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Feasibility Study on Deposition of Tribaloy T800 on Cobalt-Based L605 Using Micro-Laser-Aided Additive Manufacturing

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Abstract: In this study, deposition of Tribaloy T800 on cobalt-based L605 substrate using micro-laser-aided additive manufacturing (micro-LAAM) was explored. The micro-LAAM process was studied to achieve sound integrity of the deposited layer. The microhardness and microstructure of the deposited Tribaloy T800 layer were investigated. The results showed that the developed micro-LAAM process can achieve single-layer crack-free deposition of Tribaloy T800 onto cobalt-based L605 without pre-heating of the substrate. Surface roughness of Ra 8 μm was obtained, indicating that micro-LAAM can significantly improve the surface quality. Very high microhardness in the range of 818 to 1000 Hv was achieved. Cellular grains with very fine dendritic microstructure and Laves phase were observed in the deposited Tribaloy T800, which contributed to the high hardness. With all the results obtained, it can be concluded that it is feasible to deposit Tribaloy T800 on L605 substrate with micro-LAAM to achieve sound integrity and high hardness.

Keywords: cobalt-based L605 alloy; Tribaloy T800; deposition; micro-laser-aided additive manufacturing

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1. Introduction

Cobalt-based L605 is a nonmagnetic, chromium-nickel-tungsten-cobalt alloy possessing good oxidation and corrosion resistance as well as high strength properties at elevated temperatures [1–3]. This alloy has displayed excellent resistance to the hot corrosive atmospheres encountered in certain jet engine operations. Resistance to oxidation is good for intermittent service up to 1600 °F (871 °C) and continuous service up to 2000 °F (1093 °C). It is highly resistant to scaling and oxidation at elevated temperatures, with particularly good qualities under extreme oxidizing conditions [4,5]. Cobalt-based L605 is an important material for the modern aeroengines [6–10] where it is used for swirlers, combustion chambers and ball bearings, etc., because of its inherent corrosion resistance, high mechanical strength and excellent fatigue. The aeroengine parts made of cobalt-based L605 are subjected to corrosion and abrasion during the operation. As a result, these parts need routine repair.

Currently some aeroengine parts are repaired by thermal spraying [11–13]. Cobalt-based superalloy Tribaloy T800 powders can be utilized as an additive material [13]. This material has very high microhardness (up to 700 HV) and inhibited galling between sliding surfaces where lubrication is difficult. This provides the material with exceptional metal-to-metal wear bearing properties. However, due to the nature of process, this method cannot provide good adherence of the deposited Tribaloy T800 layer via metallurgical bonding with the cobalt-based L605 substrate, and only mechanical bonding is formed between the base material and the sprayed material. The bonding strength is limited compared to other fusion repair processes.

In order to better deposit the Tribaloy T800 powders, researchers from various countries tried other new methods to achieve the metallurgical bonding between the deposited layer and the substrate. C. Navas et al. [14] obtained Tribaloy T-800 coatings via laser cladding on flat 18/8 stainless-steel specimens (AISI 304). It was observed that high hardness (close to 850 HV0.3) can be achieved for the Tribaloy T800 laser clad coatings, which presented a wear coefficient (k) between one and two orders of magnitude lower than the substrate. T. Durejko et al. [15] deposited the T-800 alloy using a laser engineered net shaping (LENS) technique. However, lengthy pre-heating of the substrate was adopted to minimize the cracking. Hence, due to the high hardness induced sensitive cracking, it is difficult to deposit the Tribaloy T800 alloy using the fusion cladding process.

Laser aided additive manufacturing (LAAM) as a directed energy deposition (DED) technology utilizes a laser as an energy source to deposit materials for surface modification, repair and 3D printing, such as enhancing wear or corrosion resistance on the surface of a substrate with the minimum dilution from the substrate into the deposited layer [16,17]. This process can be achieved by blowing metallic powders into a laser generated melt pool on the substrate surface to melt and deposit the powders.

In this paper, deposition of cobalt-based Tribaloy T800 on cobalt-based L605 plate using micro-LAAM was studied. Cobalt-based Tribaloy T800 powders were utilized as an additive material. The micro-LAAM process was investigated to achieve sound integrity and high hardness of the deposited layer.

2. Materials and Methods

Figure 1 shows the experimental setup used in this study. The laser system utilized for the experiments was a 500 W fiber laser integrated to an industry robot. The additive materials were delivered using a coaxial powder feeding nozzle. Argon carrier gas at a flow rate of 4 L/min and a pressure of 0.2 MPa was used for the coaxial powder delivery. In addition, argon shielding gas at flow rate of 20 L/min and pressure of 0.1 MPa was used to protect the laser optics and to minimize melt-pool oxidation. The stand-off distance of the powder focus to the outlet of the powder feeding nozzle is 10 mm. The laser beam size used was 200 µm in diameter.

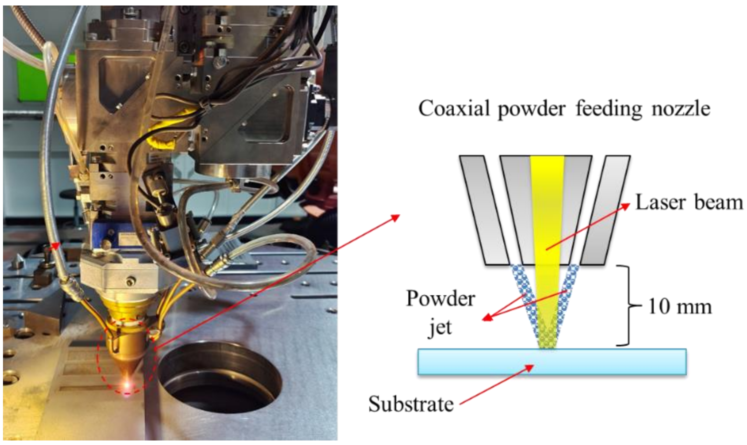

Figure 1. Experimental setup for the deposition of Tribaloy T800 using micro-LAAM.

Tables 1 and 2 show the chemical composition in weight percentage of the cobalt-based L605 and the Tribaloy T-800 alloys, respectively, provided by the material suppliers. The main elements include chromium, nickel, tungsten and cobalt. Compared to the base material, the additive material has much higher content of molybdenum. It is widely used for hard facing applications, such as jet engine components.

Table 1. Chemical composition of the cobalt-based L605 (wt%).

	Cr	Ni	Co	W	C	Fe	Mn	Si	P	S
MIN	19.0	9.0	-	14.0	0.05	-	1.0	-	-	-
MAX	21.0	11.0	Balance	16.0	0.15	3.0	2.0	0.4	0.04	0.03

Table 2. Chemical composition of the additive material Tribaloy T800 (wt%).

	Cr	Ni + Fe	Mo	Co	C	N	O	Si	P	S
MIN	16.50	-	27.00	-	-	-	-	3.00	-	-
MAX	18.50	3.00	30.00	Balance	0.08	0.07	0.05	3.80	0.03	0.03

Before laser aided additive manufacturing, the cobalt-based L605 plate was cleaned with isopropyl alcohol (IPA) to remove any grease remaining on the surface. Due to the high content of Cr, W and Mo elements and the formation of the inter-metallics during the fusion welding process, it is difficult to form the cracks in the base material as well as in the deposited layer. The main process parameters including laser power, powder feed rate and laser scanning speed were studied to investigate the voids and cracks in the deposited Tribaloy T800 layer.

After the deposition process, the specimens were cross-sectioned and ground sequentially using 600#, 1200# and 2400# silicon carbide paper. Then, the specimens were polished using 3 μm diamond suspension and rinsed using pure alcohol. After these treatments, appearance, macrostructure and microstructure of samples were observed by a MX51 optical microscope (OM, Olympus, Tokyo, Japan) and a scanning electron microscope (SEM, Carl Zeiss, Oberkochen, Germany). For the OM imaging, chemical etching was conducted using an etchant with 25 mL water, 25 mL acetic acid and 50 mL HNO_3. Furthermore, electrolytic etching was also conducted using a 1.5 V direct current power supply and stainless-steel electrodes in a solution of 10 mL nitric acid, 10 mL hydrogen peroxide and 100 mL oxalic acid. An MMT-X3 digital micro-Vickers hardness tester (MATSUZAWA, Akita-ken, Japan) was used to measure the microhardness with a load of 100 g and dwelling time of 15 s along and across the deposited layer.

3. Results and Discussion

3.1. Process Development

The process parameters were studied with the deposition of Tribaloy T800 onto flat cobalt-based L605 substrate. Figure 2 shows one example of the defects formed in the deposited layer if the process parameters were not carefully adjusted. It was found that the main issues in depositing Tribaloy T800 were the cracking and voids due to the formation of hard inter-metallics and high hardness.

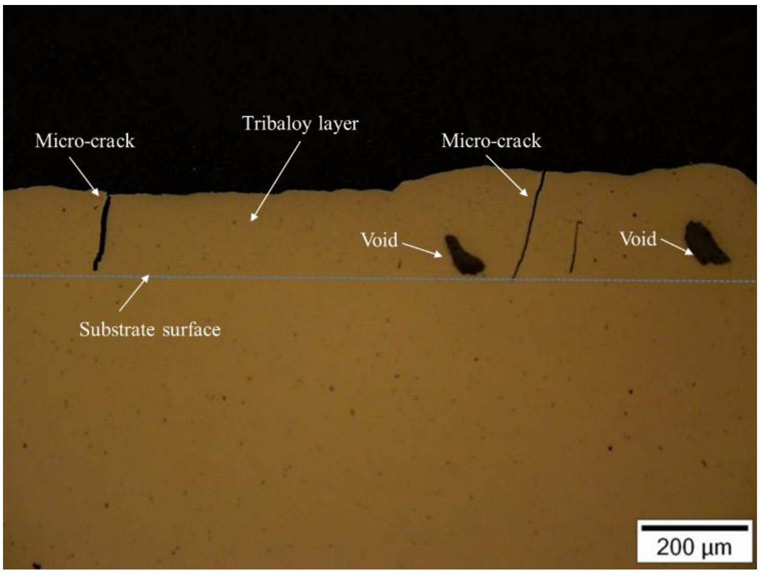

Figure 2. Defects observed in the deposited Tribaloy T800.

Table 3. The optimized process parameters.

Laser Power	Powder Feed Rate	Laser Scanning Speed	Overlapping
300 W	2 g/min	2 m/min	100 µm

3.2. Macrostructure

Figure 3 shows the surface of the deposited Tribaloy T800 using micro-LAAM. There were no obvious defects on the surface of the deposited material. The surface roughness of the sample after multi-track deposition was measured using a Stylus Profiler. Three measurements were conducted across the laser scanning direction of the last layer, as shown in Figure 3. Figure 4 shows the roughness profile of one measurement. The average surface roughness (Ra) from the three measurements of the deposited sample was only 8 µm. This also confirmed that micro-LAAM can achieve a very smooth surface.

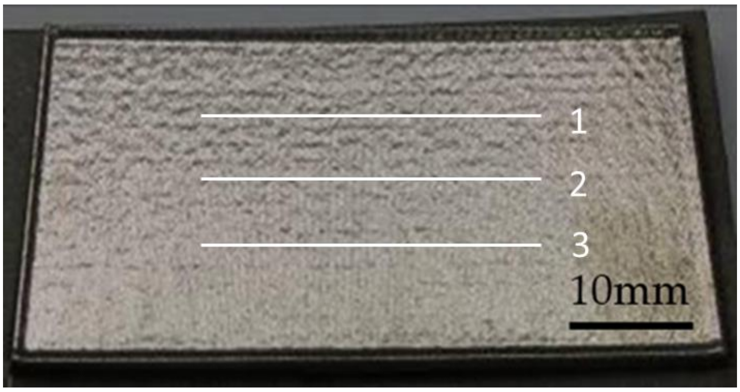

Figure 3. Top view of the deposited Tribaloy T800 surface.

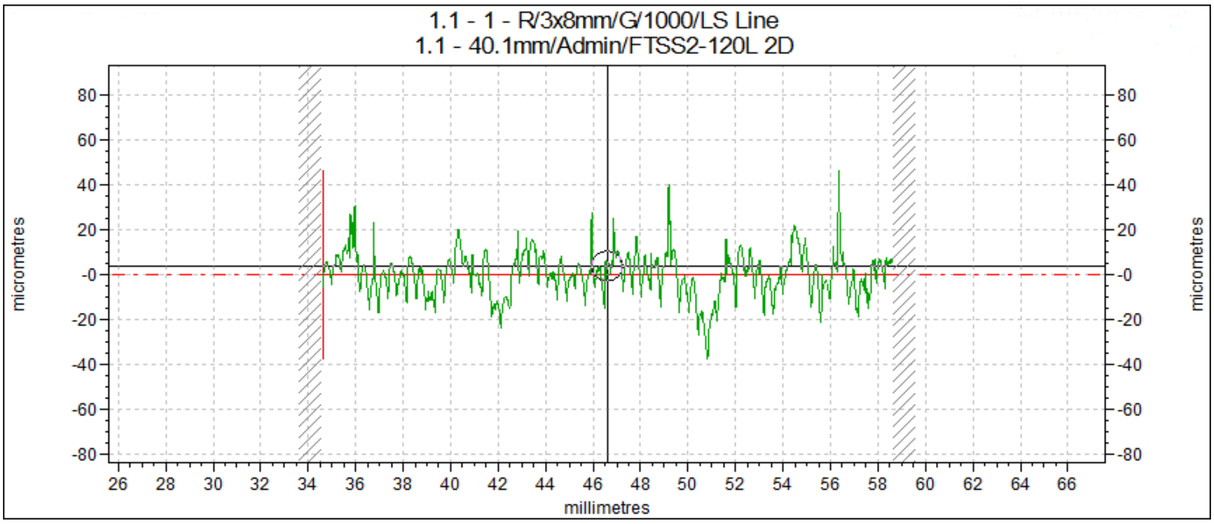

Figure 4. Measured surface roughness.

Figure 5 shows the detailed cross-section view with higher magnification of a portion of the sample to investigate the integrity of the deposited Tribaloy T800. From Figure 5 it can be observed that there are no obvious defects in the deposited layer. Very low porosity can be seen in the deposited layer, whereas large voids can be seen in the cast cobalt-based L605. The substrate surface is highlighted using the dotted line in Figure 5. Thickness of the deposited layer was measured under the microscope and was about 158 µm.

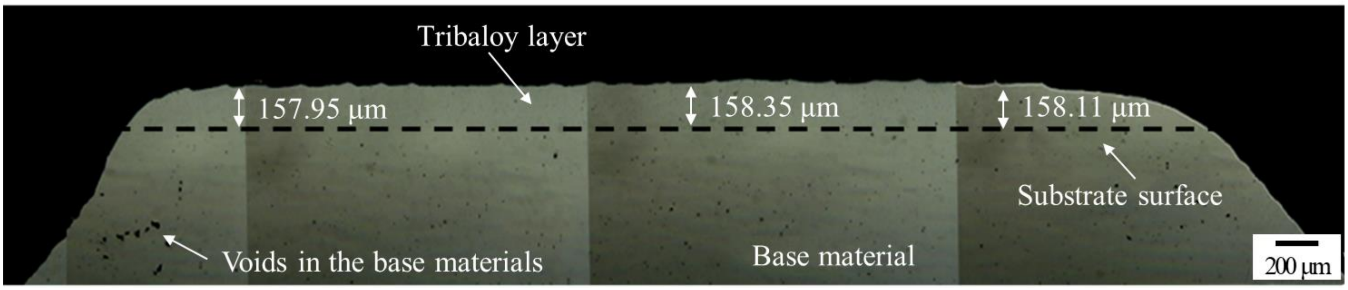

Figure 5. Cross-section view of the deposited Tribaloy T800 on L605 substrate.

3.3. Microstructure

Chemical etching was used to reveal the grain structure. Figure 6a shows the locations for observation of the microstructure of the deposited single-track Tribaloy T800, namely across the fusion line, in the deposited material near the fusion line and purely in the deposited material. It can be seen that the Tribaloy T-800 consists of very fine microstructure, regardless of the position of the deposited layer. The average grain size is smaller than 20 µm. Figure 6c shows that across the fusion line, directional solidification can be observed. This is due to the effective heat conduction and cooling during the solidification stage. In the deposited material in Figure 6b, very fine cellular microstructure with clear grain boundaries can be observed. This also verified that the micro-LAAM process applied could achieve very good controllability of heat input and formation of fine grain structure.

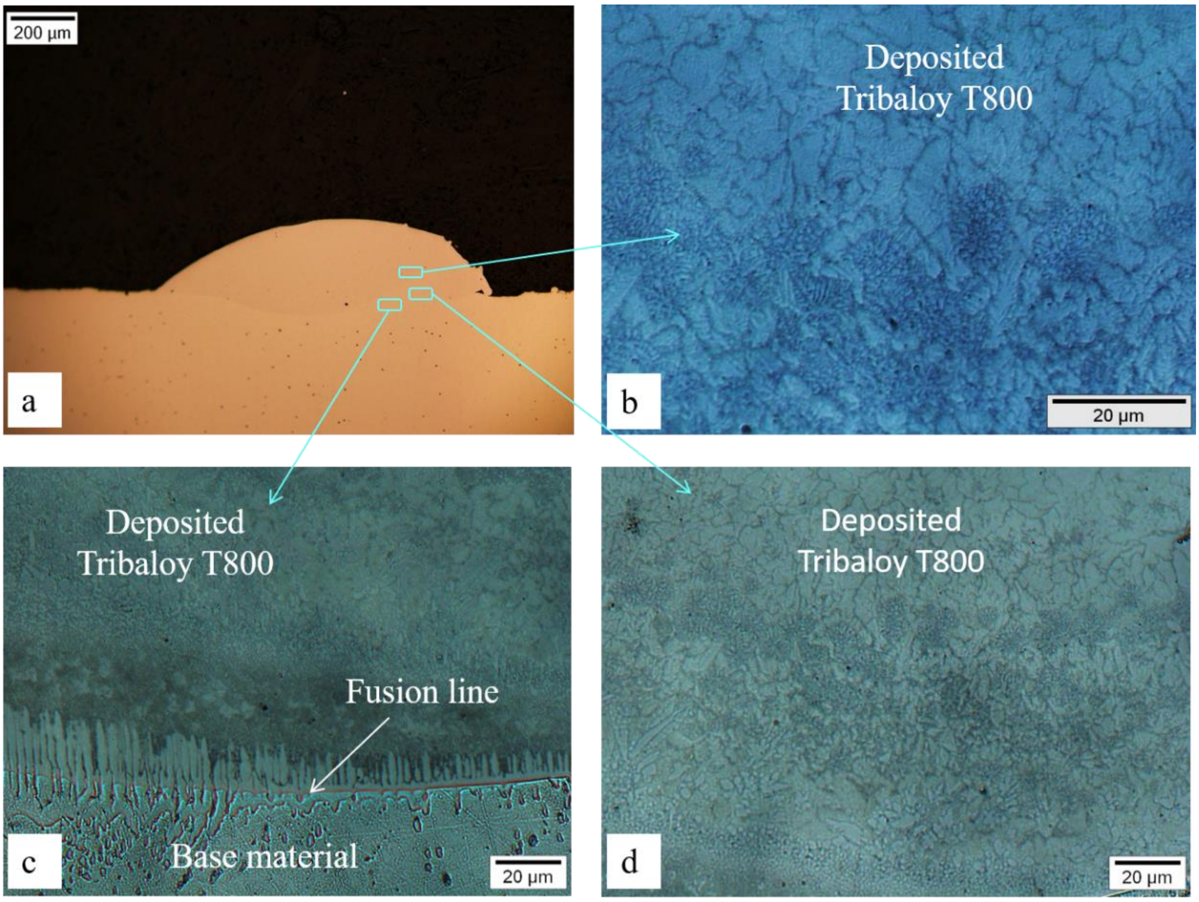

Figure 6. Microstructure of the Tribaloy T800 deposited onto L605 substrate: (**a**) the cross-section; (**b**) purely in the deposited material; (**c**) across the fusion line; (**d**) in the deposited material near the fusion line.

Electrolytic etching was applied to reveal the detailed microstructure. Figure 7a shows the general view of deposited material Tribaloy T800 and L605 substrate. As the cobalt-based Tribaloy T800 was deposited with multiple tracks, the overlap between two tracks can be clearly observed. It also clearly shows that the microstructure of the original cobalt-base cast L605 plate is very coarse. Figure 7b shows the detailed microstructure of the deposited Tribaloy T800 under higher magnification. As the cellular grain boundaries were removed by the electro-chemical etching, dendritic crystallization structure is observed, the growth direction of which is perpendicular to the interface. The dendrites grew in the direction of the heat flow and were more or less homogenous from the interface to the top surface which contributed to the high hardness of the deposited Tribaloy T800.

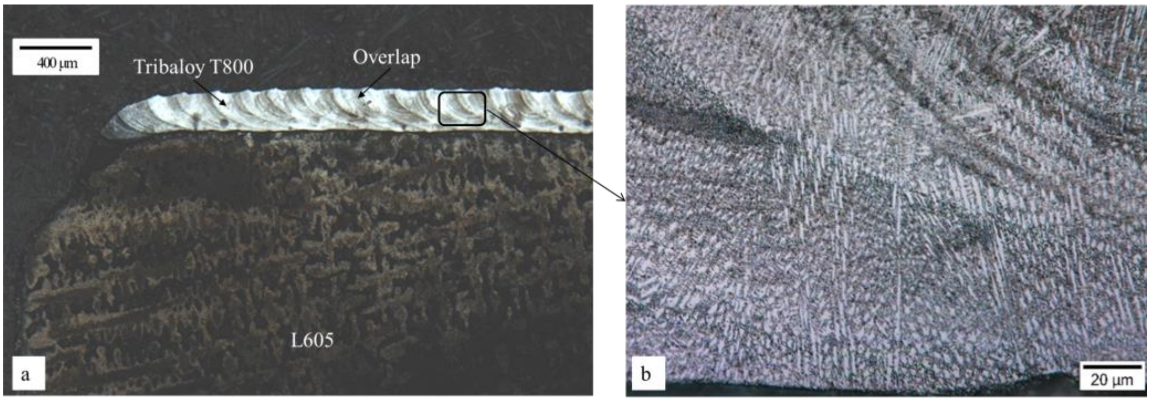

Figure 7. Microstructure of the Tribaloy T800 deposited onto the cobalt-based L605: (**a**) general view of the deposited material and substrate; (**b**) detailed view of the deposited material.

Figure 8 below shows the microstructure observed under the SEM of the deposited material Tribaloy T800. The matrix of Tribaloy T-800 was a solid solution of cobalt (Co), and the dendritic phase was a hard and wear-resistant intermetallic compound known as the Laves phase. The microstructure of Tribaloy T-800 consisted of intermetallic (Laves) phase dispersed in a softer matrix of eutectic or solid solution. These abundant Laves phases could significantly improve the wear resistance and hardness of the material. Similar results were reported by other study [15].

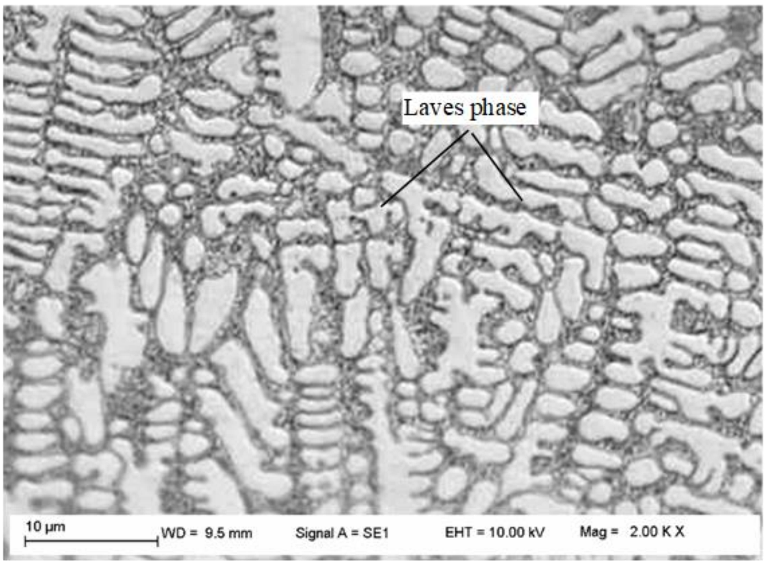

Figure 8. SEM image of the deposited Tribaloy T800.

3.4. Microhardness

The microhardness measurements were conducted in the cross-section of the deposited Tribaloy T800, same sample as shown in Figure 5. Figure 9 shows schematically the microhardness measurement along horizontal and vertical directions covering the base and the deposited materials. The measurements were conducted with 0.5 mm spacing. Table 4 summarizes the measured microhardness in Hv at different locations in the cross-section of the sample. The microhardness of the deposited Tribaloy T800 is in the range of 818 to 1000 Hv. In comparison, the measured microhardness of the substrate is around 350 Hv. The high hardness of the deposited Tribaloy T800 originated from the formation of Laves phase and the fine grain structure.

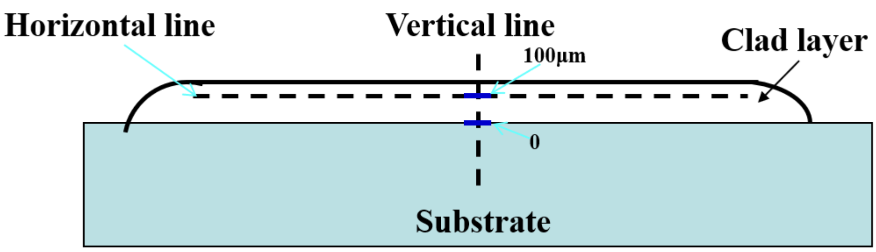

Figure 9. Schematic drawing showing the locations of the microhardness tests performed.

Table 4. Measured microhardness in Hv.

		Horizontal (mm)								
		Left				**Middle Line**	**Right**			
		−2.0	**−1.5**	**−1.0**	**−0.5**	**0**	**0.5**	**1.0**	**1.5**	**2.0**
Vertical (mm)	0.1	842.6	878.6	873.9	1011.3	856	989.5	1017.1	817.8	898.2
	0					720				
	−0.5					346.7				
	−1.0					357.2				
	−1.5					351.2				
	−2.0					331.2				

3.5. Thickness of the Deposited Tribaloy T800

Furthermore, deposition of multi-layer Tribaloy T800 was studied to verify the achievable thickness. The experiments were firstly conducted by deposition of one layer, then two layers and three layers onto flat substrates using the same process parameters. Omnidirectional deposition was performed. Figure 10 shows the cross-section view of the deposited samples. The thickness of one layer was about 160 μm. For two and three layers, the thickness that could be achieved was around 310 and 570 μm, respectively. The deposited samples of one layer and two layers did not show obvious defects in the cross-sections. However, cracks could be observed in the cross-section of the sample deposited with three layers.

For Tribaloy T800, the presence of Laves phases in a large quantity guarantees high hardness and wear resistance, but a high content of this brittle phase is simultaneously a drawback, since it favors the brittle crack formation and propagation [15]. Additionally, when multi-layer deposition was performed by micro-laser-aided additive manufacturing, the tendency for thermal cracking significantly increased due to the increased internal residual stress. Therefore, when the number of deposited layers reached three, under the simultaneous action of brittle phase and high residual stress, obvious cracks were formed in the deposition layer. For multiple-layer deposition with increased thickness, the process needs to be carefully developed to eliminate the cracks. Furthermore, Tribaloy T800 coating is mainly applied to aeroengine swirlers, combustion chambers, etc., which directly contact with high temperature gas. Although no heavy mechanical load is applied, the high hardness of the deposited coating may cause the degradation of the fatigue property during the high temperature operation of the parts. Hence, fatigue behavior of the deposited Tribaloy T800 coating needs to be investigated in future work.

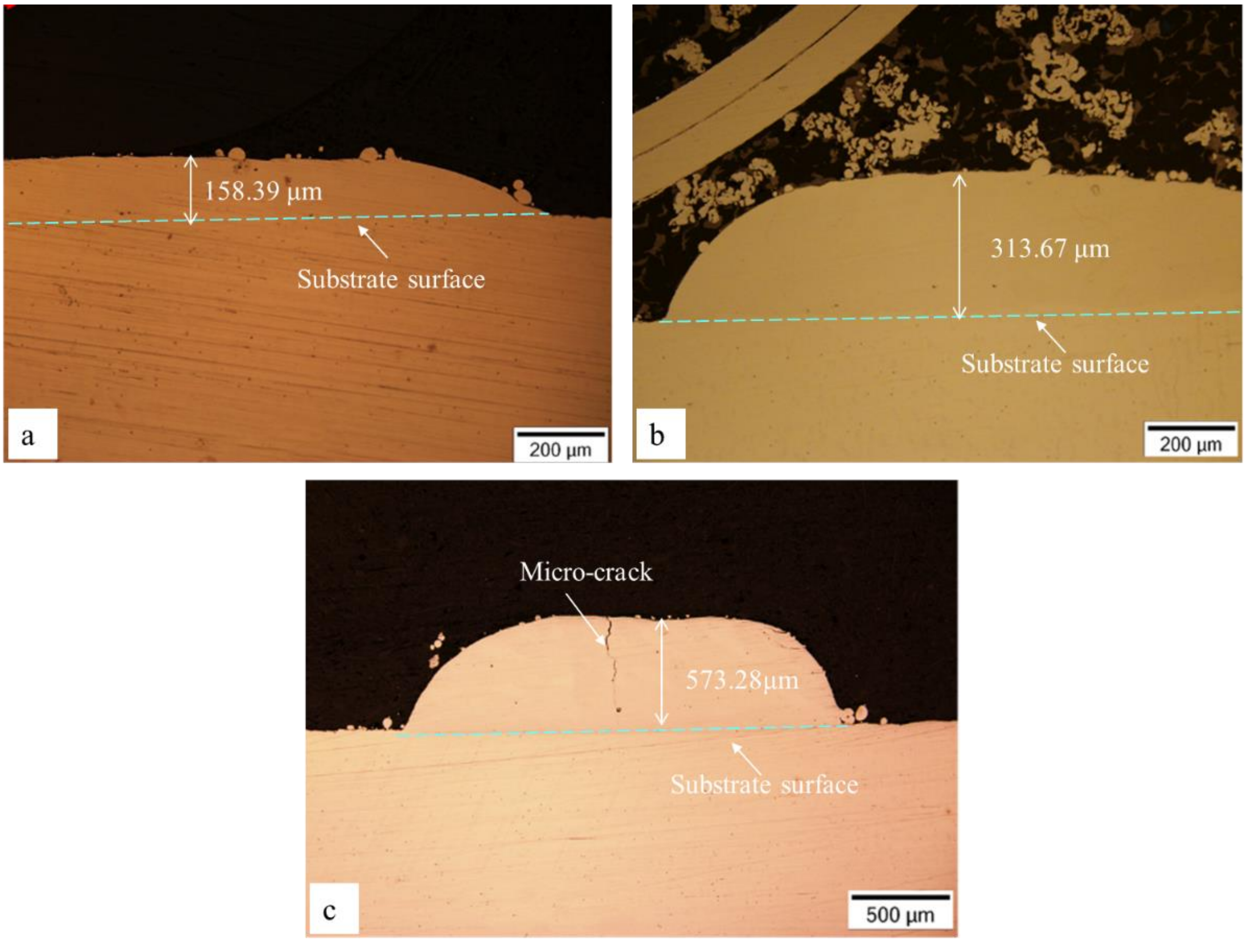

Figure 10. Cross-section view of the deposited Tribaloy T800 sample: (**a**) 1 layer; (**b**) 2 layers; (**c**) 3 layers.

4. Conclusions

In summary, the micro-LAAM process was successfully developed to deposit Tribaloy T800 powders on cobalt-based L605 substrate without pre-heating. The developed micro-LAAM process can achieve single-layer crack-free deposition. A smooth surface of Ra 8 µm was obtained, showing that micro-LAAM can significantly improve the surface quality. Cellular grains with very fine dendritic microstructure were observed in the deposited material, which were resulted from the low heat input form the micro-LAAM process. The results showed that the micro-LAAM can significantly lower the heat input, reduce the residual stress and eliminate the cracking of the deposited Tribaloy T800. Furthermore, the fine grains and Laves phase formed resulted in high microhardness in the range of 818 to 1000 Hv. With all the results obtained, it could be concluded that it is feasible to deposit Tribaloy T800 powders on cobalt-based L605 using micro-LAAM without pre-heating of the substrate.

As discussed previously, cracking is the major issue for deposition of multiple-layer Tribaloy T800. Hence, further study is necessary to develop the micro-LAAM process, with the aim of minimizing internal residual stress and the resultant tendency for thermal cracking. It is also necessary to investigate high temperature fatigue behavior.

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Data Availability Statement: The data presented in this study are available on request.

Conflicts of Interest: The authors declare no conflict of interest.

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