 방식에 의한 합금에 비해 기계적 특성을 향상시킨다. 반면, 적층과 급속 가열 및 냉각은 다량의 잔류응력 축적을 초래하는데, 추후 기계적 특성에 악영향을 미칠 수 있다. 따라서, 잔류응력을 제거하기 위해 주로 열처리를 시행하고, 회복과 재결정화에 의한 잔류응력의 감소뿐만 아니라 상변태, 석출물 및 미세구조의 균질화가 동반되어 기계적 특성의 복잡한 변화가 나타난다. 본 문헌고찰에서 코발트-크롬 합금의 제작 방식 비교 및 선택적 레이저 용융 방법으로 제작된 합금의 특징에 대해 알아보고자 한다. (대한치과보철학회지 2021;59:248-60)

주요단어

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