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Investigation of Mechanical Properties and Corrosion Behavior of Co-Cr Alloys Fabricated by Direct Metal Laser Sintering with nTopology Design

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Abstract: Co-Cr alloys are well-known material used in biomedical implants and aerospace due to their excellent mechanical strength and corrosion resistance. Direct metal laser sintering, often known as DMLS, is a method that can be utilized to fabricate intricate and functioning mechanical components via a computer-aided design (CAD) computer model. Mechanical components made using this method typically have poorer mechanical characteristics and more residual porosity than those made using more traditional methods. The present study involved the mechanical properties and corrosion behavior of a nToplogy design integration with DMLS-made Co-Cr-Mo alloy with a composition appropriate for use in biomedical applications. Mechanical properties of microhardness, flexural, compression and corrosion rate were measured for the as cast and DMLS Co-Cr alloy. The findings indicate potential new uses for the DMLS technique in manufacturing mechanical components for the medical and dental industries, particularly in cases where a high level of modification is needed. Co-Cr alloys made using nTopology design had better mechanical characteristics and corrosion resistance than conventionally made material.

Keywords: *Co-Cr, DMLS, nTopology, Biomedical applications*

1. Introduction

Currently Co-Cr (cobalt-chromium) alloys are used in various industrial sectors, mainly in biomedical applications of dental and orthopedic implants, for of their excellent mechanical properties, corrosion resistance and biocompatibility. Co-Cr are selected because of their high strength and wear resistance and strength, which are critical for confirming the longevity and reliability of medical implants [1, 2]. Conventional manufacturing approaches of casting, powder metallurgy, forging, etc. used for preparing Co-Cr alloys might face challenges to create intricate design and minimizing of material waste. The improvement of additive manufacturing (AM) technology has enabled the processing of various types of macro-porous networks called as lattice structures [3]. Recent development in manufacturing technology Direct Metal Laser Sintering (DMLS) has converted the creation of metal parts. DMLS enables the fabrication of complex shapes and personalized designs that were previously unachievable through conventional method [4]. Layer, by layer production method provide benefits in terms of effective material usage, flexible design possibilities and the ability to craft lightweight structures with custom-made mechanical characteristics [5, 6]. Integration of advanced design software nTopology, to DMLS expands the competencies of this manufacturing technique. nTopology provide efficient methods for optimizing lattice structures, weight lowering, and increasing mechanical performance without compromising structural integrity. By means of design freedom in nTopology, engineers can make Co-Cr alloy components with higher performance characteristics tailored to specific applications. The adaptability and reliability of Co-Cr alloys produced through additive manufacturing technique of DMLS, emphasizing their suitability for diverse applications requiring high mechanical strength and resist to corrosion. Cherneva et al. 2023 studied on 3D-printed Co-Cr alloys adopting selective laser melting, which enhanced the mechanical properties while compared to as cast alloys, suitable for dental applications [7]. Lambrou et al. 2022 enhanced the mechanical properties through stress-relief annealing and porcelain firing effects on Co-Cr specimens via selective laser melting [8]. Dobrzanski et al. 2020 Co-Cr alloys prepared through DMLS enhance mechanical properties of the materials [9]. The study focused on selective laser melting (SLM) for CoCr alloys and analyzed microstructure, mechanical properties, and corrosion resistance [10, 11].

Upon look over the existing literature, no studies that explore the integration of nTopology with Direct Metal Laser Sintering (DMLS) for the fabrication of Co-Cr (Cobalt-Chromium) alloys. This gap in research highlights a unique opportunity to contribute novel insights to the

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field. The prime objective of this study is to analyze the interplay between the mechanical properties and corrosion behavior of Co-Cr alloys that have optimized by nTopology in the DMLS fabrication method. By addressing this unexplored area, the study aims to provide a deeper understanding of how the advanced design optimization capabilities of nTopology can influence the performance and durability of Co-Cr alloys produced through DMLS, potentially leading to significant advancements in material science and manufacturing technologies.

2. Materials and Methods

2.1 Co-Cr Alloy Powder

The Co-Cr alloy powder employed in this current work was precisely formulated for DMLS application within the range of 15 to 45 micrometers. Table 1 shows the composition of Co-Cr alloy powder. The high chromium contented in the alloy is critical to provide unique corrosion resistance, whereas the addition of molybdenum increases the alloy's mechanical properties [12]. The occurrence of minor elements of silicon, manganese, and iron contributes to the stability and performance of the alloy. The SEM photograph shows the particle shape of Co-Cr alloy powder is presented in Figure 1(a). Powders prepared via gas atomization have particles that are spherical in shape and uniform size distribution. The spherical shape is advantageous for powder flowability in additive manufacturing processes, and the particles have a diameter ranging from around 50 to 100 µm. Image 1(b) displays an Energy Dispersive X-ray Spectroscopy (EDAX), utilized for identifying the elemental composition of the Co-Cr alloy. The spectrum reveals the presence of important elements like Chromium (Cr), Cobalt (Co), and Molybdenum (Mo). The EDAX analysis confirms the material's composition Cr and Co have sharp peaks, indicating they are the main constituents, while Mo is present in smaller quantities ensuring it meets alloy specifications for biomedical implants and aerospace components that require high strength and corrosion resistance [13].

Table 1. Chemical Composition of Co-Cr Alloy Powder (wt.%)

Element	Co	Cr	Mo	Si	Mn	Fe	C	Ni	W
Content	60-65	27-30	5-7	1-2	0.5-1	0.5-1	<0.1	<0.1	<0.1

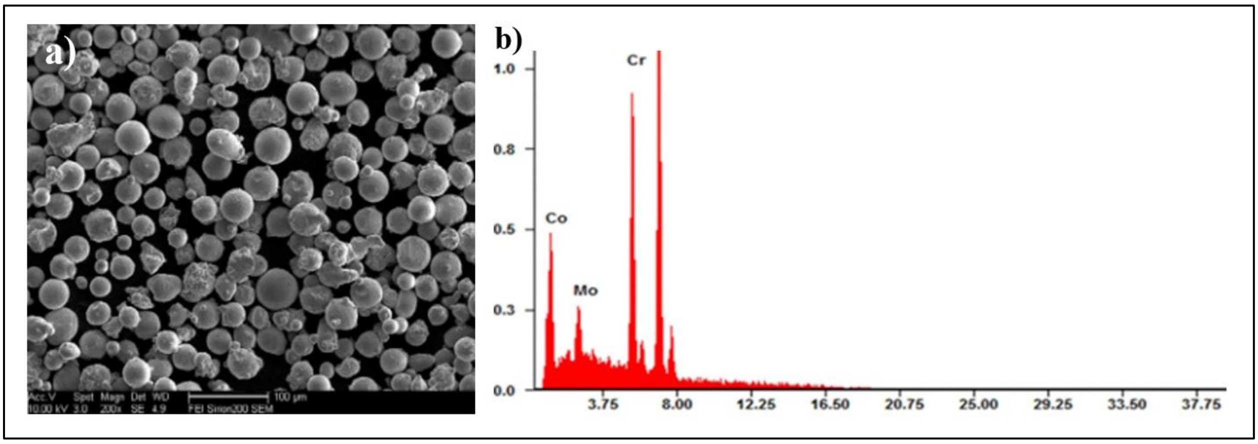

Fig. 1. (a) SEM image of Co-Cr alloy (b) EDAX of Co-Cr alloy

2.2 Direct Metal Laser Sintering (DMLS)

The DMLS process was performed in EOS M 290 system equipped with a Yb-fiber laser. An additive manufacturing process termed powder bed fusion that involves the employing a laser sintering or melting technology, is depicted in the figure 2(a). The apparatus consists of a gas controller, a chamber for construction, and a control panel. Typically, argon or nitrogen is utilized by the gas controller to maintain an atmosphere inert and prevent oxidation throughout the process [14]. The printing process actually occurs in the building chamber, where a control panel enables operational control and monitoring.

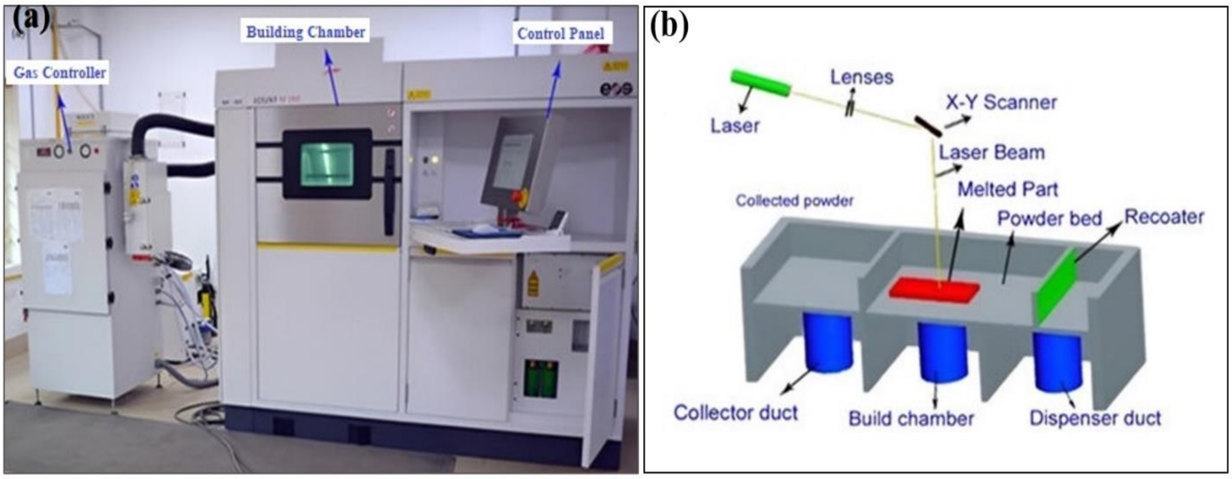

Fig. 2. (a) Experimental Setup of DMLS (b) Schematic illustration of DMLS

In figure (b), an X-Y scanner directs a laser beam via lenses onto a powder bed to selectively melt the powder and create the part layer by layer. A recoater evenly distributes new powder across the build chamber following the melting of each layer. A collector duct collects unused powder for reuse or disposal, while a dispenser duct supplies fresh powder. This process continues till the complete part is fabricated. The parameters used to fabricate the Co-Cr alloy samples at high density and desired microstructural characteristics in the DMLS process are displayed in the Table 2. According to the nTopology 3D software, the laser involves of spreading thin layer-by-layer on the build platform, followed by selective melting and sintering of the powder to fabricate the Co-Cr alloy samples. The process was repeated till the whole part was built. The use of a preheated build platform and an inert argon atmosphere helped to minimize thermal gradients and oxidation, respectively, leading to improved part quality [15].

Table 2. DMLS Process Parameters

Parameter	**Value**
Laser Power	200 W
Layer Thickness	30 µm
Speed of scan	1200 mm/s
Shielding Gas	Argon
Hatch Spacing	0.1 mm
Build Platform	Preheated to 200°C

2.3 nTopology Design Integration

nTopology software was used to design the Co-Cr alloy samples with optimized lattice structures and distribution of material. The 3D software advanced computational design competencies allowable to design complex geometries which are tough to attain in traditional design tools [16]. The process begins with the importation of the initial CAD model of the specimen into nTopology, provides a foundation for additional design optimizations. A lattice structure was made within the model to reduce the weight even though maintaining mechanical strength. The optimal laser parameters of thickness and cell size are chosen in order to obtain light weight and high strength with better mechanical performance. The uniform distribution of material in the prepared samples was graded to enhance strength and stiffness of critical areas. In order to reduce material consumption and also to attain the specified mechanical characteristics the optimizing technology tool of nTopology was integrated with the DMLS system. The design obtained at lightweight and strong

structure due to process of optimizing, removes the unnecessary material. The design file with optimized topology, functionally graded and lattice structure are uploaded in a DMLS system-compatible manner for the smooth transition of design to fabrication. By incorporating nTopology design software along with DMLS, it was possible to create Co-Cr alloy samples that were specially designed to satisfy the demands of high-performance applications, with enhanced mechanical characteristics and effective material utilization [17].

2.4 Micro-hardness Test

Micro-hardness measurement was conducted on the additively printed Co-Cr lattice sample using automated Vickers hardness equipment (shimatzuS200) shown in the figure 3. The load of 1000g and the dwell time of 10s were chosen to ensure sure that the micro-hardness evaluation was homogenous. Indentation tests were performed on both nTopology integration with DMLS Co-Cr alloy and as cast Co-Cr samples, and the average micro-hardness values were obtained from a total of three readings [18, 19].

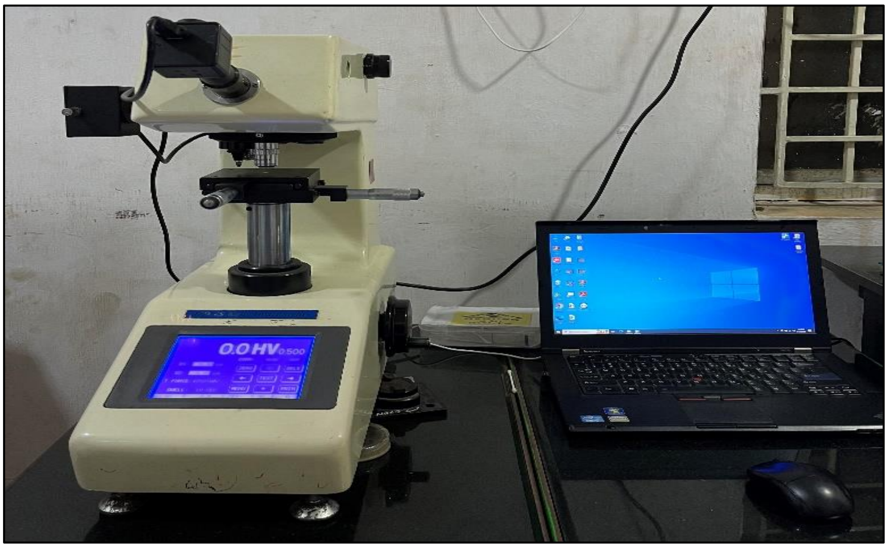

Fig. 3 Experimental setup of Vickers hardness testing machine

2.5 Compression Test

Compression tests were performed using an Instron 5566 testing machine shown in the figure 3. For the axial compressive strength tests, the samples were prepared as in the form of cylinders with a height of 30 mm and a diameter of 10 mm × 10 mm. An apparatus with a strain gauge head capable of measuring forces up to 10 kN was utilized. The experiment was conducted in a controlled environment with a constant strain rate of $V\varepsilon = 10^{-3}\ s^{-1}$ at a temperature of 37 °C [20].

Fig. 4. Experimental setup of Compression Testing Machine

2.6 Flexural Test

The flexural test (displayed in the Figure 5) well-known as a bending test, to measures the material behavior when subjected to simple beam loading. The specimens are prepared from the conventional and nTopology design integration with DMLS in a rectangular shape according to ASTM E290. The prepared specimen exposed to flexural test with the load applied at a constant speed of 1.5 mm/min till the material fracture [21].

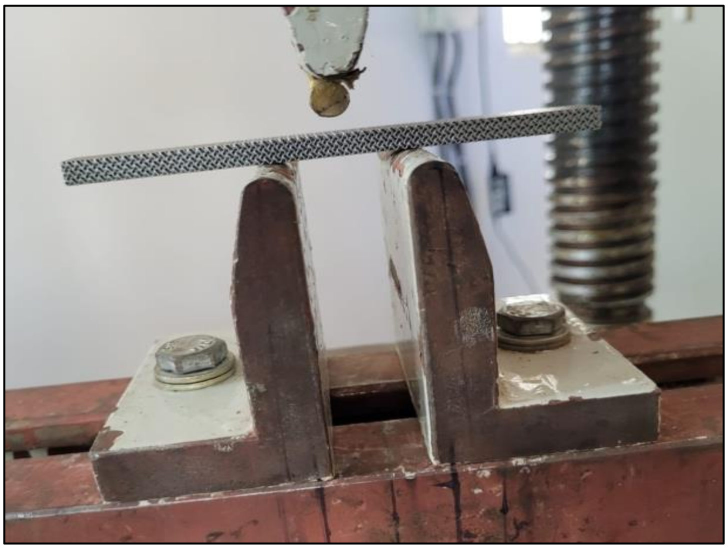

Fig. 5. Experimental setup of Flexural Testing Machine

2.7 Corrosion Test (Potentiodynamic Polarization Test)

Material corrosion is studied using a potentiodynamic polarization test, which measures current responsiveness as a function of applied potential. In order to achieve a steady state condition, the specimens were immersed for 45 minutes before each test. The open circuit potential (OCP) was then measured.

Potentiodynamic polarization (displayed in the Figure 6) measurements were performed at a scanning rate of 1 mV/s from − 250 to 1500 mV vs. open circuit potential. Corrosion parameters (icorr, βa, βc, and Ecorr) were determined using the Tafel extrapolation method [22].

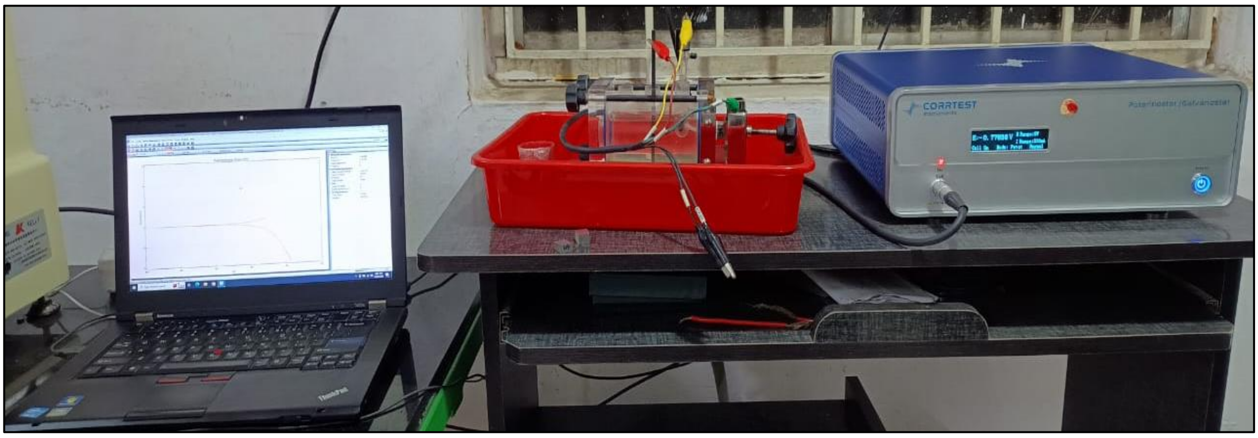

Fig. 6. Experimental setup of Potentiodynamic polarization Test

3. Results and Discussion

3.1 Micro-Hardness Test

The Vickers hardness tester is used to measure the values of micro-hardness for the DMLS fabricated Co-Cr alloys are shown in the Figure 7. The Co-Cr alloys fabricated via DMLS with nTopology design revealed higher micro-hardness values compared to traditionally manufactured alloys. The higher hardness values of the DMLS-fabricated alloys can be attributed to the refined microstructure and optimized material distribution achieved through nTopology design. The measured value of micro-hardness of the DMLS-fabricated alloys was 440 HV,

while the traditionally produced alloys exhibited a value of the micro-hardness as 380 HV. Uniform load distribution and lowering stress concentrations, the nTopology optimized DMLS fabricated Co-Cr alloy increases its value of micro-hardness. This specifically developed lattice structure guarantees adequate mechanical performance. As a result, it is suited for use in biomedical applications where resistance to stress and weight reduction are both essential. The increased value of micro-hardness enhances the wear resistance properties and durability of the material, making it suitable for biomedical applications requiring high mechanical performance.

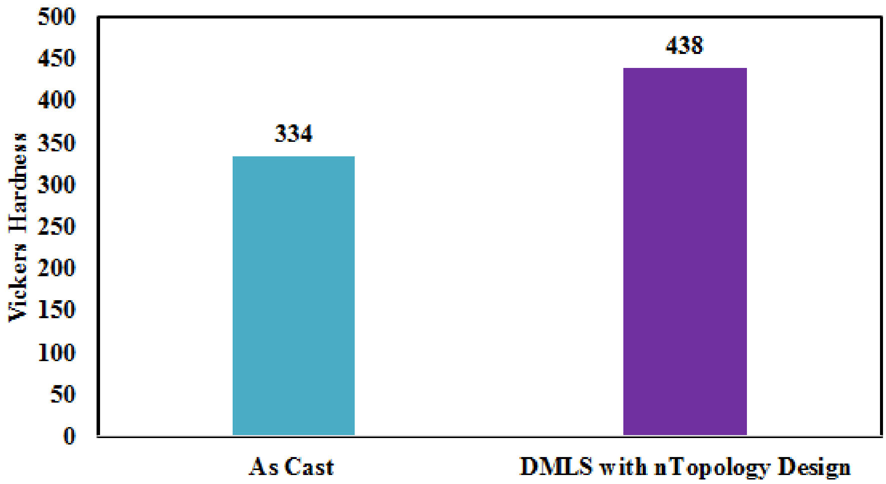

Fig. 7. Comparison of micro-hardness (As cast vs DMLS with nTopology Design)

3.2 Compression test

The specimens were subjected to compression tests at room temperature in accordance with ASTM E9. Samples of both as-cast Co-Cr alloy and DMLS fabricated Co-Cr alloy with nTopology design integration were prepared with the dimensions of ASTM E9 standards. All specimens were subjected to a uniform compressive force in a universal testing machine, which maintained a constant rate of deformation. Load and deformation were recorded until specimen failure. The DMLS made-up Co-Cr alloy with nTopology design revealed higher compressive strength than the as-cast Co-Cr alloy. This improvement is attributed to the optimized lattice structures formed through nTopology design, effectively distribute the loads and reduction of stress concentrations. The lattice framework in the DMLS alloy exhibits unique mechanical properties, allowing it to tolerate larger compressive forces than the dense but potentially less homogeneously stress-distributed as-cast alloy. The layer-by-layer fabrication of DMLS allows accurate microstructure control, improving mechanical performance even with intended porosity. DMLS manufactured Co-Cr alloy with nTopology design has greater compressive strength due to these features, making it a viable material for high-strength, low-weight applications.

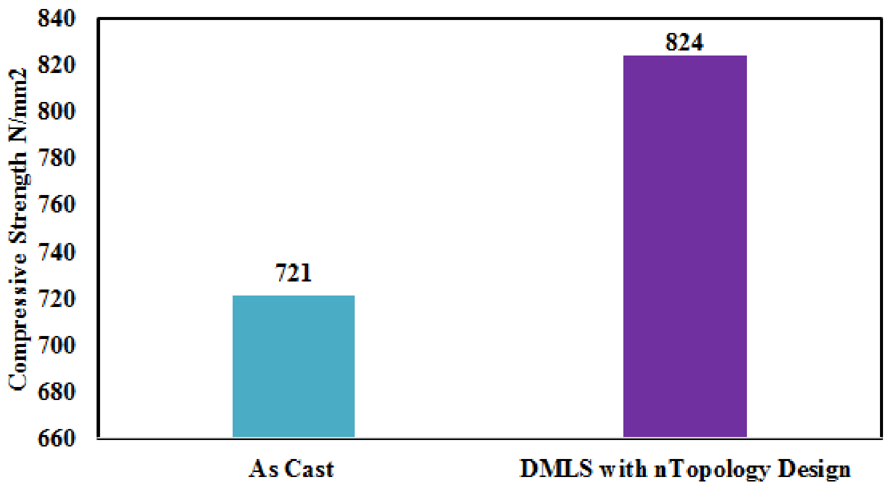

Fig. 8. Comparison of compressive strength (As cast vs DMLS with nTopology Design)

3.3 Flextural Test

The flexural tests were performed in accordance with ASTM E290, which outlines the standard test methods for bend testing of metallic materials. Specimens of both as-cast Co-Cr alloy and DMLS fabricated Co-Cr alloy with nTopology designs were prepared with precise dimensions as per ASTM guidelines. Each specimen was placed on a three-point bending fixture within a universal testing machine. A load was applied at the midpoint of the specimen at a constant rate of deformation until failure occurred. The load and corresponding deflection were recorded throughout the test. Flexural strength was calculated using the maximum load and the specimen's dimensions. The flexural strength of the DMLS fabricated Co-Cr alloy with nTopology design was found to be higher than that of the as-cast Co-Cr alloy. This superior performance is attributed to the optimized lattice structures engineered through nTopology design, which enhance load distribution and reduce stress concentrations, particularly under bending loads. The as-cast alloy, while dense and uniform, may not distribute stress as efficiently across its structure, leading to lower flexural strength. In contrast, the DMLS process allows for precise control over the microstructure and geometry, enabling the creation of complex lattice designs that provide better mechanical performance. These optimized structures can effectively withstand bending forces, resulting in higher flexural strength. This advantage makes the DMLS fabricated Co-Cr alloy with nTopology design a valuable material for applications that require high strength and durability under flexural loads.

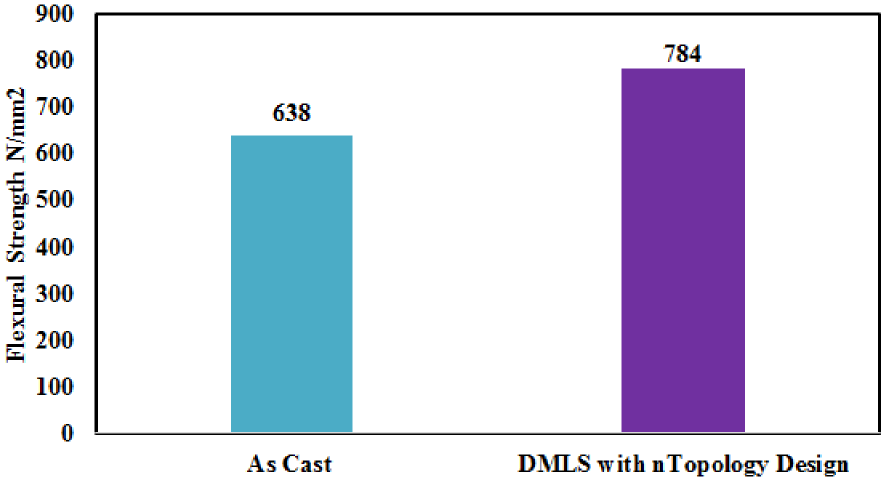

Fig. 9. Comparison of flextural strength (As cast vs DMLS with nTopology Design)

3.4 Corrosion Behaviour

Electrochemical corrosion tests were carried out to assess the corrosion behavior of the DMLS fabricated Co-Cr alloys in a simulated physiological environment (0.9% NaCl solution). The potentiodynamic polarization curves of conventional and DMLS with nTopology Design Co-Cr Alloys datas are shown in Figures (a & b) respectively. The significant corrosion parameters with corrosion potential (Ecorr), corrosion current density (Icorr) and corrosion rate (mm/year) are shown in the in Table 5.

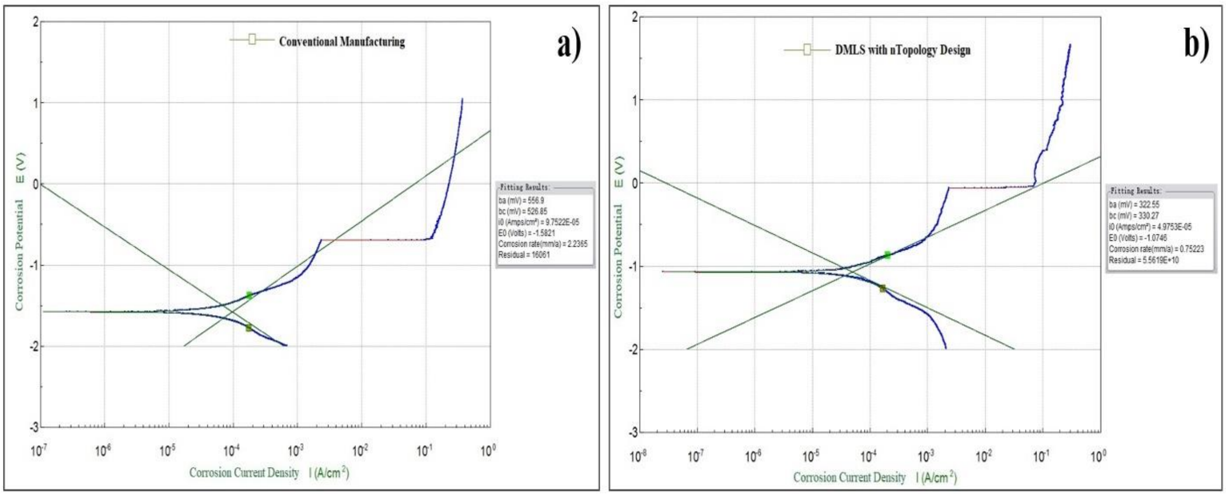

Fig. 10. Potentiodynamic Polarization Curves of Co-Cr Alloys (a) Conventional Manufacturing and (b) DMLS with nTopology Design

Table 3. Comparison of Ecorr, Icorr and Corrosion Rate

Sample	Ecorr (V)	Icorr (A/cm²)	Corrosion rate (mm/year)
DMLS with nTopology Design	-1.0746	4.97×10^{-5}	0.7522
Conventional Manufacturing	-1.5821	9.75×10^{-5}	2.2365

Fabrication of Co-Cr alloys adopting DMLS with nTopology design showed superior corrosion resistance compared to traditionally manufactured alloys. The Ecorr value of the DMLS with nTopology design was -1.0746 V, signifying a more noble (less negative) corrosion potential than the -1.5821 V observed for the as cast Co-Cr alloy. A more noble corrosion potential proposes better stability and lower tendency to corrode. The Icorr value of the DMLS with nTopology design was 4.97×10^{-5} A/cm², significantly lower than the 9.75×10^{-5} A/cm² observed for the as cast alloy. The lower value of Icorr shows a reduced corrosion rate and better corrosion resistance. Importantly, the calculated corrosion rate for the DMLS-fabricated Co-Cr alloy was 0.7522 mm/year, which is substantially lower than the 2.2365 mm/year observed for the conventionally manufactured Co-Cr alloy. The improved corrosion resistance of the DMLS-fabricated alloys can be attributed to the homogeneous microstructure, refined grain size, and uniform elemental distribution achieved through nTopology design and the controlled DMLS process.

4. Conclusion

This study determines the significant improvements attained by incorporating nTopology design software with Direct Metal Laser Sintering (DMLS) for the production of high-performance Co-Cr (Cobalt-Chromium) alloys. This investigation focused on assessing the mechanical properties, corrosion behavior, and microstructural characteristics of the produced alloys, revealing substantial improvements compared to traditionally manufactured Co-Cr alloys.

The fabricated Co-Cr alloys by means of DMLS along with nTopology showed better mechanical properties of hardness, compression strength and flexural strength. nTopology design contributed for the enhancements The enhancements of the material properties obtained. The optimal lattice structures and distribution of material attained through nTopology design contributed to these enhancements. The mechanical properties of DMLS fabricated alloys shows an improvement upto than the as cast alloy. Enhancements are attributed to the refine microstructure, reduction of porosity, and effective load distribution occurred by the optimized lattice structures.

The electrochemical corrosion tests revealed that the DMLS-produced Co-Cr alloys showed enhancement of corrosion resistance in a simulated functional environment (0.9% NaCl solution). The corrosion potential (Ecorr) value of DMLS produced alloys were more noble at -200 mV vs. SCE, and the corrosion current density (Icorr) were lower at 0.5 μA/cm², showing better stability and lower corrosion rates compared to the conventional alloy.

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