OBTAINING A DISSIMILAR METALLIC JOINT BY ADDITIVE MANUFACTURING

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ABSTRACT

Additive manufacturing is a novel technique that allows, for example, the fabrication of metal parts with high precision and complex geometries. However, most metal products manufactured by these techniques employ only one metal or metal alloy. The manufacturing of multi-component metal parts by additive manufacturing is a field that is beginning to be explored for the fabrication of parts with dissimilar joints or compositional gradients for various types of applications. One of the obstacles is the incompatibility between one or more pairs of metallic elements used to manufacture the multicomponent parts, due to the formation of intermetallic compounds at the interface, weakening the joint region. One proposal to study this issue is to obtain, by additive manufacturing, dissimilar joints using intermediate elements, thus avoiding the contact of the materials that would form undesirable intermetallic compounds, analogously to the welding of dissimilar materials. This work proposes the feasibility of the union between Titanium and Iron, using Molybdenum and Chromium as intermediate materials. For this, layers of Molybdenum on Titanium and on the other side Chromium on Iron were produced to analyze the interface region and the formed compounds. The pairs formed were characterized by optical and electron microscopy and instrumented indentation. The results of this research are a contribution to the fabrication of multi-component parts by additive manufacturing.

Keywords: *Dissimilar joint, Intermetallic compounds, titanium alloy, additive manufacturing.*

INTRODUCTION

Titanium (Ti) and its alloys are known to be among the best engineering materials, covering extensively applications, where characteristics such as high strength-to-weight ratio make them ideal for their respective use. In order to combine the good mechanical and metallurgical properties of Ti with the availability or affordability of other alloys, there is a growing interest in joining Ti alloys with different steels, stainless steels, structural or just alloys containing a considerable percentage of iron (Fe). Unfortunately, the traditional titanium-iron weld joining has not been technically effective. Due to a metallurgical incompatibility between them, they generate intermetallic compounds such as TiFe and $TiFe_2$ which embrittle the joint and end up causing a collapse at the interface due to residual stress and excessive deformation generation.[1]

Taking into account the above, many authors have carried out studies to make this joint viable by employing different techniques such as thermal fusion welding, friction stir welding, diffusion welding, and other techniques that are grouped within additive manufacturing, such as Direct Laser Deposition, Friction Stir Layer, Laser Welding, etc. The researchers searched for the right metal or alloy to use as intermediates to eliminate or alleviate the influence of intermetallic compounds at the interface, often based on binary phase diagrams, to get a sense of the outcome[1,2,3].

Based on these investigations and the aforementioned phase diagrams[3], we proceeded to find metals that were compatible with Ti and Fe. Molybdenum (Mo) and Chromium (Cr) were found to be candidates for a joint, avoiding the formation of intermetallic compounds between Ti and Fe by additive manufacturing. Using equipment own design, which allows the powder bed fusion technique to be reproduced, an initial study of the compatibility between the metals was carried out, manufacturing beads at different laser powers and number of layers, thus finding the compositions of the interfaces and preliminary results that allow us to report positive results in the viability of this joint.

MATERIALS AND METHODS

In the following, the most relevant materials and equipment of this research will be presented.

Substrate and powdered metals

A substrate of commercially pure Ti (TiCp) was used, hardened and reduced in grain size, on which Mo, Cr, and Fe powders were deposited, followed by a substrate of AISI 1020 steel on which Cr layers were deposited to validate the compatibility of both metals. Table 1 shows the powders and substrates' chemical composition given by the manufacturers. Slot holes with an approximate depth of 0.23 mm were made to simulate a layer suggested in previous works[4].

Table 1. Chemical composition of powders and substrates.

Material	Procedence	Chemical composition (%)					
		Cr	Mo	Fe	Ti	O	Si
Cr Powder	Alfa Aesar	99	-	0,045	-	0,563	<0,010
Mo powder	ThermoFisher	-	99,95	0,001	-	0,0053	0,0015
Fe powder	Sigma Aldrich	-	-	99	-	-	-
Ti substrate	Realum	-	-	-	99,3	-	-
Steel 1020	Trefita	-	-	99	-	-	-

Laser procedures equipment

Due to the high reactivity of titanium with oxygen in the environment and the possible hindrance of oxygen in the procedures, it was necessary to use a controlled atmosphere with as little oxygen as possible. Figure 1 (a) shows an MB-200b glovebox from the MBRAUN company that provides a space in which oxygen is replaced by Argon through an automatic pressure and purification control, reducing the concentration of oxygen and nitrogen in the air to parts per million, sufficient to prevent adverse reactions at the time of the laser procedures; by using a Ytterbium-doped fiber laser controller (IPG photonics YLR-500), and moving a CNC table of own design, we carried out the bead and coating manufacturing procedures in the different stages of the process.

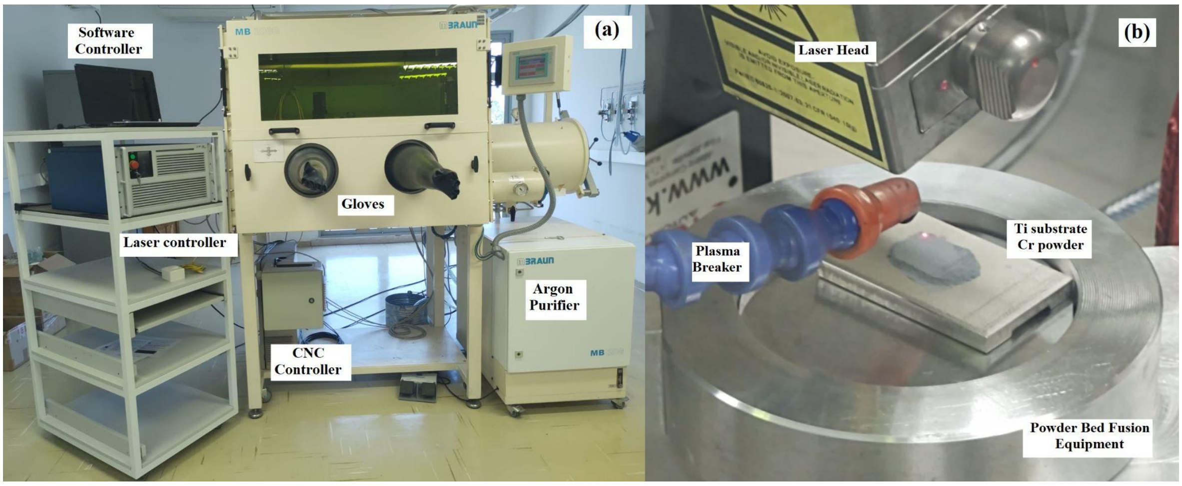


Figure 1. (a) Laser and environment controller, glovebox MBraun and (b) Own-designed powder bed fusion equipment.

Finally, we can see in Figure 1 (b) a part of the own design equipment, which allows varying the layer thickness and recovering the powder after each laser application, thus allowing the powder bed fusion procedure to be more viable for carrying out studies of multi-materials and functionally graded materials, in addition to having the option to vary for each layer parameters like speed, energy and focal length as it can be done in an additive manufacturing equipment.

Procedure and analysis equipment

The raw materials to be used were initially analyzed using Scanning Electron Microscopy (SEM), in this case Mo, Cr, and Fe. After that, laser tests were performed on the Mo on Ti substrate with laser power varying between 150 W, 300 W, and 450 W to make simple beads without reworking. In the case of Cr on Ti substrate, a power of 300 W was used, and for Fe on Ti substrate, two powers, 150 W and 300 W, were used. A preliminary test was conducted by adding two layers of Mo to a Ti substrate and then adding an additional layer of Cr. The layers mentioned above have a thickness of 0.25 mm[4].

Using a Struers Mesotom cut-off cutter, samples were cut. In the next step, the samples were cold pressed with Arotec acrylic resin, and they were sanded and polished with Arotec equipment. Sandpaper with descending grain size was used: 100, 220, 400, 600, 600, 1200 and diamond paste of 9, 6 and 3 um. As a final step, it was polished with Buehler VibroMet 2 equipment. Finally, we conducted a SEM analysis. The results presented below were obtained by using secondary electron detection techniques, Backscattered Electrons (BSE) and Energy Dispersive Spectroscopy (EDS). A Zeiss EVO MA15 microscope was used for these analyses[4].

RESULTS AND DISCUSSION

Metal powders analysis

Mo, Cr, and Fe metal powders were analyzed by SEM. We can observe in Figure 2 that all the above-mentioned present an amorphous morphology, a variable particle size, and for the case of Figure 2 (a) and (b) a similarity in grain size as specified by the manufacturer (US mesh 170, < 88 μm), while Mo presents a smaller particle size referenced as US mesh 325 (< 44 μm). In addition to the above, we can observe that for Mo there is a perception of agglomeration due to the particle size, humidity and analysis technique (graphene tape was used for its fixation).

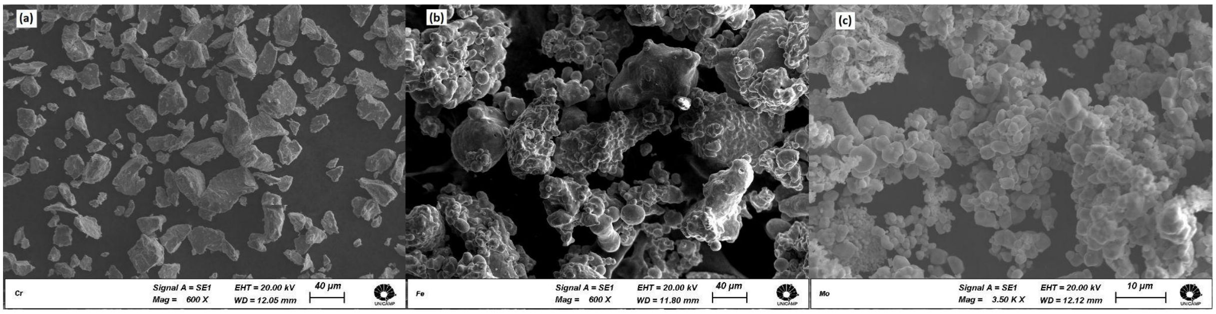


Figure 2. SEM images of Cr (a), Fe (b) and Mo (c) powder materials.

Pair tests

To validate the compatibility between the materials to be used, we proceeded to perform single and dual tracks varying the laser power. Taking into account previous research, we used powers of 150 W, 300 W, and 450 W. The most relevant images from the SEM with BSE and EDS detection are shown below.

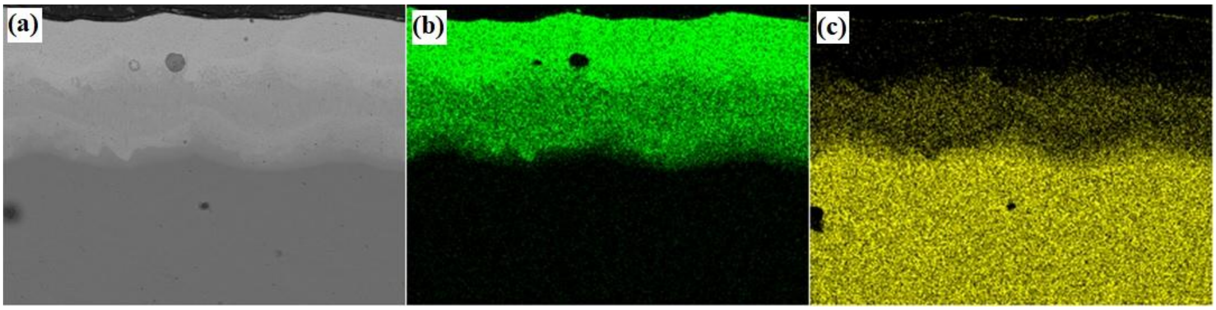
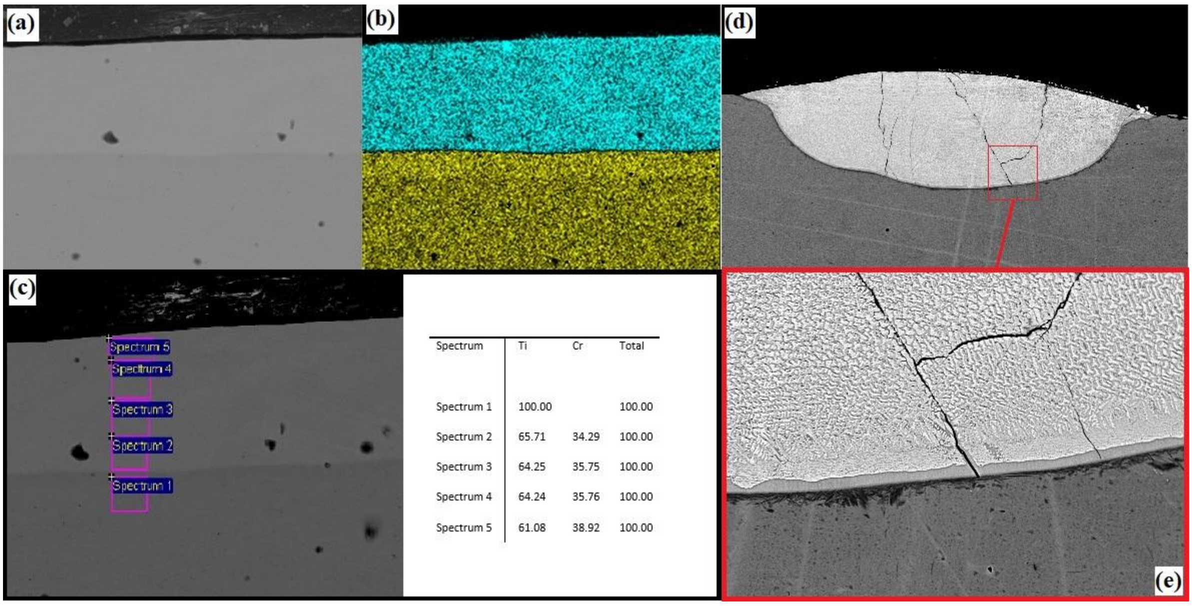


Figure 3. BSE from Ti with two Mo layers sample (a) Sem image (b) Mo detection (green) (c) Ti detection (yellow).

Tests were carried out for the Ti-Mo joint with two Mo layers, obtaining a successful union between these two metals as expected taking into account the results of previous research[4]. The power used to obtain the results presented in Figure 3 was of 200 W, reaching this choice due to the fact that in the 300 W and 450 W potencies the formation of a "*key-hole*"[4] type union occurs, where a deep fusion pool is formed to avoid having a high concentration of Mo on the surface, to avoid the presence of another element in contact with Ti that can generate intermetallic compounds as in the case of Cr and Fe. Additionally, there is a gradient of functionality, in this case of Mo concentration from the surface to the interior of the sample.

The surface of the sample shows some porosity and punctual defects, but they do not affect the Ti-Mo joint results.



Spectrum	Ti	Cr	Total
Spectrum 1	100.00		100.00
Spectrum 2	65.71	34.29	100.00
Spectrum 3	64.25	35.75	100.00
Spectrum 4	64.24	35.76	100.00
Spectrum 5	61.08	38.92	100.00

Figure 4. Ti-Cr BSE map analysis(a)(b) , single spectrum test(c) and Ti-Fe sample 150W(d)(e).

When analyzing the Ti-Cr sample, a stable joint between Cr (cyan) and Ti (yellow) was found as shown in Figures 4 (a) and (b). However, performing a spectral analysis of the concentration of the elements along the sample, it was found that the concentration of Cr did not exceed 40% (Figure 4 (c)) therefore it did not generate the intermetallic compounds present in the literature[3], which can embrittle this joint.Due to their metallographic nature, the test results of Fe on Ti substrate (Figure 4 (d)(e)) were expected. The junction of these metals generates intermetallic compounds, and we observed the formation of fissures derived from the residual stresses caused by the appearance of these compounds[1].

<u>Ti-Mo-Cr and final piece</u>

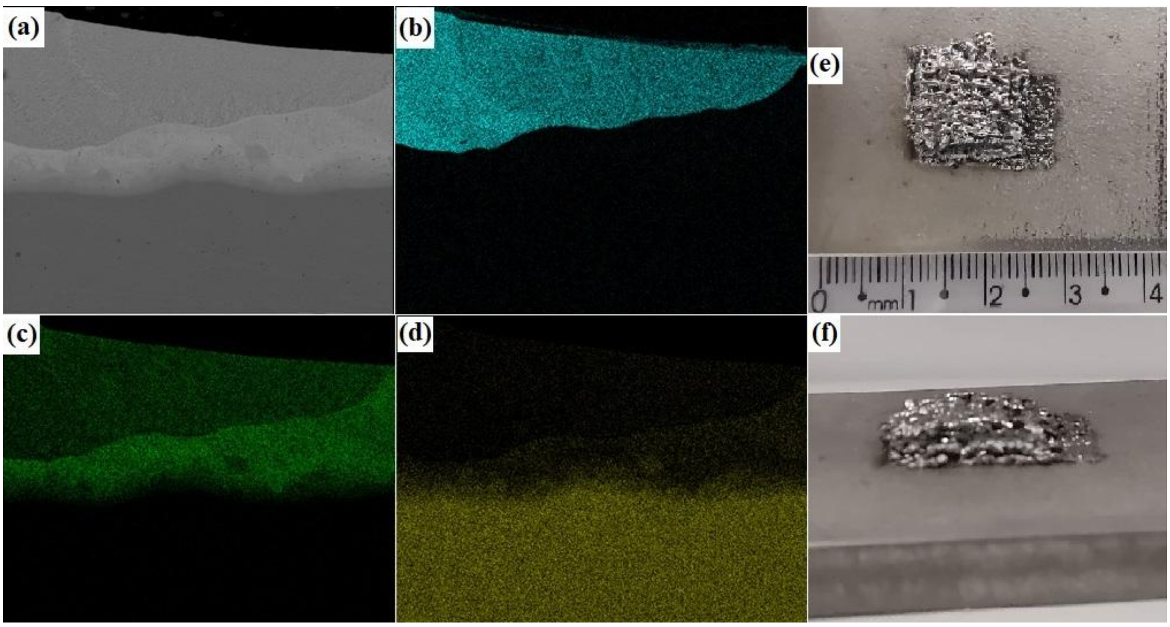


Figure 5. Ti (d)- Mo (c)- Cr (b) EDS analysis, BSE image from that piece.

Figure 5 shows the Ti(yellow)-Mo(green)-Cr(cyan) system, which was analyzed in the SEM and mapping of the elements present. It can be seen how there is a separation between Ti and Cr by Mo and how this is combined with both by the propagation of Mo in the structures of Ti and Cr. And finally, a complete part was manufactured with three layers of Mo, two of Cr, and two of Fe shown in Figure 5 (e)(f). Decreasing the laser power as the number of layers increases also decreases the refusion of the previous layer.

CONCLUSIONS

In order to study powder bed fusion, it is efficient to use and save materials by using own-designed equipment that recreates additive manufacturing conditions.

Validating the compatibility between the materials used, Mo in Ti has a high mixing capacity, and for each new layer of Mo that was added, the previous one was refused, which generated a dilution of Mo in Ti, thus forming a concentration gradient; this being directly proportional to the laser power.

The Ti-Cr system presents limited compatibility based on the binary phase diagram presented in the literature[3] and the results obtained in the laser joint. However, when an additional layer is used, the Cr concentration increases at the joint interface, which will proceed to generate intermetallic compounds and fractures in the interfase.

At all laser powers, the Ti-Fe binary system produces fractures in the Fe structure deposited on the Ti substrate.

Using the results obtained from the study of metal pairs, a Ti-Mo-Cr part was fabricated in which a mixture between Ti-Mo and Cr-Mo can be seen, avoiding the presence of Cr on the Ti substrate and, in the same way, hindering the formation of intermetallic compounds at the interfaces.

In addition, a dissimilar joint was obtained between Ti and Fe multi-materials with the use of Mo and Cr intermediates, as seen in Figure 5 (e) (f). Studies in metallography, microscopy, and mechanics will be performed to validate its use in different applications.

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REFERENCES

[1] MURRAY, Joanne L. The Fe− Ti (iron-titanium) system. Bulletin of Alloy Phase Diagrams, v. 2, n. 3, p. 320-334, 1981.

[2] SZYMLEK, Krzysztof. Review of titanium and steel welding methods. Advances in materials science, v. 8, n. 1, p. 186, 2008.

[3] SWARTZENDRUBER, L. J.; ASM Handbook. 3: Alloy Phase Diagrams, v. 3, 1998.

[4] LEVA, E.S. Modificação superficial a laser para obtenção de gradientes de dureza e módulo de elasticidade em titânio. 2016, 140p, Tese (Doutorado em Engenharia Mecânica) University of Campinas, Campinas/SP, Brazil.