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Additive Manufacturing of H11 with Wire-Based Laser Metal Deposition

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Abstract: Laser additive manufacturing (LAM) is a near-net-shape production technique by which a part can be built up from 3D CAD model data, without material removal. Recently, these production processes gained attention due to the spreading of polymer-based processes in private and commercial applications. However, due to the insufficient development of metal producing processes regarding design, process information and qualification, resistance on producing functional components with this technology is still present. To overcome this restriction further studies have to be undertaken. The present research proposes a parametric study of additive manufacturing of hot work tool steel, H11. The selected LAM process is wire-based laser metal deposition (LMD-W). The study consists of parameters optimization for single beads (laser power, travel speed and wire feed rate) as well as lateral and vertical overlap for layer-by-layer technique involved in LMD process. Results show that selection of an ideal set of parameters affects substantially the surface quality, bead uniformity and bond between substrate and clad. Discussion includes the role of overlapping on the soundness of parts based on the height homogeneity of each layer, porosity and the presence of gaps. For the conditions tested it was shown that once the deposition parameters are selected, lateral and vertical overlapping determines the integrity and quality of parts processed by LAM.

Key-words: Laser additive manufacturing; Hot work tool steel; Parametric study; LMD-W.

Manufatura Aditiva do Aço Ferramenta H11 por Deposição Metálica de Arame a Laser

Resumo: Manufatura aditiva a laser é uma técnica de produção por camadas na qual uma peça pode ser produzida a partir de um modelo 3D sem remoção de material. Recentemente, esses processos ganharam atenção devido à disseminação de processos com polímeros em aplicações privadas e comerciais. Entretanto, devido ao desenvolvimento insuficiente da manufatura aditiva com metais há uma resistência na produção de componentes funcionais com esta tecnologia. Portanto, para superar essa limitação, o presente artigo propõe um estudo nos parâmetros de processo de deposição metálica de arame a laser (LMD-W) do aço ferramenta para trabalho a quente, H11. O estudo consiste na otimização de parâmetros para cordões individuais (potência do laser, velocidade de deslocamento e de alimentação do arame), bem como sobreposição lateral e vertical para a técnica de camada por camada envolvida no processo. Os resultados mostram que a seleção de um conjunto ideal de parâmetros afeta substancialmente a qualidade superficial, a uniformidade dos cordões e a aderência entre o substrato e o cordão. A discussão ainda inclui a função da sobreposição na estabilidade do processo em relação à homogeneidade da altura de cada camada, porosidade e presença de falhas. Foi comprovado que após a seleção dos parâmetros de deposição, a sobreposição lateral e vertical determina a integridade e qualidade das peças manufaturadas aditivamente.

Palavras-chave: Manufatura aditiva a laser; Aço ferramenta para trabalho a quente; Parâmetros de processo; LMD-W.

1. Introduction

Additive manufacturing (AM) is a near-net-shape production process that involves material joining with layer-by-layer technique to produce complex parts [1]. Popularly known as 3D Printing, AM is currently achieving a great progress in producing parts made of polymers/plastics. A variety of AM technologies is adopted in order to manufacture visual aids, presentation models, patterns for prototyping tooling and patterns for metal casting. The most common non-metallic materials used in these processes are epoxy resin, acrylate (polyjet), paper, rubber and polyester [2]. The favorable use of polymers is related to their low melting point and high viscosity which do not require complex heat input mechanisms and nozzle designs to produce parts [3].

Several industries started by adopting AM for prototyping, using metallic alloys, as it is a fast and economic route to verify the conditions of a part in real size prior to its industrial production. As an alternative to traditional manufacturing processes, such as machining, in which material is subtracted from a block, AM offers production with minimal scrap, offering a more efficient material usage [4]. Another advantage over processes like foundry is that a mold is not necessary. Furthermore, this manufacturing process can build-up a part using three dimension models under computer control. It is a technology in progress which is able to offer reduction on production costs and time. AM is becoming popular in various industries, ranging from aerospace to die & mold manufacturing. This is essentially because of the benefits presented in the process: 3D modelling, flexible microstructure architecture, geometry and temperature control [5].

A variety of metals and metal alloys, such as Stellite, Inconel alloys, H13 and WC-Co, have been studied in order to fabricate additive manufacturing components [1]. The aim of additive manufacturing is to reduce material wastage, production time and manufacturing cost while maintaining the quality of the finished product [3]. In this regard, AM for metallic materials have a great potential when dealing with high-cost and hard-to-cut materials. For instance, titanium alloys are attractive materials for many components in aerospace industry and more recently, in biomedical applications, such as prostheses and implants [6].

Some processes have already been developed to additive manufacture metallic components, namely, direct metal deposition (DMD), laser engineered net shaping (LENS), selective laser melting (SLM), laser metal deposition (LMD), direct light fabrication (DLF), electron beam melting (EBM), among others [2]. Laser beam is especially used as an energy source in AM process for metals due to controllable heat input mechanisms [3]. Despite the potential advantages and the technologies developed, there are significant challenges when a metallic part is additive manufactured due to the lack of processes characterization and knowledge. AM can be accomplished by powder-based spray or sintering, such as thermal spray and selective laser sintering, respectively. Furthermore, both metallic wire and/or powder can be selected as the feedstock material for fusion-based processes which can use laser beam, electron beam, plasma and electric arc as the energy source [3].

The present research presents a parametric-study to evaluate the feasibility of producing functional components especially for automotive industry. The selected AM process is wire-based laser metal deposition (LMD-W) in which laser beam is the energy source and the feedstock material is in the form of wire. AM processes in automotive industry are already included in the production of many parts, such as tooling and on repair of parts [7]. However, further developments are required to manufacture functional parts, for example powertrain components. Therefore, a study is conducted to evaluate laser additive manufacturing of hot work tool steel H11 on 42CrMo4 alloy steel as the substrate material. The substrate material was chosen since it is commonly used in functional automotive components, like shafts and gears. Additionally, a wire form of H11 was used due to its good weldability, high hot strength and temper resistance.

2. Laser Metal Deposition

Laser metal deposition (LMD) is a fusion-based process based on laser cladding technology. In this process, parts are manufactured by melting wire or powdered material that subsequently solidifies as the laser beam moves along a predesigned path [8]. The building principle behind this process is to deposit the feedstock material tracks side-by-side and layer-upon-layer [9]. In LDM process, wire is fed into the melt-pool via lateral nozzle, while lateral or coaxial powder nozzle can be used in powder depositions [10]. The working principle of LMD is schematically shown in Figure 1.

Powder-based LDM process is suitable to create functionally graded materials with complex geometries; however, powder toxicity which can lead to health issues and high material cost are some disadvantages of the process [11]. On the other hand, the system that supplies the feedstock material in wire form offers higher deposition efficiency, less expensive feedstock material and lower material wastage when comparing with powder. Nevertheless, unstable material feed rate control, reduced variety of materials, radiation absorption dependence on surface finish of wire and higher dilution of the deposited material with the substrate are some shortcomings of wire-based processes [12].

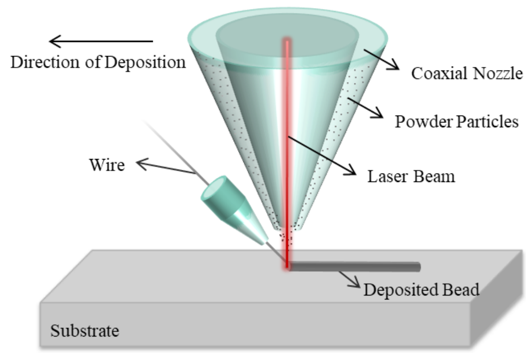

Figure 1. Schematic representation of laser metal deposition (LMD).

Laser processes like laser alloying, laser sintering and laser cladding have already been used to enhance the surface integrity of metallic parts. These processes are able to improve wear, corrosion and oxidation resistance, and to some extent fatigue resistance [13]. For laser surface treatment applications, the substrate can be a wrought product, a forge, cast or a worn part. For the applications where a complete part is fabricated, the substrate is a plate which supports the first deposited layer. Resource and energy considerations together with industry demands are stimulating the progress of Laser Additive Manufacturing (LAM). Essential production components, such as forging tools, dies and molds and extrusion tools, have already been benefited from LAM of advanced materials to achieve required properties [10].

The critical requirements to a successful laser metal deposition are solid bond between the deposited material and the substrate or between layers, low porosity and crack-free deposition. A thin layer of the substrate will be simultaneously melted to obtain a metallurgical bond. However, excessive dilution is not desirable in the majority of applications. When compared to welding and thermal spraying, laser cladding technology presents an advantageous feature regarding the accurate control of energy and material delivery [14].

3. Materials and Methods

3.1. Equipment description

The LDM experiments were performed in a 5-axis CNC machine (Alzmetall GX1000/5-T-LOB). This machine was fully adapted by Fraunhofer IPT from its original milling function to conduct laser processes. After connecting feedstock material feeding systems, gas supply systems and laser source, integrating laser optics and removing the milling spindle, Alzmetall-LOB was ready to perform LAM processes.

A Laserline LDF 4500-30 VGP Diode laser system was coupled to Alzmetall-LOB in order to provide the laser source. The laser beam is guided through a glass fiber and the laser optics inside the machine allows the variation of the focal point. With 21 mm distance from the bottom of the laser nozzle to the zero position on the work piece, the focused diameter was set to be approximate 1.1 mm.

The wire feeding system developed by Dinse, provides adjustable torque to uncoil the wire and move it from the reel holder to the wire arm. The wire feeder was adapted with a wire straightener by Fraunhofer IPT. The feedstock material in wire form is laterally fed by a wire feeding arm relating to the laser beam.

3.2. Substrate and feedstock materials

The 42CrMo4 alloy steel was chosen as the substrate material because it is commonly used in automotive components, such as shafts, gears, connecting rod and engine cylinder. The substrate plate was 10 mm thickness, 100 mm width and 100 mm length. Since 42CrMo4 steel has a limited weldability, H11 tool steel was chosen to be the welding material. It shows good toughness and appropriate hardness after being welded due to its hot working usage. The H11 wire was a solid wire with 1.2 mm of diameter and a very thin copper coating which minimizes corrosion, ensures good electrical conductivity and reduces friction during welding. Chemical composition of both substrate and welding wire are shown in Table 1.

Table 1. Chemical composition of substrate (42CrMo4) and wire (H11) material.

Grade	C%	Si%	Mn%	Cr%	Mo%	V%	P%	S%
H11	0.33-0.41	0.80-1.20	0.25-0.50	4.80-5.50	1.10-1.50	0.30-0.50	max 0.03	max 0.02
42CrMo4	0.38-0.45	max 0.40	0.60-0.90	0.90-1.20	0.15-0.30			

3.3. Wire-based LMD parameters

Wire deposition processes have shown to be particularly sensitive these process parameters: laser power, laser scanning speed, wire feed rate, wire deposition direction, wire incidence angle, wire position and inert gas flow [15]. Laser power, laser scanning speed and wire feed rate are the focus of this study, all the other parameters being kept constant. The wire deposition direction was selected as towards x-direction and remained the same during the entire study. In Figure 2, pictures during the process show the deposition direction towards x-axis.

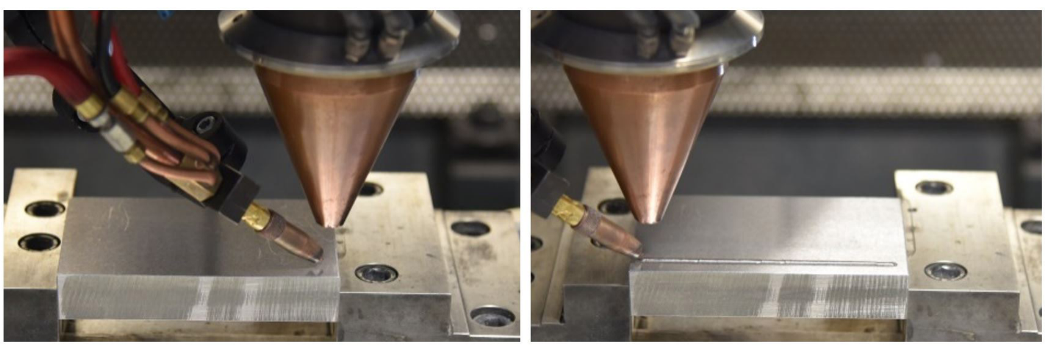

Figure 2. Pictures of a process on its start and end, showing the deposition direction.

The wire incidence angle was measured preceding any experiment to confirm that it was within the limits of previous researches (46.5°) [16]. Also, argon gas was used to protect molten material during the entire process. Before each deposition, the substrate was cleaned with acetone to avoid any oxide layers and contamination on the surface of the base material.

As mentioned before, an issue that can have the greatest influence on the stability of wire-based LMD is the wire position according to the melt pool. This set-up can vary with the chemical composition of the wire or substrate. Therefore, the wire position was set for the current investigation previously to the parametric study and it was checked from time to time with a camera installed inside the Alzmetall-LOB machine and a program created to compare the actual to previous wire position.

3.4. Parametric-study

The study was carried out in three sequential stages to obtain parameters optimization for single beads, single layer and multiple layers. Laser power, travel speed and wire feeding rate were analyzed in the first stage. The single and multiple layer stages aimed at optimizing lateral and vertical overlap rates, respectively.

3.4.1. Single beads

Three variables were investigated: laser power, laser scanning speed and wire feed rate. All these parameters influence the quality of the deposition and the geometrical characteristics of the bead [17]. The selected range of parameters was based on previous researches with H11 wire [18]. The line mass is defined by the ratio between wire feed rate and travel speed. It gives the amount of deposited wire per bead [19] and was chosen to be a variable instead of the two parameters individually.

The DOE chosen consists in 3 factors with 3 variables, as shown in Table 2, totalizing 27 set of parameters. As each set of parameters was repeated three times in order to guarantee its reproducibility, a total of 81 experiments were carried out. For each set of parameters, a 45 mm length bead was deposited.

Characterization of each bead included surface quality, bond between bead and substrate and geometrical cross-section of beads. Analysis of polished cross-section of beads was carried out in an optical microscope for the presence of pores, cracks or undercuts, and to measure width and height of each bead, also to verify reproducibility of beads with the same set of parameters.

Table 2. Process parameters and values considered on the study.

Laser Power [W]	Travel Speed [mm/min]	Line Mass
945	600	1
900	500	1.1
845	400	1.2

3.4.2. Single layer

A single layer was processed depositing beads side-by-side and the amount of lateral overlap investigated, which is schematically shown in Figure 3. In additive manufacturing, the topography of the first layer has a determining role on the quality of subsequence deposited layers. The aim is to minimize surface roughness while maintaining material usage efficiency to avoid the formation of gaps during multilayer processing.

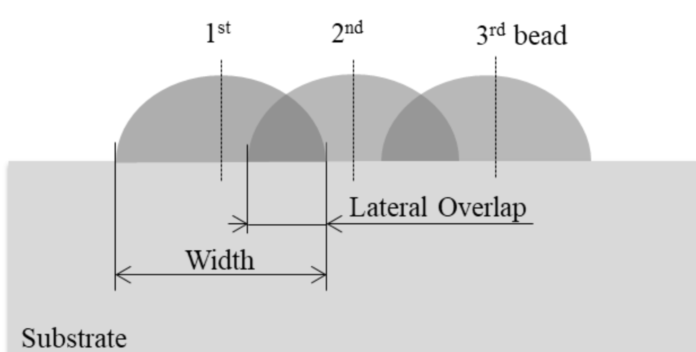

Figure 3. Schematic drawing of a layer with three tracks.

The lateral overlap percentage refers to the width of one bead that is overlapped during the deposition of the next bead. The lateral overlap percentage changes by lateral displacing the focal point for the deposition of the subsequent bead. Twelve different layers with tree tracks each with lateral overlap ranging from 36.1% to 5.6% were produced and characterized.

3.4.3. Multiple layers: additive manufacturing

Vertical overlap (distance in Z-direction between each layer) is a critical parameter in additive manufacturing processing and was assessed during the last stage of this investigation. Surface topography of each deposited layer is the roughness caused by changes in the height of each bead deposited in the previous layer. Vertical overlap was measured by the laser displacement sensor, in order to define what would the distance in Z-direction to add one layer on top of the previous. Since the focal point is set-up for each deposited layer, surface topography can affect the deposition sequence and compromise the process.

Three vertical overlaps were tested: 0% vertical overlap, laser focal point set considering the average height of the previous layer, 10% above the average height and 10% below the average height. Blocks were built up and the ideal distance was established by larger number of layers successfully deposited. Between each layer, a waiting time of 5 to 10 minutes was adopted to guarantee that the temperature of the block has no influence in the study.

Cross sections of samples were prepared by standard metallographic procedures for specimen preparation and etching. Analysis at the cross section was carried out in a Scanning Electron Microscope (SEM) for the presence of pores, cracks and to visualize the profile. Micro-hardness was measured with Vickers hardness test with a load of 0.2 kilopound.

4. Results and Discussion

In order to gain information required to additive manufacture a part, the experiments were divided in sequential steps. The parametric study results of single layer and multiple layers depend on its previous stages of the investigation. Therefore, the analysis sequence will remain the same as the experiments were conducted.

4.1. Parametric study for single tracks

There are critical characteristics which determine whether the track quality is acceptable or not. This qualitative analysis was based on the surface quality, bead uniformity, absence of visual cracks or pores and bond between substrate and clad material [20]. The Figure 4 shows one substrate plate with several deposited tracks, where it is possible to observe different physical characteristics between them, like surface quality and bead uniformity. Highlighted in the image are two regions, region A shows some examples of acceptable depositions and region B shows some unacceptable clads regarding surface quality and bead uniformity.

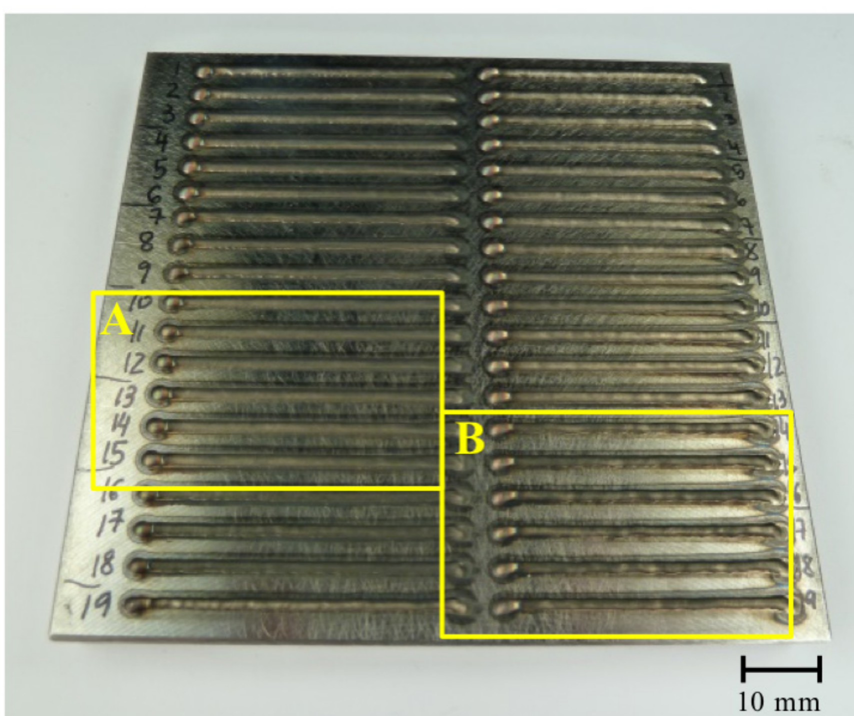

Figure 4. Set of single tracks deposited with increasing laser power and regions (A) and (B) indicates some acceptable and unacceptable clads, respectively.

The wettability of each track is a determining feature when processing layers with lateral deposition of tracks. Figure 5 shows the cross section of individual tracks with an acceptable wettability and an unacceptable wettability. The latter induces the formation of gaps during lateral deposition of multiple tracks to obtain a layer.

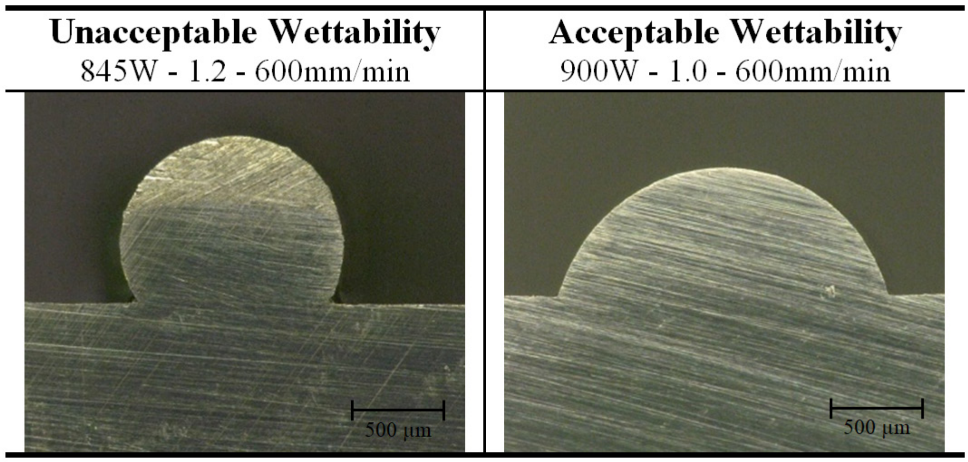

Figure 5. Cross section of single bead tracks showing a good wettability (right) and a non-acceptable wettability (left).

Figure 6 summarizes the results of this qualitative analysis showing for each laser power (945, 900 and 800 W) good, acceptable and unacceptable depositions considering the travel speed (400, 500 and 600 mm/min) and the line mass of 1.0, 1.1 and 1.2 (ratio between wire feed rate and travel speed). The results were grouped according to laser power because it is considered a key parameter on characterization of beads for laser cladding processes [21].

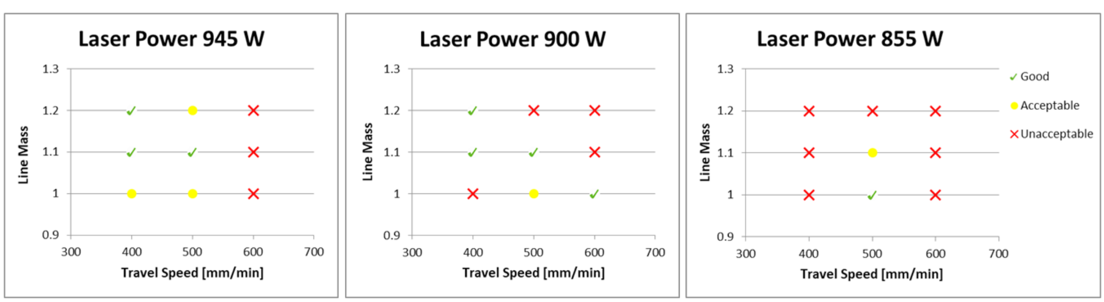

Figure 6. Results of the parametric study conducted for single tracks.

It is possible to associate an increasing number of unacceptable depositions with a decrease in laser power. Also, the largest amount of good and acceptable depositions is obtained for the higher laser power used, 945 W and 900 W. Furthermore, it is possible to observe some combinations of travel speed and line mass which do not offer acceptable depositions regardless of laser power, for instance, 1.2 and 600 mm/min. Results indicate that processing parameters should be selected within the range 945-900W of laser power, 400-500mm/min travel speed and 1-1.1 mass line.

Hardness profiles also contributed to the analysis of the processing parameters. Figure 7 shows the hardness profiles measured at the cross-section of tracks organized according with the laser power used. Also, each profile designates a set of travel speed and line mass, respectively. Red line profiles refer to depositions that were classified as unacceptable on the previous qualitative analysis and shades of blue represent good or acceptable deposits.

Hardness profile were mainly determined by the characteristics of the deposited material, regardless of previous classification. This result was somehow expected since the material is the same between the experiments and the energy input during processes have not changed drastically.

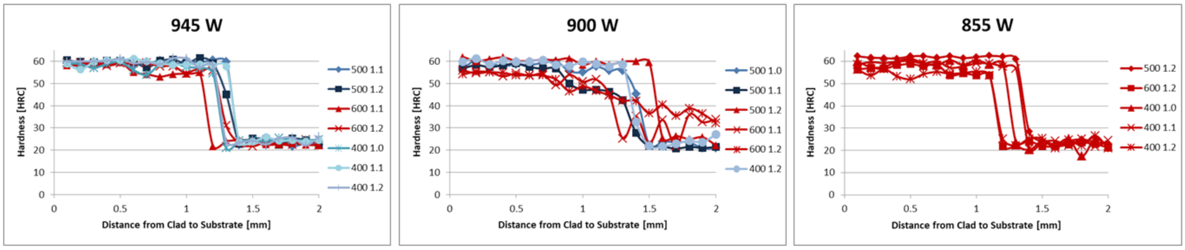

Figure 7. The effect of process parameters on hardness profiles.

In spite of the determining role of the chemical composition of the deposited material on hardness, detailed analysis near the fusion line, shown in Figure 8, revealed that dilution with the substrate exhibited fluctuations depending on the parameters used. Considering that a sharper slope refers to a lower dilution, it is possible to observe that processing with laser power of 945 W had a more consistent set of results exhibiting a lower dilution compared to 900 W deposits. Hardness profiles measured on deposits processed with a laser power of 845 W showed a larger dispersion of results in accordance with the discrepant geometrical characteristics of unacceptable depositions.

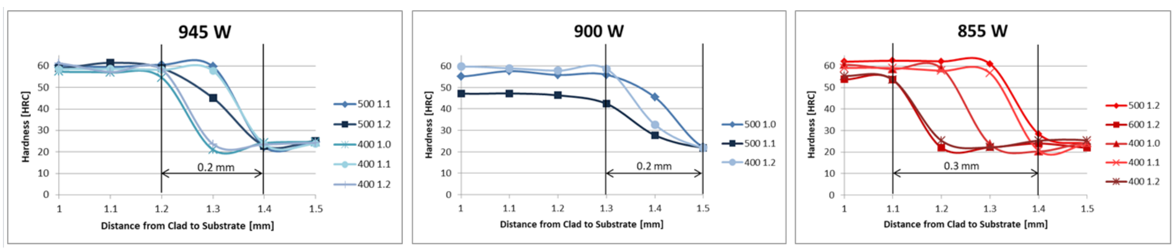

Figure 8. Detail of the hardness profiles across the fusion line.

Based on the discussed results, a set of parameters was selected for the subsequent experiments, Table 3. The selection took into consideration the quality of depositions energy consumption and productivity as well. Similar parameters were identified in the literature for laser metal deposition with H11 wire and Nb powder [18], authors used 900 W of laser power, 400 mm/min of travel speed and 500 mm/min of wire feed rate, giving a line mass of 1.25.

Table 3. Ideal set of parameters for H11 wire-based laser deposition.

Laser Power	Travel Speed	Wire Feed Rate	Line Mass
900 W	500 mm/min	550 mm/min	1.1

Cross section analysis of an acceptable elliptical-shaped track is shown in Figure 9. Detailed analysis of the fusion line, insert in Figure 9, revealed small solidification cracks. However, since this region will be remelted due to the lateral overlap of the next deposited track during a W-LMD process, these cracks were not an important defect.

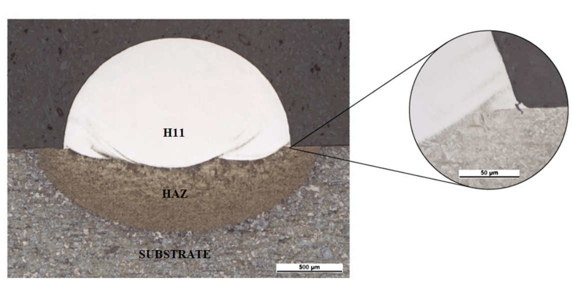

Figure 9. Transverse cross-section microstructure of a single bead.

4.2. Lateral overlap analysis

Lateral overlapping rate was the parameter analyzed on the investigation of a single layer. As mentioned before, the height homogeneity of the layer is critical for successful fabrication of a multi-layer part. Figure 10 shows a schematic representation of extreme overlapping rates. If the lateral overlap rate is too high, material usage efficiency is compromised. If the lateral overlap rate is too small, a rough surface topography with deep vales between tracks is formed which might impact negatively on the next layer producing gaps on a multi-layer part.

Figure 11 shows overlapping rates ranged from ~ 36% to 5.6%, left to right respectively.

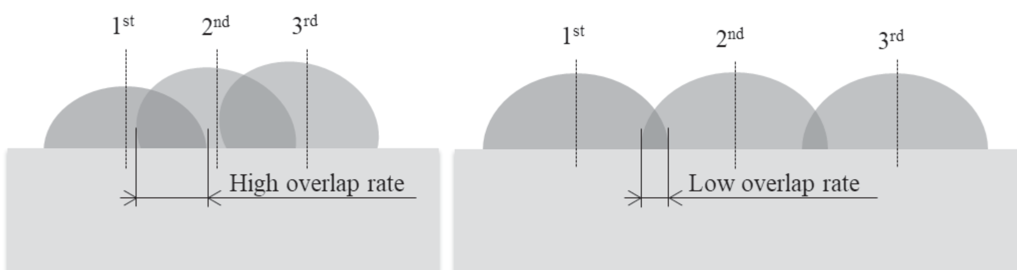

Figure 10. Schematic representation of extreme lateral overlapping rates.

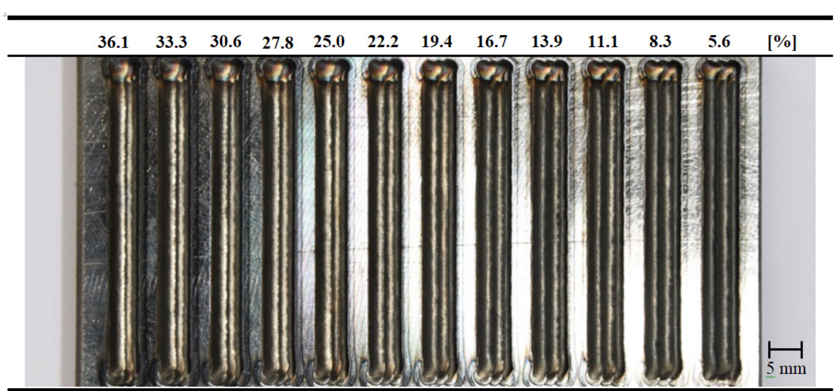

Figure 11. Substrate plate with several single layers deposited and each layer with different lateral overlap rate.

Analysis of the overlap rate involved determining the surface profile measured with a laser displacement sensor, Figure 12. A balance between the deposited width and the topography of the surfaces of the deposited set of beads will give the best overlapping rate.

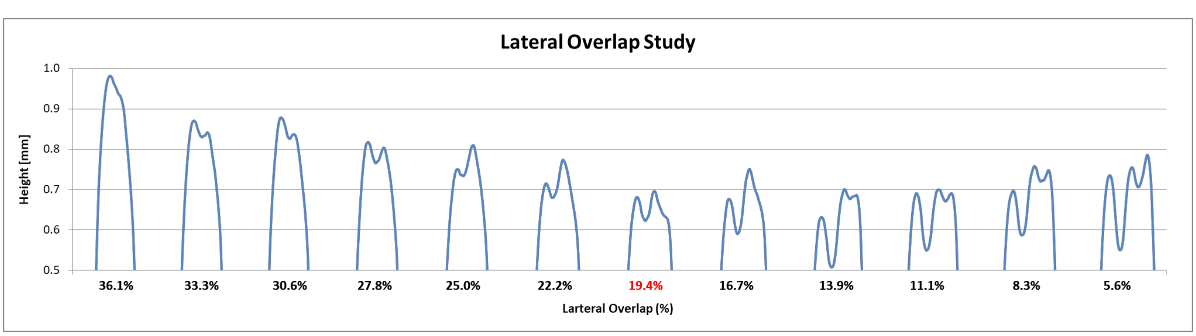

Figure 12. Layer profiles considering distinct lateral overlap rates.

Analysis of the set of results presented in Figures 11 and 12 revealed that lateral overlap rates higher than 25% result on a lower material efficiency, whereas for lateral overlap rate below 13.9% surface topography was compromised. Hence, overlapping rates ranging from 25% to 19.4% resulted on smoother surfaces. Refinement of this analysis included the deposition of six (6) adjacent tracks with a lateral overlap rate ranging from ~18% to 20.8%, their topographic profiles showed the lower overlapping rate to give the best results, Figure 13.

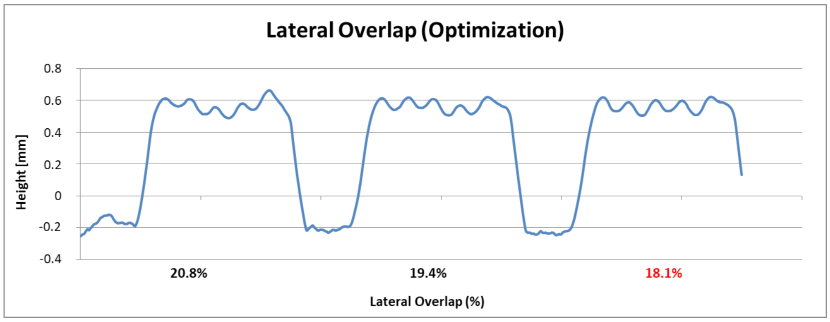

Figure 13. Optimization on analysis of lateral overlap.

Surface profiles revealed that further improvements could be achieved if the height of the first deposited tracks was controlled. As the first bead was deposited on a cold substrate it had a lower wettability and consequently the second deposited track is slightly higher than the average height of the layer suggesting that a different overlap rate could be used for the initial tracks. Figure 14, shows that once the ideal overall overlap rate was defined to be 18.1%, the overlap between the first and second track could be slightly lower than the rest of the layer. Results showed that a smoother surface profile was achieved when the overlap between the first and second deposited track was set at 12.5%.

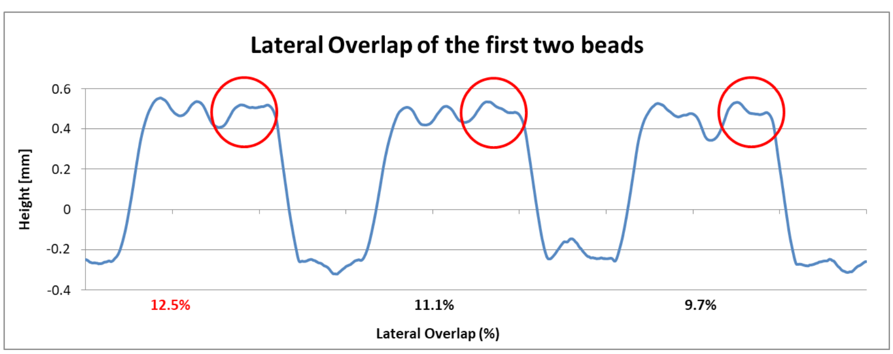

Figure 14. Analysis of lateral overlap rate between 1st and 2nd tracks.

Figure 15 shows a typical the cross-section of a layer composed of 15 individual tracks with overlap rates of 18.1% and 12.5% (between 1st and 2nd deposited track). The total length of layer is identified and the HAZ on the substrate observed as a dark region in the substrate near the deposited layer. This would be the first layer on laser additive manufacturing process. An example of a defect, an undercut, associated with a poor overlap rate is shown in the insert of figure 16.

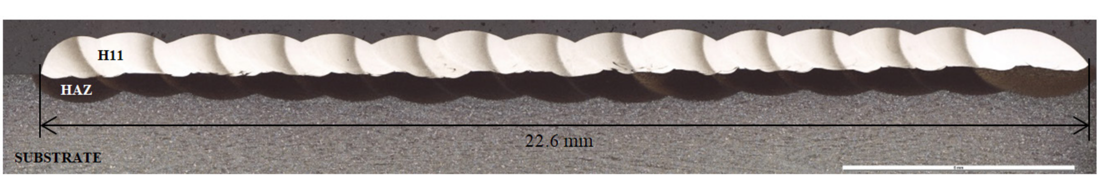

Figure 15. Transverse cross-section microstructure of a single layer and its total length.

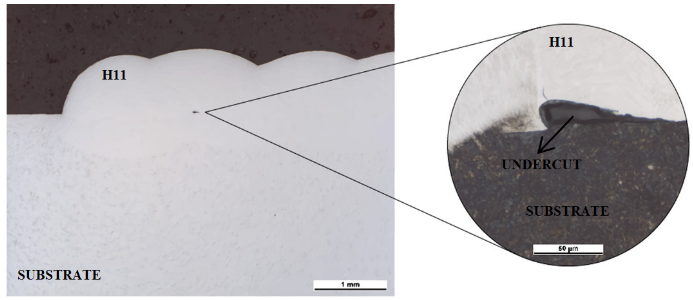

Figure 16. Cross- section of single layer showing an undercut, defect associated with inadequate overlap rate.

4.3. Vertical overlap analysis

Vertical overlapping rate was the parameter analyzed on the investigation of multi-layers. The previous stages of this study aimed to identify the processing parameters adequate to process a sound and homogeneous layer though in a wire-based process small discontinuities on the layer profile will always be present but do not compromise soundness of the part. Nevertheless, it is worth noting that in an additive manufacturing process, a discontinuity would be magnified as subsequent layers are deposited. In order to mitigate height variations along a layer it is fundamental to for building a part to assess the impact of the vertical overlap between layers, Figure 17.

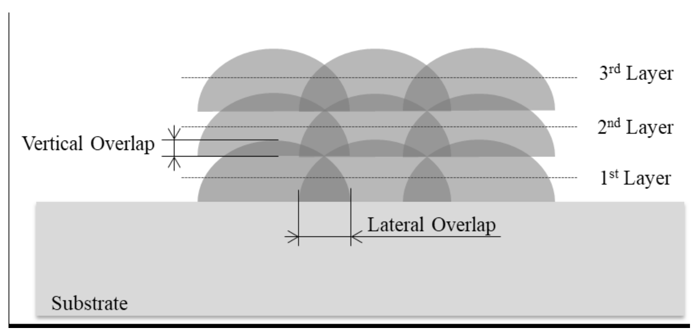

Figure 17. Schematic drawing of vertical and lateral overlaps.

Three blocks were deposited with different vertical overlap and the profile of each layer measured immediately after its deposition with a laser displacement sensor. The vertical overlap rate considered the laser focal point and distance overlap 10% above and below the focal point. Figure 18 shows the profile of each layer for each vertical overlap tested. Best response was given by the higher number of deposited layers achieved when the laser focal point was set below the average surface roughness of the previously deposited layer.

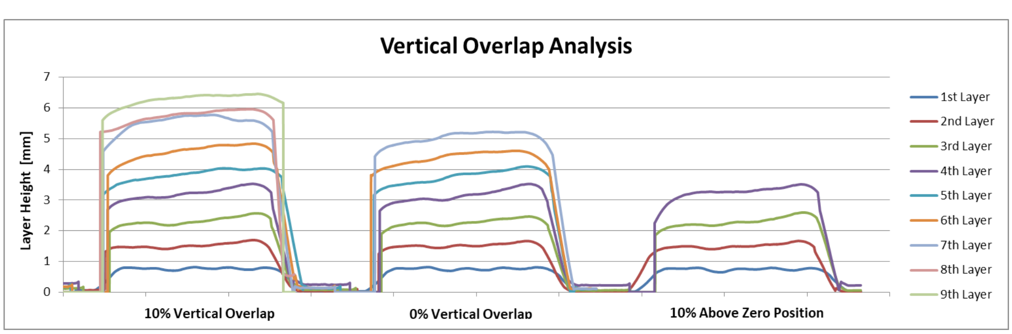

Figure 18. Layer profiles considering distinct vertical overlap rates.

For each block, sequential layers were deposited until the automated process stopped or if an error occurred during the deposition, such as wire dripping and stubbing. Processing with a vertical overlap of 10% above the average roughness of the previous layer allowed depositing four (4) consecutive layers. If the vertical overlap rate referred the average roughness seven (7) were processed but for overlap rates obtained when setting the laser focal point 10% below the average roughness of the previous layer, processing was stopped on the 10th layer.

The vertical overlap is an important parameter for productivity, so it should be kept to the minimum that offers highest build-up rates possible.

Cross section analysis of a multi-layer structure is shown in Figure 19, revealing the tracks in each layer. A small rim of heat affected zone (HAZ) composed of lath martensite phase is developed on the process. Inserts highlight some of the defects identified in the deposition. The one on the left-side is on the interface between 1st and 2nd deposited track and substrate, with the same characteristics discussed for a single-layer analysis. Nevertheless, other undercuts were found between layers (images on the right side of Figure 19). It is shown that further analysis of the vertical overlap rate is required to obtain a sound AM part. Further development to mitigate height heterogeneity of each deposited layer could also include a change in the processing direction by depositing perpendicular layers or rotating 180º the substrate, so for each layer deposition would started at the end of the previous layer.

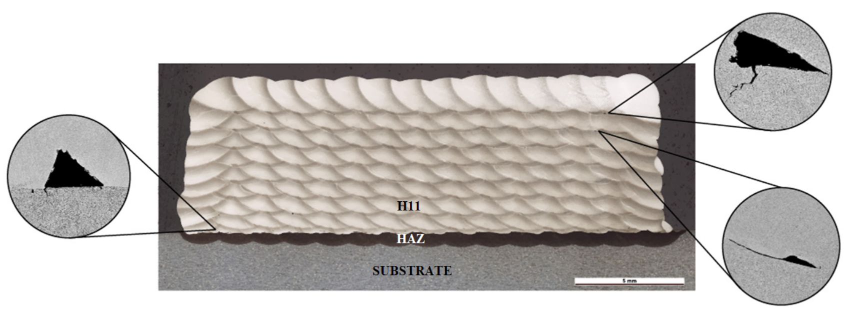

Figure 19. Transverse cross-section microstructure of a multi-layer structure. Inserts show defects identified between layer.

Further analysis of region near the defects revealed fluctuation in the chemical composition, Figure 20 and Table 4. Region A, the closest to the defect, showed higher traces of copper (Cu) than regions B and C. Although this segregation did not affect microstructure it suggested that the Cu in the wire is playing a role. A more detailed analysis must be considered to evaluate the formation of defects and required procedures to enhance the quality of LMD-W parts.

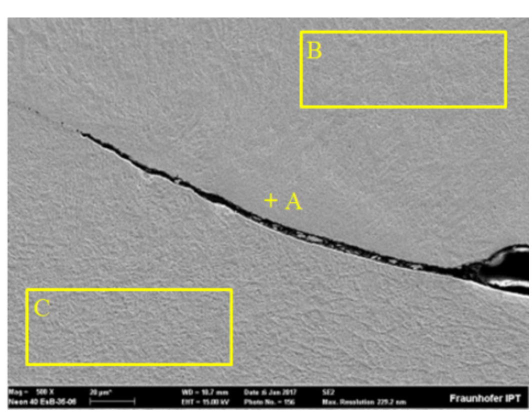

Figure 20. Defect between layers on a multi-layer structure and regions (A), (B) and (C) where chemical compositions were determined.

Table 4. Chemical composition of regions analyzed according to Figure 21.

	Si %	V %	Cr %	Fe %	Cu %	Mo %
Region A	1.00	0.52	4.82	83.09	8.52	2.05
Region B	1.16	0.44	5.30	90.18	1.09	1.83
Region C	1.17	0.37	5.33	90.62	0.72	1.79

Analysis of the microstructure of the deposited layers showed a typical solidification structure with fine dendrites, Figure 21, that exhibited epitaxial growth contributing to strengthen the bond between layers [22]. Chromium, molybdenum and vanadium carbides concentrate at the interdendritic region.

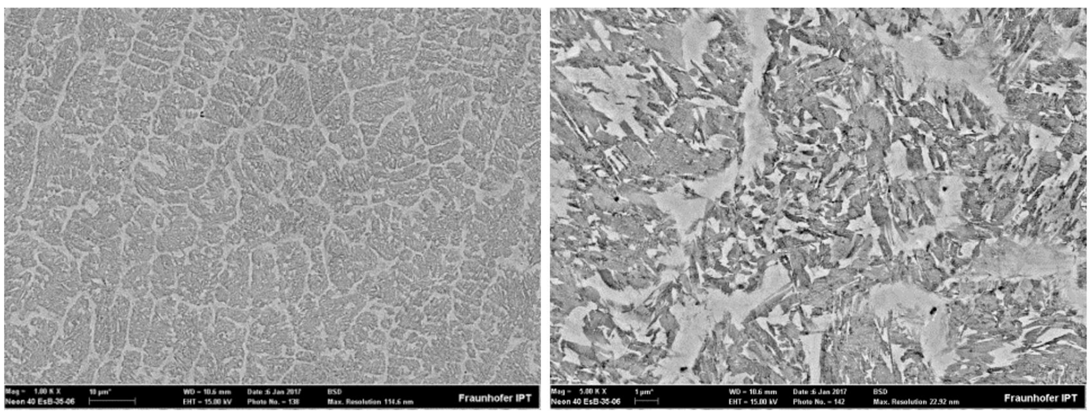

Figure 21. Microstructure of the clad zone (H11) with magnitude of 1000x and 5000x, respectively.

The impact of multi-layer processing can also be identified correlating hardness profile of multi-layer structure and single track deposits processed with the same parameters, Figure 22 (for correlation purposes profiles considered the number of indentations, the distance between measurements was of 0.1 mm to 0.5 mm for multi-layers and single track samples, respectively). Three different zones can be identified in the Figure 22: clad zone (CZ), heat affected zone (HAZ) and substrate (SS). The multiple thermal cycles caused by the melting and reheating of the deposited material in multilayer parts accounting for the reduction in hardness measured in the multi-layer samples.

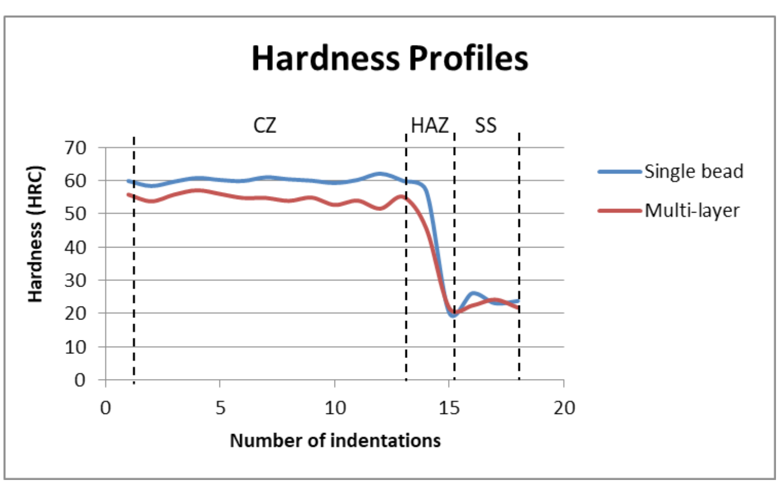

Figure 22. The effect of multi-layer process on microhardness profile of the clad sections.

5. Conclusion

A parametric study for H11 wire-based laser metal deposition was designed and accomplished. Results showed that processing parameters affected substantially the surface quality, track uniformity and interface between substrate and H11 steel tracks. It was shown that there is not just one adequate set of parameters, but there is a limited range of laser power that allows for a stable deposition. For the conditions tested, the variation of processing parameters did not influence significantly the hardness of single track deposits. However, the multiple thermal cycles experienced by the multilayer structure caused a reduction in hardness.

The study also highlighted that lateral and vertical overlap rates were key factors to build a part by LMD-W. Extreme high/low lateral overlap rates compromised the multilayer structure of an additive manufacturing process. Vertical overlapping depended on the height homogeneity of each layer, a key factor to the success of a layer-by-layer technique. Nevertheless, the presence of processing defects formed during lateral and vertical overlapping revealed that overlap rates need to be controlled to obtain homogeneity allowing to fabricate a sound part without the presence of gaps or pores.

References

[1] Shah K, Haq I, Khan A, Shah SA, Khan M, Pinkerton AJ. Parametric study of development of Inconel-steel functionally graded materials by laser direct metal deposition. Materials & Design. 2014;54:531-538. http://dx.doi.org/10.1016/j.matdes.2013.08.079.

[2] Klocke F, Arntz K, Teli M, Winands K, Wegener M, Oliari S. State-of-the-art laser additive manufacturing for hot-work tool steels. Procedia CIRP. 2017;63:58-63. http://dx.doi.org/10.1016/j.procir.2017.03.073.

[3] Kobryn P, Ontko NR, Perkins LP, Tiley JS. Additive manufacturing of aerospace alloys for aircraft structures. In: Meeting Proceedings RTO-MP-AVT-139; 2006; Neuilly-sur-Seine, France. France: RTO.

[4] Cawley J. Solid freeform fabrication of ceramics. Current Opinion in Solid State and Materials Science. 1999;4(5):483-489. http://dx.doi.org/10.1016/S1359-0286(99)00055-8.

[5] Mazumder J, Song L. Advances in direct metal deposition. In: American Society of Mechanical Engineers – ASME. Advanced manufacturing. San Diego: ASME; 2013

[6] Arcella F, Froes F. Producing titanium aerospace components from powder using laser forming. Journal of the Minerals Metals & Materials Society. 2000;52(5):28-30. http://dx.doi.org/10.1007/s11837-000-0028-x.

[7] Paul S, Thool K, Singh R, Samajdar I, Yan W. experimental characterization of clad microstructure and its correlation with residual stresses. Procedia Manufacturing. 2017;10:804-818. http://dx.doi.org/10.1016/j.promfg.2017.07.081.

[8] Sears J. Direct laser powder deposition state-of-the-art. In: The Minerals, Metals and Materials Society. Powder materials: current research and industrial practices. Warrendale: TMS; 1999. p. 213-226.

[9] Vilar R. Laser cladding. International Journal of Powder Metallurgy. 2000;37:31-48.

[10] Lauwers B, Klocke F, Klink A, Tekkaya AE, Neugebauer R, Mcintosh D. Hybrid processes in manufacturing. CIRP Annals. 2014;63(2):561-583. http://dx.doi.org/10.1016/j.cirp.2014.05.003.

[11] Shishkovsky I, Missemer F, Smurov I. Direct metal deposition of functional graded structures in Ti-Al system. Physics Procedia. 2012;39:382-391. http://dx.doi.org/10.1016/j.phpro.2012.10.052.

[12] Keicher D, Smugeresky J. The laser forming of metallic components using particulate materials. Journal of the Minerals Metals & Materials Society. 1997;49(5):51-54. http://dx.doi.org/10.1007/BF02914686.

[13] Costa A, Craievich A, Vilar R. Niobium and chromium rich coatings tailored by laser alloying: XRD analysis at high temperatures. Materials Research. 2004;7(1):49-52. http://dx.doi.org/10.1590/S1516-14392004000100008.

[14] Vilar R. Laser alloying and laser cladding. Materials Science Forum. 1999;301:229-252. http://dx.doi.org/10.4028/www.scientific.net/MSF.301.229.

[15] Abioye T, Folkes J, Clare A. A parametric study of inconel 625 wire laser deposition. Journal of Materials Processing Technology. 2013;213(12):2145-2151. http://dx.doi.org/10.1016/j.jmatprotec.2013.06.007.

[16] Mok SH, Bi G, Folkes J, Pashby I. Deposition of ti6al4v using a high power diode laser and wire, part i: Investigation on the process characteristics. Surface and Coatings Technology. 2008;202(16):3933-3939. http://dx.doi.org/10.1016/j.surfcoat.2008.02.008.

[17] Fallah V, Corbin S, Khajepour A. Process optimization of Ti-Nb alloy coatings on a Ti-6Al-4V plate using a fiber laser and blended elemental powders. Journal of Materials Processing Technology. 2010;210(14):2081-2087. http://dx.doi.org/10.1016/j.jmatprotec.2010.07.030.

[18] Klocke F, Arntz K, Teli M, Wegener M, Winands K, Oliari S. Parametric study for wire + powder fed laser deposition welding of H11. In: Proceedings of the 9th International Conference and Exhibition on Design and Production of Machines and Dies/Molds; 2017; Kusadasi. Kusadasi; 2017.

[19] Kaplan A, Weinberger B, Schuoecker D. Theoretical analysis of laser cladding and alloying. In: Proceedings of Lasers in Material Processing; 1997; Munich. United States: SPIE; 1997. p. 499.

[20] Zhou S, Dai X, Zeng X. Effects of processing parameters on structure of Ni-based WC composite coatings during laser induction hybrid rapid cladding. Applied Surface Science. 2009;255(20):8494-8500. http://dx.doi.org/10.1016/j.apsusc.2009.05.161.

[21] Parekh R, Buddu RK, Patel RI. Multiphysics simulation of laser cladding process to study the effect of process parameters on clad geometry. Procedia Technology. 2016;23:529-536. http://dx.doi.org/10.1016/j.protcy.2016.03.059.

[22] D'Oliveira AS, Silva PS, Vilar R. Microstructural features of consecutive layers of Stellite 6 deposited by laser cladding. Surface and Coatings Technology. 2002;153(2-3):203-209. http://dx.doi.org/10.1016/S0257-8972(01)01687-5.