SINGLE BEAM LASER REMELTED MOLYBDENUM LAYER ON ALUMINUM SUBSTRATE

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Abstract

In this article, the reactions and optimal parameters were investigated for molybdenum layers produced on aluminum substrate using single beam ytterbium fiber laser. To produce these layers the molybdenum powder (25-45 μm in size) was placed on the aluminum sheet substrate and successfully treated - along the entire length with 16 different irradiation modes. The microstructure of the prepared samples of welded joints was observed by using a light microscope (LM) and a scanning electron microscope (SEM). Reactions between molybdenum powder and aluminum substrate were examined by energy dispersive X-ray analysis (EDX). The evaluation of optimal parameters was determined from appearances of welded joints, namely their heights and depths.

Keywords: Molybdenum, aluminum, SLM, ytterbium fiber laser

1. INTRODUCTION

Selective laser melting (SLM) is a progressive and an advanced method which belongs to additive manufacturing technologies. This method allows producing objects from (i) metal powder with complex geometry and (ii) from new design perspectives in terms of materials, shapes and mechanisms. This technology is suitable for all stages of the product development - from design concept to low volume production. Many metallic materials have been fabricated by SLM, like for example stainless steel, copper, titanium and aluminum based alloys. Mechanical properties of produced objects are comparable to those of bulk materials. In the SLM process powders are deposited on the substrate before they are selectively melted in the line-by-line or layer-by-layer manufacturing modes. Melted powders are supposed to form a continuous track under the irradiation of a moving laser spot according to the computer aided design (CAD). The most common defects encountered using SLM technology are pore defects, cracks and balling “phenomenon”. The balling phenomenon is known as a broken molten track at a certain point. As mentioned above, the tracks formation during SLM and the occurrence of the defects and the balling phenomenon is strongly defected by many processing parameters and material-based input parameters, e.g.: used powders, laser power, scanning speed, scan line spacing and working atmosphere [1 - 3]. This is especially relevant for materials aimed for high-temperature applications, such molybdenum (Mo), tungsten (W) etc., since they have high melting temperature, high heat conductivity and susceptibility to cracking due to accumulation of residual stresses. High melting point leads to the fact that the molten drops may freeze on the cold substrate plate before they can spread completely, especially if substrate is composed of easily melted metals, e.g. aluminum (Al) [4 - 5]. Thus, it is highly important to get extensive knowledge about the nature of track formation behavior for refractory metals. The aim of this article is to study the production of Mo layers on Al substrate via SLM process and to evaluate the optimal process parameters. A special attention was drawn to the study of microstructural and chemical features of the produced layers, and the presence of the defects.

2. EXPERIMENTAL MATERIALS AND METHODS

2.1. Experimental materials

Molybdenum powder (GTV, Germany) was supplied in agglomerated and sintered state. The chemical composition of this powder was 99.0 wt. % Mo and 0.1 wt. % O. The particle size was within the range 25 - 45 μm. The typical morphology of this powder is shown in **Figure 1**, where it can be seen that powder has a spherical shape and is formed from smaller particles.

As a substrate material, 99.999 % pure aluminum sheet was used in this study.

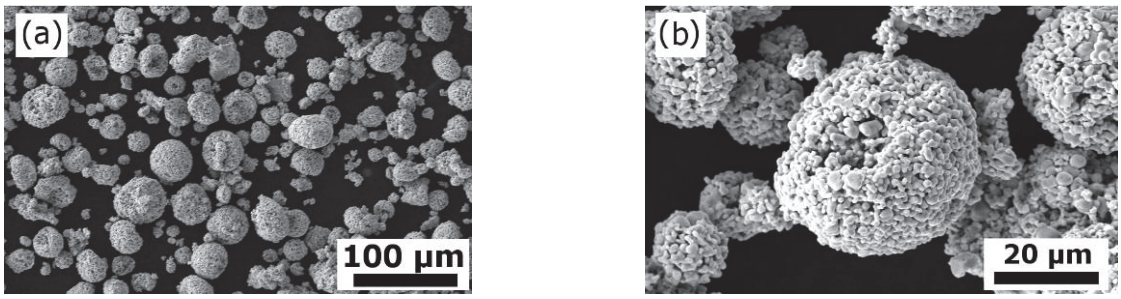

Figure 1 (a) Morphology of Mo powder, (b) detail of Mo powder, (SEM-SE)

2.2. SLM processing and microstructural analysis

The selective laser melting experiments were carried out using SLM machine SLM 280 ^{HL} (SLM Solutions, Germany), which utilizes YLR-Faser-Laser with a spot size of 82 μm as a source of radiation. To study the effect of SLM processing parameters, in these experiments the power and the scanning speed of laser were varied. A series of laser melted tracks were produced changing these parameters. During SLM processing, the layer of Mo powder was put on the surface of reducing plate and laser irradiated using different power ranged from 100 W up to maximum power of 400 W with a step size about 50 W. The maximum laser scanning speed was 15 m / s and minimum layer thickness was 20 μm. The scanning speed was ranged from 500 mm / s up to 1000 mm / s with a step size of 100 mm / s. The distance between each track was about 1 mm. In total, 34 tracks were done by SLM. As a source of protective gas, a mixture of Argon and Nitrogen was used with maximum flow of 2.5 l / min.

A precision geometry platform was designed for the clamping of the reducing plates (see **Figure 2**). This platform is made of Aluminum alloy EN AW 2007 and its main advantage is a cutting of inline plates for easier preparation of metallographic samples. This reducing plate is consolidated to this platform by three screws.

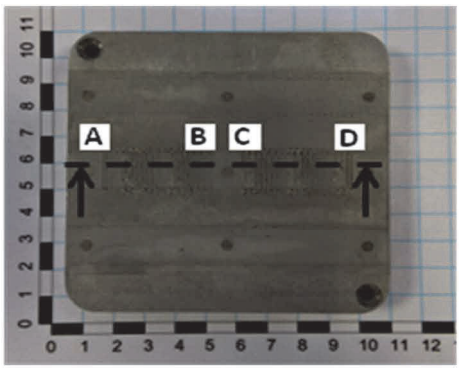

Figure 2 A precious geometry platform with reducing plates and welded joints (the letters show the sections AB and CD reducing plates used for microstructural analysis)

Prepared samples were cut on cut-off machine Secotom 50 (Struers, Denmark). Metallographic samples were prepared on the sample cross-sections by wet grinding and polishing with diamond suspensions (Struers, Denmark) using an automatic preparation system Tegramin 30. Final polishing was realized by OP-Chem Suspension (Struers, Denmark). Each sample was etched using the Fuss etchant for visualization of the microstructure. Metallographic samples were analyzed using a light microscope DSX510 (OLYMPUS, Japan) and scanning electron microscope LYRA 3 (Tescan, Czech Republic) equipped with the energy dispersive X-ray analysis (EDX) module (BRUKER, USA) for the chemical microanalysis.

3. RESULTS AND DISCUSSION

3.1. Metallographic analysis

The appearance of laser tracks is shown in **Figure 3**. Two areas ("AB" and "CD") of weld deposits were cut off from the reducing plate and prepared for metallographic analysis (previously shown in **Figure 2**). The quality of tracks was visually analyzed, and the majority of these laser tracks were inhomogeneous with irregularity, drops and distortion. Some tracks showed the balling phenomenon, which was observed for the minimum laser power within the range 150 - 200 W, and for the highest scan speeds. The tracks with smooth surface and continuous weld were considered as optimal.

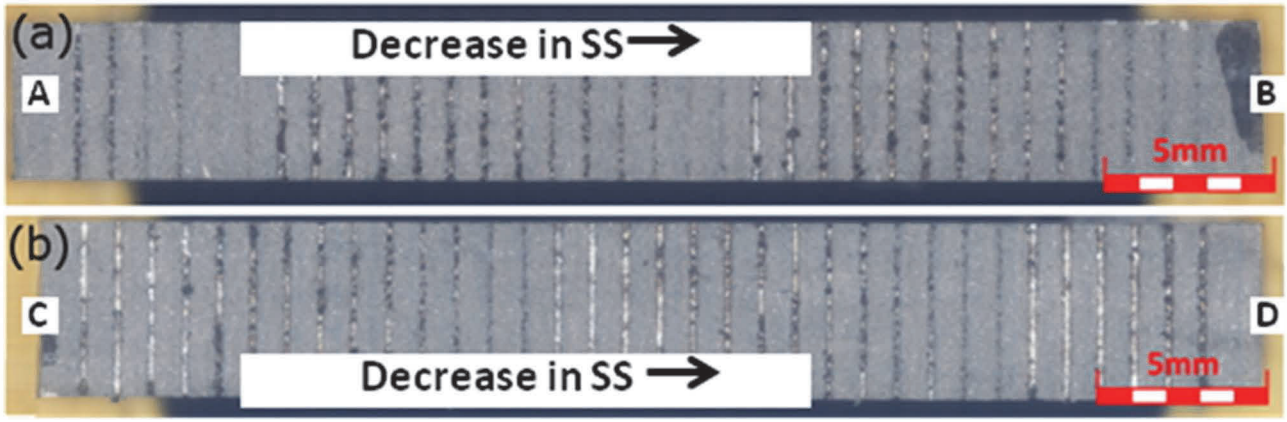

Figure 3 The appearance of laser tracks in the areas (a) AB and (b) CD

Microstructure of each welded joint was evaluated and documented. Some pore defects were observed. The quality of welded joints was assessed by the measurement of their depths and heights. Examples of the welded joints are shown in **Figure 4**, whereas the welded joint I was done by LP = 400 W, SS = 800 mm / s, welded joint II was obtained by LP = 400 W, SS = 700 mm / s and welded joint III was created by LP = 400 W, SS = 500 mm / s. The closer detail of the area in welded joint (**Figure 4(d)**) shows probably small molybdenum particles or some phases inside aluminum matrix, which can be $Al_{12}Mo$ and Al_5Mo compounds. As can be seen in **Figure 4(e)** and **(f)**, there are two illustrations of balling phenomenon, which occurred in this experiment and is mentioned above. In this case, molybdenum powder did not react with aluminum substrate and coagulate into a "ball". In this figure, molybdenum is bright and below it is the aluminum substrate with a slightly darker color.

As the best process parameters, the following parameters were evaluated: (i) LP = 350 W, SS = 900 mm / s; (ii) LP = 400 W, SS = 800 mm / s and (iii) LP = 300 W, SS = 700 mm / s.

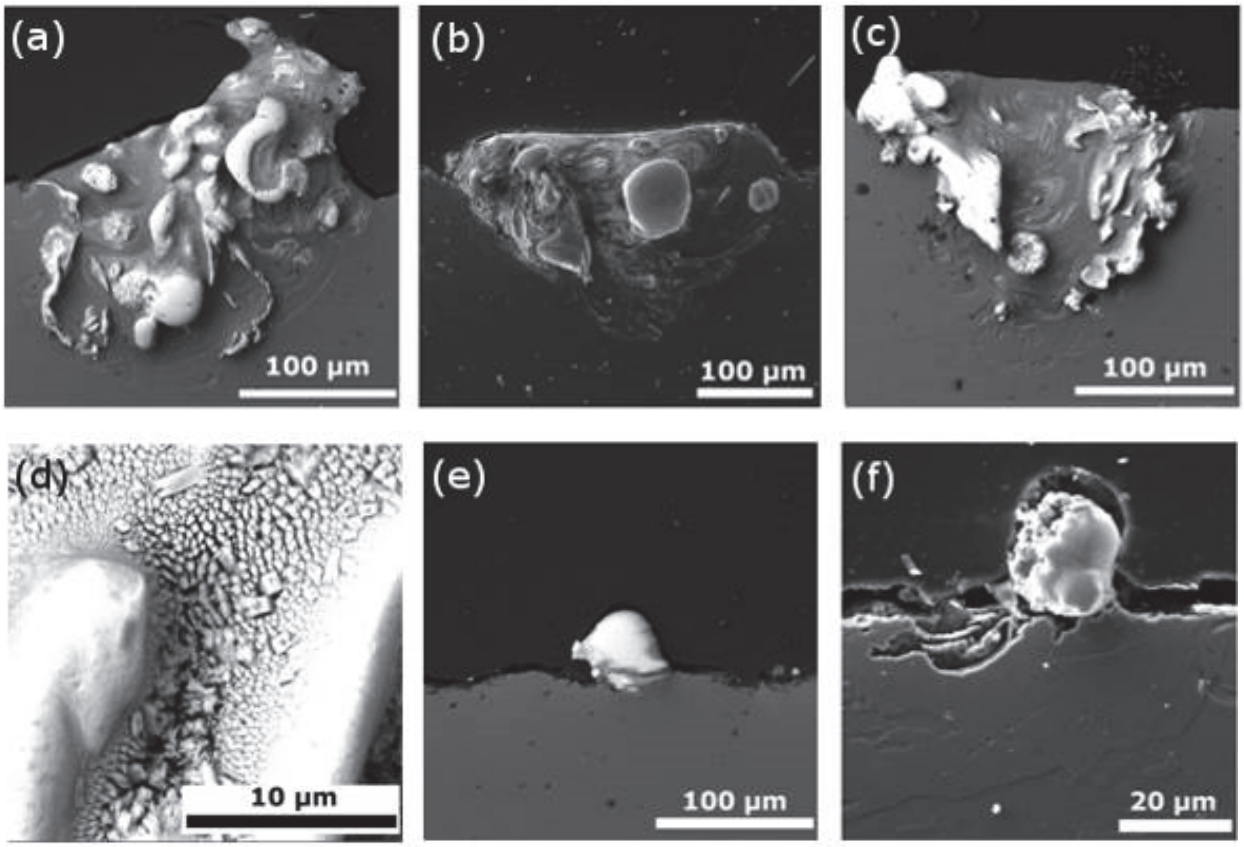

Figure 4 Microstructure of: (a) welded joint I (SEM-BSE), (b) welded joint II (SEM-SE), (c) welded joint III (SEM-BSE), (d) detail of welded joint III (SEM-BSE), (e) balling phenomenon, area AB (SEM-BSE) and (f) balling phenomenon, area CD (SEM-SE)

3.2. Chemical analysis and elemental mapping of the welded joints

Chemical micro-analyses of welded joints were done by mapping and point analyses. These data from point analyses are given in **Table 1** and mapping data are given in **Table 2**. Documentation of one set of point analyses is shown in **Figure 5**. From these results is obvious that the area of welded joints is formed mainly by aluminum matrix and molybdenum particles. This statement is also confirmed by the EDX mapping analyses (see **Figure 6** and **Figure 7**), where elemental molybdenum is marked with green color and aluminum is marked with red color. Any specific reactions are not observed from these analyses. As can be seen in **Figure 7**, local reaction of Mo and Al occurred in some areas where a successful melting of Mo and Al were done.

The chemical composition of welded joints in area "AB" is approximately 98.8 at. % Al and 1.2 at. % Mo. The chemical composition of welded joints in area "CD" is about 96.1 at. % Al and 3.9 at. % Mo. According to Mo-Al phase diagram [7], phases $Al_{12}Mo$ and Al_5Mo could form in welded joints.

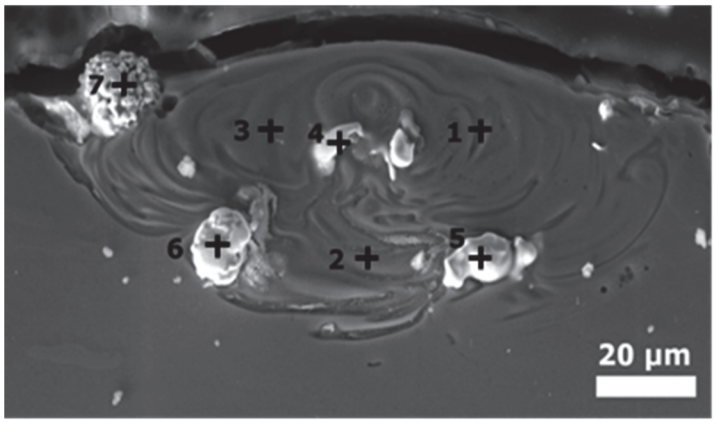

Figure 5 Schematic illustration of EDX ponit analysis

Table 1 Summary of EDX point analysis of welded joint - (from SE image in **Figure 5**)

Element (at.%)	Al	Mo
1	99.6	0.4
2	99.3	0.7
3	99.9	0.1
4	13.9	86.1
5	16.5	83.5
6	1.7	98.3
7	19.8	80.2

Table 2 Chemical composition of welded joints - (EDX elemental mapping analyses presented in **Figure 6**)

Section	AB		CD	
Element (at.%)	**Al**	**Mo**	**Al**	**Mo**
1	98.6	1.4	95.0	5.0
2	99.5	0.5	94.6	5.4
3	98.4	1.6	98.8	1.2
Avarage	**98.8**	**1.2**	**96.1**	**3.9**

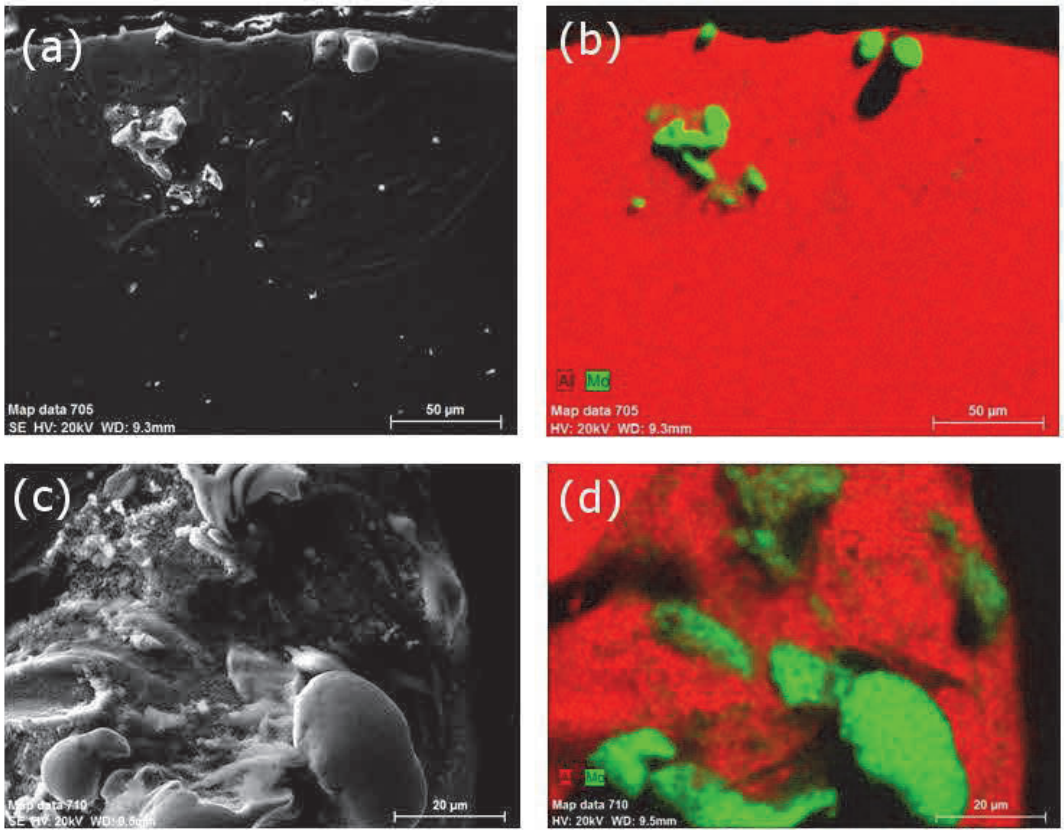

Figure 6 Two sets of mapping analyses (a) area of mapping I, (b) result from area I, (c) area of mapping II and (d) result from area II

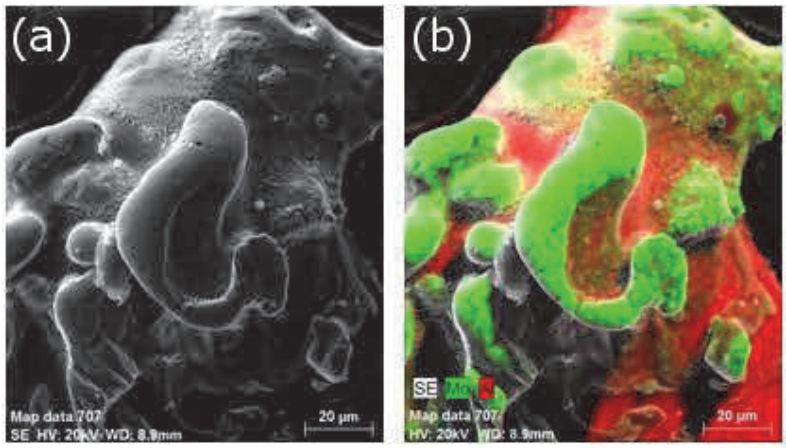

Figure 7 Mapping analysis of successfully melted area

4. CONCLUSIONS

In this article, analysis of the formation of single tracks produced by SLM using molybdenum powder and aluminum substrate was conducted under the different power and scanning speed of laser. Optimal process parameters were elaborated. Microstructural examination showed that most of produced laser tracks were inhomogeneous. The major instabilities appear at high scanning speed in the form of distortions, irregularities and balling effects. This balling effect was observed for the minimum laser power (150 - 200 W) and for the highest scanning speed. Good process parameters were evaluated as: (i) LP = 350 W, SS = 900 mm / s; (ii) LP = 400 W, SS = 800 mm / s and (iii) LP = 300 W, SS = 700 mm / s.

The majority of welded lines were formed by aluminum matrix (at least 96.1 at. %) and molybdenum particles, while the chemical reactions between Al and Mo occurred only in local areas. The phases formed by these reactions are probably $Al_{12}Mo$ and Al_5Mo. Further phase determination requires additional analysis (X-ray, EBSD). Moreover, experiments with different powder layer thickness, physical properties and granulomorphometry of the used powder should be done.

ACKNOWLEGMENT

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