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Joining Dissimilar Steels by Means of Selective Laser Melting: Material Microstructure and Interfacial Characteristics

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Abstract

The increasing demand for designing complex structures using Functionally Graded Material boosts the research on reliable joining processes. For several industrial applications in the automotive, tooling, and petrochemical industries, the joining of a stainless steel with a low-alloy steel is often required to obtain a variation of mechanical and corrosion properties when different parts of the same structure are subjected to different working conditions. Welding a stainless steel with a low-alloy steel is a challenging operation because it is not easy to control the microstructure of the welded joint and to avoid metallurgical defects such as hot cracks. Moreover, traditional welding methods can only be applied to relatively simple geometries. To design and produce multi-material components, characterised by complex geometries, Selective Laser Melting process capabilities can be exploited. In this paper, an AISI 316L stainless steel is joined to 16MnCr5 steel by carefully tuning the process parameters. Metallurgical investigations coupled with Energy Dispersion Spectroscopy analyses allowed to evaluate the soundness of the joint and the effect of the process thermal cycle on the alloy microstructures and properties. The results are very promising and show that a careful selection of process parameters allows to obtain a continuous joint.

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Keywords: Functionally Graded Material, Selective Laser Melting, AISI 316L, 16MnCr5, Microstructure.

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1. Introduction

The increasing demand for designing complex structures using Functionally Graded Material (FGM) [1] boosts the research on reliable joining processes. For several industrial applications in the automotive, tooling, and petrochemical industries, joining a stainless steel with a low-alloy steel is often required to obtain a variation of mechanical and corrosion properties when different parts of the same structure are subjected to different working conditions. Welding a stainless steel with a low-alloy steel is a challenging operation because it is not easy to control the microstructure of the welded joint and to avoid metallurgical defects such as hot cracks. Moreover, traditional welding methods can only be applied to relatively simple geometries.

To overcome such limitations and to directly realize joints between different metallic materials, Additive Manufacturing can be efficaciously applied. The production of FGMs [2,3], in which the properties, such as chemical composition or microstructure gradually change along one or more main directions, is now possible using existing technologies, such as Laser-Powder Bed Fusion (L-PBF), which allows the creation of simple joints whose characteristics, however, need to be thoroughly analysed. FGMs are applied in applications in which different properties (i.e., hardness, tensile yield, etc.) are necessary for the performance of a specific component, like those that are frequently used in important industry sector such as energy, aerospace, automotive and medicine. Among L-PBF technologies, the Selective Laser Melting (SLM) is the promising in terms of isotropy and quality of materials produced and it can be applied to design and produce multi-material components, characterised by complex geometries.

In the last few years, examples of such multi material junctions have been proposed. For example, Tungsten-Copper (W-Cu) is a typical Plasma-Facing Components (PFC), which are essential for the operation of new fusion reactor (i.e., ITER and DEMO): W is a promising material because of its inherent high melting temperature, while Cu is a perfect heat-sink material because of its high thermal conductivity. However, applying also the SLM technique there are some important issues, which originate from the mutual effects between materials and laser source, such as the low laser energy absorption of Cu with infrared laser and the mutual insolubility between W and Cu, suggesting a limited bonding strength [4]. Talking about Cu and Cu alloy (e.g., CuCrZr) [5,6], one of the most studied joints is certainly with stainless steel, such as AISI 316L. This steel was one of the first materials to be processed with SLM and combined with Cu has great potential in several different industrial fields (e.g., aerospace, power generation, heat transfer devices, and nuclear industries), making it possible to produce components both with good electrical/thermal conductivity and high corrosion resistance. Considering other multi-material systems obtained by using SLM technology, there is the bonding between Inconel and stainless steel (e.g., IN718 and 316L) where, for example, it is shown that the homogenization heat treatment improves elemental diffusion with respect to the as-built bonding, resulting in a gradual material transition without a distinct interface [7]. Other combinations are the bonding of aluminium alloys and the bonding of steel with other steel, nickel-based alloys, and ceramics [8].

Usually, these types of SLM joints are create along one main direction, using the available vertical size of the building chamber. The first part of the component is produced with one material and the next one is produced with another, using the surface of the previously produced part as the initial base of production. The first part of the component sticks to the original building plate of SLM machine, appropriately chosen according to the compatibility between materials (e.g., stainless steel, brass, etc.), while the adhesion of the second part is a function of the compatibility between the materials to be joined. The choice of SLM process parameters, such as the Laser Power (P), Laser Scanning Speed (v), Hatch Distance (h) and Layer Thickness (t), as well as the study of the junction and the a priori materials compatibility is of fundamental importance for the manufacturing of the multigrade component.

In this paper, an AISI 316L stainless steel is joined to 16MnCr5 case hardening steel by carefully tuning the SLM process parameters. Metallurgical investigations coupled with Energy Dispersion Spectroscopy (EDS) analyses allowed to evaluate the soundness of the joint and the effect of the process thermal cycle on the alloy microstructures and properties. The results are very promising and show that a careful selection of process parameters allows to obtain a continuous joint.

2. Materials joining

The joint between AISI 316L and 16MnCr5 steel was realized by means of a standard SLM machine, whose main characteristics are shown in Table 1. The machine, equipped with an InfraRed (IR) laser source up to 175 W, is provided with a cylindrical building chamber which allows the manufacture of components with a maximum height of 90 mm. For both materials, the metal powder was supplied by the Metals4Printing (M4P) company [9,10]. The grain size is between 15-45 µm.

Table 1. SLM Machine Characteristics.

Characteristic	
Model	SISMA MySint100 PM/RM
Building volume	Ø 100 mm x 90 mm
Laser source	Up to 175 W InfraRed (λ = 1070 ± 10 nm)
Laser spot	30 µm
Layer thickness	20-40 µm
O_2 sensor	100 ppm

The materials joining was produced with two successive phases: the first one, where the AISI 316L steel part was produced directly on the machine building plate (which is also made of stainless steel), while the second one, where the 16MnCr5 steel was built on the previous AISI 316L part, as shown in Fig. 1. Between the two building phases, the powder material in the supplier and the building cylinder were replaced.

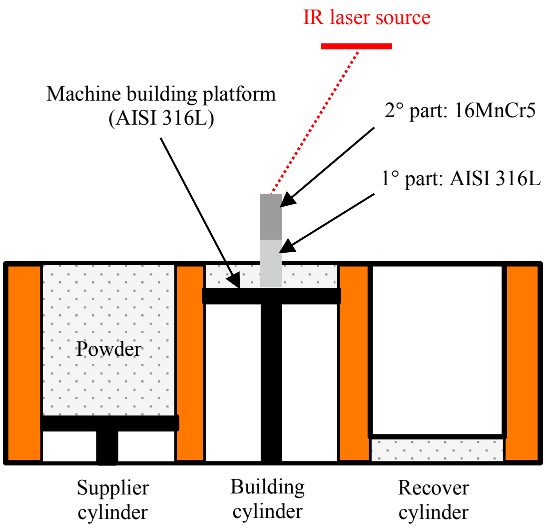

Fig. 1. Joint between AISI 316L and 16MnCr5: SLM scheme procedure.

Previously optimised SLM process parameters were used for each part to ensure a density of over 99% for each material: the values and the resulting Volumetric Energy Density (VED) (1) applied on the powder bed are shown in Table 2.

$$\mathrm{VED} = \frac{\mathrm{P}}{\mathrm{t\,v\,h}}\ [\mathrm{J/mm^3}] \tag{1}$$

Table 2. SLM process parameters.

Parameter	AISI 316L	16MnCr5
Laser Power (P)	175 W	175 W
Scanning Speed (v)	1450 mm/s	1150 mm/s
Hatch Distance (h)	70 µm	70 µm
Layer Thickness (t)	40 µm	40 µm
Scan Strategy	Meander 67°	Meander 67°
Inert Gas	Argon	Argon
Volumetric Energy Density (VED)	43.1 J/mm^3	54.3 J/mm^3

A tensile test specimen, according to the ISO EN 6892-1 standard [11], was chosen as the reference geometry. This geometry was chosen to validate the joining process between the two materials and to evaluate later with further works the mechanical properties. The specimen was built vertically with minimal support structures. It was then CNC machined and then analysed (Fig. 2).

Fig. 2. Multi-material tensile specimen: AISI 316L and 16MnCr5 steel.

3. Microstructure analysis

To evaluate the continuity and structure of the joint the central part of the specimen was embedded in a resin, grinded by using SiC papers up to 2400 grit and then polished with 1 µm alumina suspension. To study the joint microstructure a double etching was performed: chemical etching with Nital2 for highlighting the low alloy steel microstructure and electrochemical etching with oxalic acid to observe the stainless steel microstructure. Microstructural investigations were performed using optical and Scanning Electron Microscope (SEM) equipped with Energy Dispersion Spectroscopy (EDS) analysis system. Change of the mechanical properties of the built part across the joint was evaluated by performing Vickers microhardness tests with a test load of 100 gf (HV0.1). After polishing, the specimen was observed by using both SEM and optical microscope. A careful observation of Fig. 3 reveals that the joint between the two steels is continuous and defect-free. In the SEM image, few microcavities are visible, but they are located only in the bulk of materials. To reveal the alloys microstructure in the as-built state, they have been etched and analysed by the optical microscope.

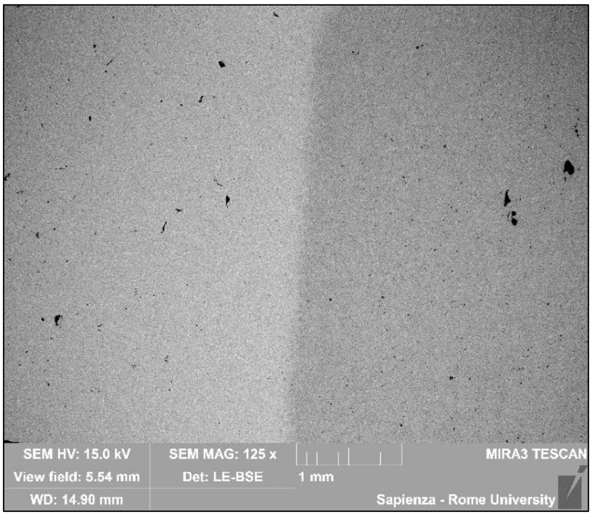

Fig. 3. SEM micrograph showing the joint between AISI 316L (left) and 16MnCr5 (right).

The 16MnCr5 alloy shows some microcavities and the melting pool boundaries are barely visible (Fig. 4a). The steel appears to have a very fine bainitic microstructure: in fact, as discussed in many papers available in the literature, the microstructure of low alloyed steels produced by additive manufacturing is generally martensitic/bainitic or bainitic [12-14]. Since SLM is a process characterised by high cooling rates reaching 10^6 – 10^8 K/s, the solidification process does not follow the equilibrium diagram. Some studies have shown that while the very rapid solidification of the melt pool promote the formation of martensite, the thermal accumulation promote bainite formation. A recent study [14] demonstrated that during melt pool solidification it is possible to obtain a bainite-like microstructure despite the very high cooling rates. This confirms our finding. The other steel produced in this study is the AISI 316L stainless steel. Fig. 4b shows its microstructure after electrochemical etching. This figure clearly shows the boundaries of the melting pool and the sub grain structure where columnar grains pass through multiple laser tracks, as highlighted by other papers [15,16]. After double etching, it is also possible to analyse the joint area. Fig. 5a shows that the joint area is about 200 µm thick and it appears as an area that separates the two different steels. By observing that area we can notice that into the melt pool there are intermixed phases. This can be explained considering that inside the melt pool there is a rapid variation of the temperature that determines a variation of the surface tension. This promotes Marangoni convection as shown in Fig. 5b. This circular flow favours the bonding at the interface between dissimilar alloys by enhancing element diffusion.

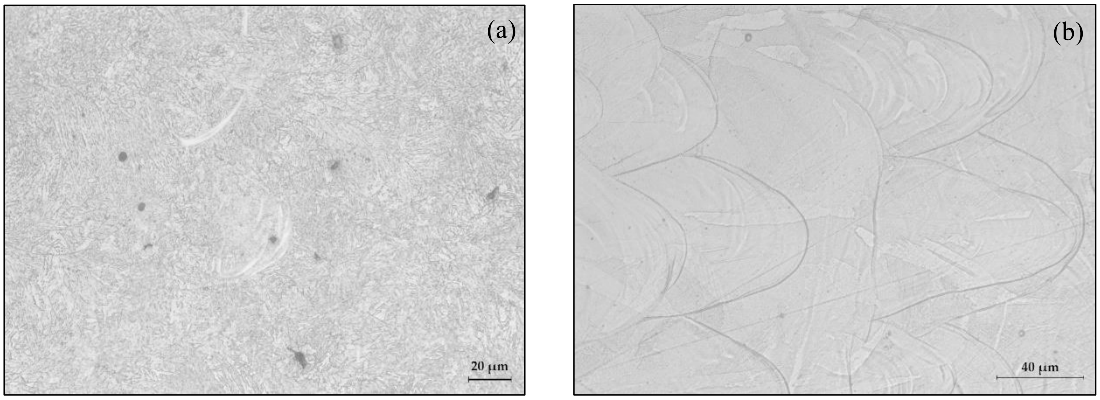

Fig.4. Optical micrographs showing the microstructure of 16MnCr5 (a) and AISI 316L (b) after etching.

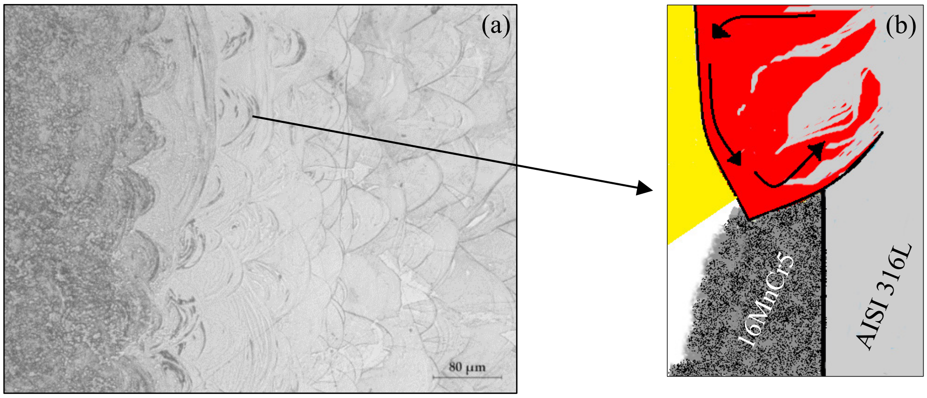

Fig. 5. Optical micrograph showing the joint between 16MnCr5 (left) and AISI 316L (right) after double etching (a) and a detail illustrating the formation mechanism of the joint related to the Marangoni convection in the melt pool (b).

To study the joint area, we also performed EDS analyses together with X-ray maps for the evaluation of the elements distribution. Fig. 6 shows a SEM micrograph of the interface between the two steel and X-ray maps of the boxed area. By analysing the distribution Cr, Ni and Mn we can say that there has been a good interdiffusion of the different elements and that the interdiffusion area is, as said before, about 200 µm thick. Moreover, X-ray maps confirm the presence of intermixed phases due to the Marangoni convection in the melt pool.

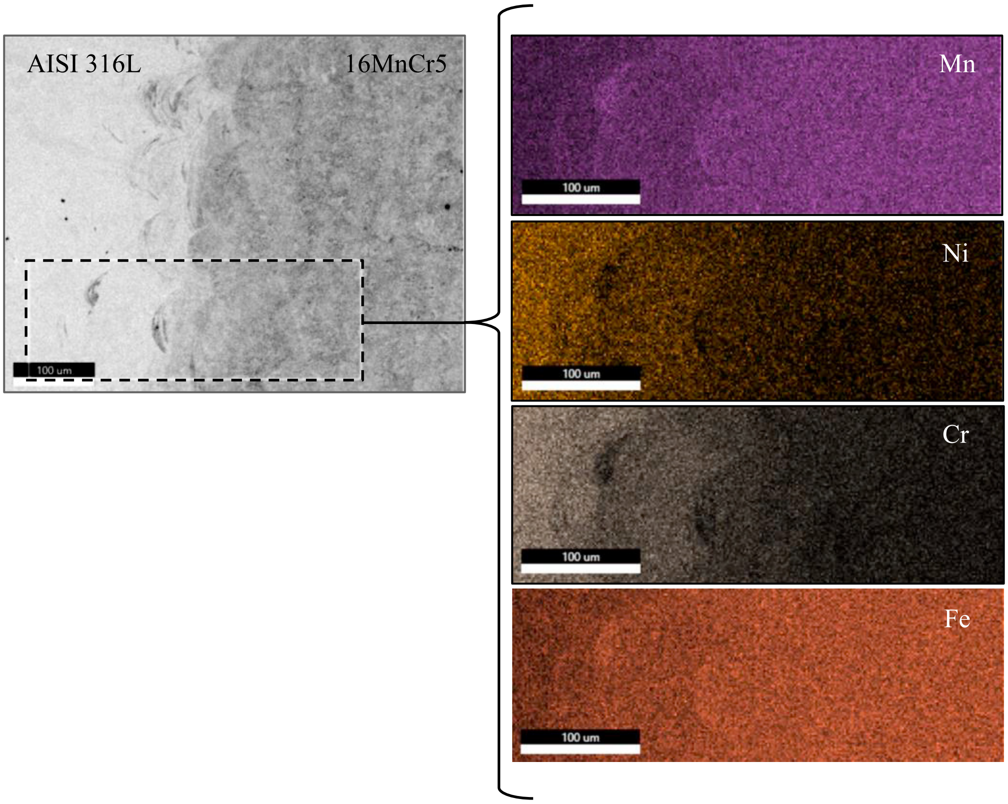

Fig. 6. X-ray maps showing the distribution of Fe, Cr, Ni and Mn in the joint area.

Considering that across the joint we could have variation of the mechanical properties, microhardness tests have been performed starting from an initial position, which has been selected as the centre of the joint area (Fig. 7).

Obviously, these measurements are critical because the presence of micro voids, just below the surface, could alter the hardness measured values.

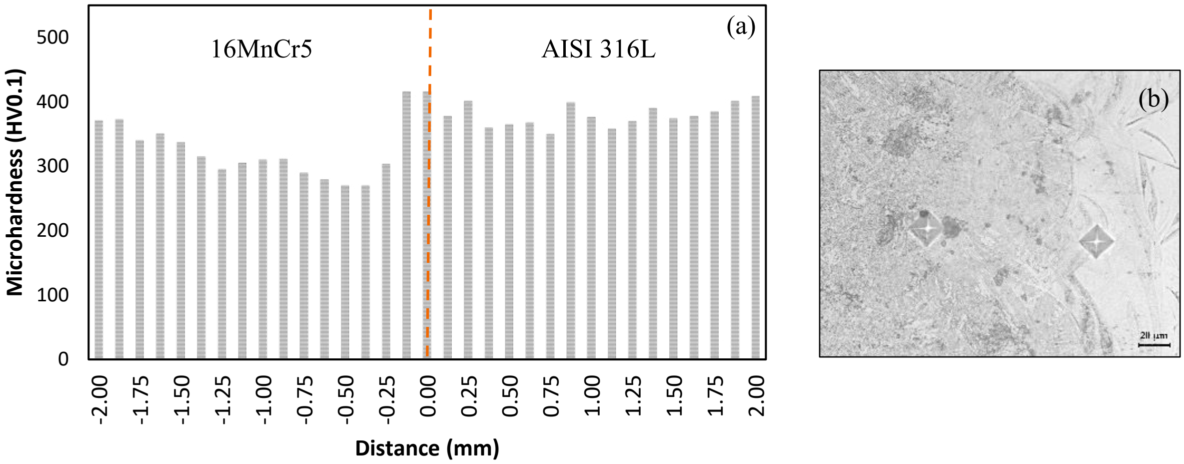

Fig. 7. Microhardness (HV0.1) measured across the joint (a) and optical microscope micrograph showing a couple of indentations (b).

Analysing Fig. 7a, it is possible to notice a rapid variation of the hardness across the joint. 16MnCr5 is characterised by a hardness value that is slightly below the value measured for the bainite-like structure in [14], while the microhardness values characterising AISI 316L stainless steel are higher than those reported in the literature [17]. These differences can be easily understood because the SLM process parameters affect not only the alloy porosity, but also the cooling rates that changes the alloy microstructure and mechanical properties.

4. Conclusions

To understand the feasibility of Functionally Graded Materials with SLM technology, a simple joint between AISI 316L stainless steel and 16MnCr5 case hardening steel has been produced by carefully tuning the process parameters. The microstructural investigation was performed with optical and Scanning Electron Microscope, together with an EDS system. Also, the mechanical properties have been evaluated with a Vickers microhardness test. The results show how it possible obtain continuous multi-material joint free of defects with a good interdiffusion of the different elements and mechanical properties equal to or higher than those reported in the literature. The factors that influence the properties of the materials and the joint are the high cooling rate of SLM technology ($10^6 – 10^8$ K/s) and the convective flow in the melting pool (i.e., Marangoni effects). These preliminary results make it possible to further evaluate other types of multi-material junctions realized with SLM and their different physical properties (e.g., mechanical, thermal, etc.).

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