Laser beam induced surface alloying of aluminum with niobium

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Abstract. A summary is presented of the investigations on the mechanism of alloyed layer formation during laser beam surface alloying of aluminum with Nb. Surface alloys were produced by a two-step process: at first, commercially pure Al substrates were alloyed with Nb by injecting an Al-Nb powder mixture into the melt pool generated using a CO₂ laser; the microstructure was then refined by laser melting. In the first step, Nb concentrates near the surface of the melt pool during solidification, resulting in the production of surface layers of Al-Nb alloys. These alloys are heterogeneous and contain pores and undissolved Nb particles for all the processing parameters used. Their microstructure is formed from large dendrites of Al₃Nb and interdendritic α-Al solid solution. Laser remelting of the alloyed layers results in a complete elimination of the defects and homogenization of the material. The Vickers microhardness of the surface alloys varies from 450 to 650 HV, depending on the volume fraction and dendrite spacing of Al₃Nb.

1. Introduction

Aluminum alloys are widely used in high-performance automobiles, railway cars, aircraft and spacecraft, light ships, etc., due mainly to their excellent mechanical strength, low specific weight, good formability and relatively low cost. However, the widespread use of these materials has been limited by their low wear resistance, particularly at high temperatures. Modifying the chemical composition by adding alloying elements greatly enhances the wear and corrosion resistance of aluminum alloys. Surface treatment of aluminum alloys by laser alloying with niobium has been reported by several authors [1, 2, 3, 4] and leads to considerable improvement of the corrosion, wear resistance and surface hardness. It has been found that in laser alloying of Al with Nb the latter leads to the formation of a considerable amount of Al₃Nb, which is a hard intermetallic compound [1, 2]. In these works it is reported that Al₃Nb and Nb₂Al phases are formed during laser cladding of aluminum with niobium and vanadium. The formation of these metastable phases is attributed to the non-equilibrium solidification involved in laser cladding. Results obtained in [3, 4] during laser alloying of Al with Nb suggest that Nb is a very promising alloying element to improve the wear resistance and strength of aluminum alloys.

In this study, we demonstrate the possibility of producing surface layers with high hardness and sufficient toughness for practical applications by laser alloying of Al with Nb. The results published so far are different, since the initial chemical composition (Al-50wt%Nb and Al-75wt%Nb) and the processing conditions used by various authors are different.
2. Experimental
Commercially pure aluminum plates were used as substrates. The laser alloying was carried out by a CO₂ laser: power from 2 up to 2.5 kW, scanning speed of 8 mm.s⁻¹ and powder flow rate of 0.02 g.s⁻¹. Complete surface coverage was achieved by 50% overlapping of adjacent tracks. A mixture of Al-50wt%Nb and Al-75wt%Nb high purity powders was used. Laser alloyed surface layers were remelted in a direction perpendicular to the direction used for alloying, with scanning speeds of 10 mm.s⁻¹ and laser processing parameters similar to those used previously.

The microstructure was observed by optical and scanning electron microscopy. The phases formed were identified by X-ray diffraction analysis performed on polished samples. Chemical analysis of selected samples was carried out using an electron probe microanalyser (EPMA). Hardness depth profiles were established by measuring the microhardness of transverse cross-sections along the central lines of the tracks.

3. Results and discussion
An examination of the cross-section of the layer alloyed with overlapping (figure 1) reveals two different zones: a top layer(A) where the niobium has concentrated and has formed an aluminum-niobium alloy by way of mixing with aluminum, and a bottom layer(B) that is formed essentially by resolidified aluminum solid solution.

![Figure 1. Alloyed layer after overlapping tracks.](image1)

After remelting (figure 2) the structure is homogenized and the pores and undissolved particles are eliminated. The depth of the remelted layer R varies between 100 μm and 550 μm. The alloyed layers are heterogeneous and contain pores and undissolved niobium particles in zone A (figure 2).

![Figure 2. Alloyed layer after remelting.](image2)

Figure 3 shows the niobium concentration distribution along the depth of the alloyed layer for different compositions of the starting powder mixture: curve 1 Al-25 wt% Nb [3, 4]; curve 2 Al-50 wt% Nb; curve 3 Al-75 wt% Nb obtained after alloying at laser power 2 kW, with interaction
times during alloying and remelting 0.24 s and 0.12 s respectively. These results indicate that niobium is unevenly distributed along the depth of the alloyed layer and that the concentrations of Nb and Al are very different from the composition of the starting powder mixture. As the Nb content in the starting mixture increases, the depth of the layer decreases. The alloyed layer formation is hindered and, if formed, the layer has irregular surface and cracks. An alloyed layer is not formed at any laser technological parameters when pure Nb has been used for alloying. Using staring mixture with decreased Nb content (25 %) could easily be melted due to the presence of Al which has a lower melting point than Nb.

The formation of alloyed layers in the present study can be explained qualitatively in terms of the existence of a reverse vortex in the melting pool. It is well known that convection flows are responsible for mixing alloyed elements in the molten pool [6, 7, 8, 9]. Anthony and Cline [6] made an analysis of the surface tension driven flow within the molten pool. Kou and Wang [7] developed a three-dimensional model for convection in a laser molten pool using both surface tension and buoyancy driven flow. These works show that surface tension is responsible for the fluid flow and convection during laser beam treatment in surface melting mode (figure 4). During laser surface alloying, a temperature gradient extends radially away from the center of the laser beam. Thus, at the center the temperature of the liquid metal is at its highest and the surface tension of the liquid is at its lowest value. As the temperature of the liquid metal decreases away from the center of the laser beam, the surface tension increases. As a consequence, a force \( F = \nabla \gamma \) (\( \gamma \) being the surface tension) is generated. Since the force \( F \) activates a motion in the liquid metal, the alloyed elements circulate several times by convection. It is reported in reference [8] that the distribution of the alloyed elements depends on a primary \( V_1 \) and a secondary \( V_2 \) downward vortexes which are formed in the molten pool (see figure 5).

**Figure 3.** Concentration profiles of niobium along the depth.

**Figure 4.** Surface tension driven flow within the melt pool [6].

**Figure 5.** Schematic cross section of convection of a half of a melt pool.
Mazumder and coworkers [9] studied the mass transport in molten pools using a numerical model. They concluded that the extremely fast homogenization frequently observed in laser alloying can only be explained by the intense Marangoni convection caused by the high temperature gradients within the melt pool. They also found that diffusion plays only a minor role. They suggested that the influence of convection in liquid homogenization could be characterized by the surface tension number, $S$, which relates the thermocapillarity-induced convection velocity and the laser beam scanning speed. When $S$ is low ($S \leq 45\,000$ [9]), convection is negligible. Due to the short lifetime of the melt pool, mass transport will be insufficient for the process of melt pool homogenization. When $S$ is high, convection plays a dominant role in transport phenomena in the melt pool. Calculation of the $S$ number for Al melted under the conditions of the experiments described leads to a fairly low value (about 42 000) [6], showing that convection is low. Therefore, insufficient homogenization of the melt pool is to be expected (figure 1). A further difficulty arises when the alloyed elements react with the melt pool material and form insoluble high melting temperature phases. In the Al–Nb system at temperatures below the melting temperature of Al$_3$Nb (1680°C), pure Nb reacts with liquid Al to form the intermetallic compound Al$_3$Nb. The formation of the two different areas is due to the high specific gravity and melting temperature of Nb; its particles sink to the bottom of the Al melt pool during melting. Since convection-driven homogenization is negligible, and due to the high melting temperature of Nb and the relatively low melting temperature of Al, the latter starts to solidify before the Nb particles dissolve, forming a bottom layer that consists essentially of the starting material (zone B in figure 1). In the upper layer, due to the higher temperature of the melt (probably higher than the melting temperature of Al$_3$Nb), the Nb particles dissolve in the liquid Al.

Figure 6 shows the Vickers microhardness profiles measured along the depth of the cross-sections of alloyed layers. The maximum hardness was observed in the remelted layer, with value 650-500 HV01. This high hardness results from the large volume fraction of Al$_3$Nb present in the structure and also from the refinement of the microstructure following the remelting treatment. The exact value of the hardness depends on the scanning speed; higher scanning speeds during remelting lead to finer dendrites and consequently, to harder structures. The intermetallic compound was identified as Al$_3$Nb by X-ray diffraction, as shown in [3, 4, 5].

Figure 7 shows a micrograph of the cross-section of the layer obtained after alloying with 50%Nb powder mixture and remelting with an interaction time during remelting processes 0.12 s. It is seen that the microstructure of alloyed layers is composed of intermetallic compound Al$_3$Nb and a small volume fraction of interdendritic $\alpha$-aluminium solid solution.
4. Conclusions
By varying the initial composition of the Al and Nb powder mixture and laser technological parameters, an alloyed layer with very high hardness was obtained on an Al base metal. The hardness of the remelted layers ranges from 500 to 650 HV. The structure of the layers consists of dendrites of Al₃Nb intermetallic compound and α-aluminium solid solution. The results obtained suggest that Al-Nb alloys produced by laser alloying may be interesting for wear resistance applications.

5. References
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