Laser processing and microstructure of Al-Cu-Fe quasicrystalline coatings on Al-base materials

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Abstract :

There is a large interest in using high power lasers for surface alloying or cladding on aluminium alloys, in order to enhance hardness and to improve wear resistance. A partly quasicrystalline surface layer (QC) (Al-Cu-Fe coating) has been obtained by laser cladding on Al-base materials. In addition to crystalline phases (Al_5Fe_2 and $Al_{13}Fe_4$, with dissolved copper), a quasicrystalline Al-Cu-Fe phase is detected. However, crystallization of this quasicrystalline phase occurs during isothermal heat treatment at 525 °C. A mechanism is proposed for the solidification process resulting from laser cladding.

I - Introduction:

Aluminium alloys are being used to an increasing extent, especially as cast components for automotive or aircraft applications, in order to produce lighter parts. Unfortunately, surface properties of aluminium alloys are not good enough for many technical applications ; in particular, their tribological properties (wear resistance) are poor.

Since the discovery in 1984 (1) of the first quasicrystalline alloy (hereafter called QC) in Al-Mn, many other Al- base alloys have been investigated with regard to the occurrence of QC. More than one hundred of such systems have been reported (2, 3). Most of these materials are metastable and can be obtained only by rapid solidification techniques. However, more recently, different stable QC phases have been detected, either directly after quenching, or by using more conventional techniques of crystalline growth. Such stable phases were first observed in Al-Cu-Li (4), and then principally in Al-Cu-M (M = Fe, Ru, Os, ...)(5). Klein (2) has given an exhaustive list of the different stable phases which may be found in Al-Cu-Fe alloys, either binary (Al_2Cu , $Al_{13}Fe_4$, ...) or ternary (Al_7Cu_2Fe , ...). In any case, rapid quenching offers different advantages, especially the fact that the equilibrium phase diagram is quickly "crossed", limiting therefore the precipitation of perfect and stable crystalline phases. Thermal spraying processes, and especially laser cladding, induces such rapid cooling. A surface layer with a given composition is then achieved on a given substrate. By modifying both laser parameters and powder content, different materials can be elaborated. To our knowledge, this method has never been used for the obtention of QC layers and, as that quasicrystalline Al-Cu-Fe alloys are known to exhibit attractive mechanical and tribological properties (6), development of such surface layers can offer large possibilities of technological applications. The present work reports on this subject.

II - Experimental procedure :

Al-7%Si alloys were used as substrate. Parallelepipedic samples (100*50*10 mm³) were polished and then sand blasted before laser treatment. Granulometry of the different pure powders (Al, Cu, Fe) is in the range 45-90 µm.

Coatings are prepared by using the laser cladding technique (7). The following system was used :

- a CW CO₂ laser, supplied by CILAS (CI4000), operating between 2 kW and 3 kW;
  - a 10" ZnSe focusing lens ; the focal point is located in the sample and the laser beam diameter on the specimen surface is about 1.5 mm. Width of the treated zone is about 1.2 mm. Parallel tracks are achieved with a shift $\delta = 0.8$ mm between two adjacent treatments.
  - a powder injection system (Plasma Technik, Twin 10C) ; the different powders have been injected, through a coaxial nozzle with argon gas acting as support.
- Specimens are mounted on a numerically controlled X-Y table. Scanning speed under the laser beam is in the range 10-25 mm/s.
- Characterization of the treated zones is carried out using the following techniques :
- optical microscopy (etching mixture : Keller reagent),
  - scanning electron microscopy, on polished and unetched cross-sections. Either backscattered or secondary electrons are used for imaging (BEI or SEI mode). EDS microanalysis was also performed.
  - X-ray diffraction experiments were carried out, with a Cu K α radiation.

III - Experimental results and discussion :

1 - Microstructure of the coatings :

A representative micrograph of an Al-Cu-Fe laser coating on an Al-Si substrate is shown in fig. 1. Different zones may be observed, i.e. from the bottom to the top of the sample :

- substrate, containing dispersed silicon particles in an aluminium matrix.
- interfacial zone, in which a partial melting has occurred. Substrate was only slightly heat affected and melting concerns only a very thin zone at the surface ; so, dilution of the addition element is very limited. Nevertheless, this melting enables the formation of a metallurgical bonding between the coating and its support.
- coating, with a mainly dendritic microstructure. Thickness of the surface layer depends on experimental conditions, but is always in the range 0.5 - 1 mm. Different zones can be detected in the coating :
  - some large particles; the average composition (determined by EDS) of their inner part is about 61%Al - 25%Fe - 14%Cu,
  - dendrites (72%Al - 22%Cu - 6%Fe),
  - interdendritic areas (69%Al - 10%Cu - 21%Fe).

2- Phases observed in the coatings :

Fig. 2 shows the X-ray diffraction pattern which corresponds to a coating, directly after quenching. In addition to the peaks relative to the Al₁₃Fe₄ phase, we observe different peaks which may be attributed to a quasicrystalline phase, by comparison with the results reported by different authors in similar Al-Cu-Fe alloys (8-10).

Let us mention that when the laser-powder particle interaction time is not long enough, these particles can not be fully melted in the coating; then X-ray diffraction patterns reveal the existence of pure Al, Cu and Fe phases, and small amounts of intermetallic compounds, especially Al₂Cu. This result can be easily explained : temperature reached in these particles is not high enough and only those with low melting temperature (T_M) can be dissolved in the layer : Al ($T_M = 660^\circ\text{C}$) and Cu ($T_M = 1083^\circ\text{C}$) are melted and can form Al₂Cu, while the melting temperature of Fe particles ($T_M = 1535^\circ\text{C}$) is always lower than T_M .

3 - stability of the different phases :

In order to determine the stability of the different phases obtained in the surface layer, we have performed isothermal heat treatment at 525°C (798K), with increasing durations. Evolution of the coating is characterized by X-ray diffraction.

Intensity of the peaks corresponding to the quasicrystalline phase decreases when annealing duration increases ; this evolution can be interpreted as due to a partial crystallization. In contrast, the intensity of the peaks due to Al₁₃Fe₄ is progressively increasing ; the small distortion introduced in the position of the peaks may be associated to dissolved copper. Chuan Dong et al (9) have given the following composition for the θ phase : Al₇₃Cu₅Fe₂₁.

Fig. 1 : micrograph showing a typical Al-Cu-Fe coating ; laser power : $P = 2800\text{W}$; scanning speed: $v = 1.5\text{cm/s}$; diameter of the laser beam on the sample : $d = 1.25\text{mm}$; magnification : $G = 200$.

Fig. 2 : X-ray diffraction pattern for an Al-Cu-Fe coating, as elaborated ; laser power : $P = 2800\text{W}$; scanning speed : $v = 1.5\text{cm/s}$; diameter of the laser beam on the sample : $d = 1.25\text{mm}$.

Different authors have carried out annealings at higher temperatures, for example up to 820°C. However, due to the existence of the Al-Si substrate, with a fairly low melting temperature ($T_M \approx 600^\circ\text{C}$), such isothermal heat treatments cannot be performed in the present case without deleterious effects.

4 - Solidification mechanism :

From these different results, the following explanation may be proposed for the solidification mechanism in the surface layer :

- due to the interaction with the laser beam, the different powder particles (Al, Cu, Fe) melt and form a liquid pool on the surface of the substrate which undergoes only a limited melting ; consequently only a slight dilution of the addition elements is achieved. The very small content of silicon in the different zones in the coating is in agreement with this explanation.

- convection movements in the melted pool, resulting from the Marangoni effect, induce a mixing of the various elements and then the different species are distributed fairly homogeneously throughout the surface layer.

- solidification starts with the formation of some large particles; the Al and Fe contents correspond approximatively to those of Al_5Fe_2 (η phase).

- solid growth goes ahead with dendrites formation, with a composition approximatively near to $\text{Al}_{13}\text{Fe}_4$ (with a low content of dissolved copper) (θ phase).

- at the end of the solidification sequence, the interdendritic areas, enriched with copper, are composed of a mixture of Al, Cu and Fe, which corresponds to, about, $\text{Al}_{70}\text{Cu}_{20}\text{Fe}_{10}$ (QC).

This description is in complete agreement with the mechanism proposed by Dong et al (9): quasicrystalline phase is formed by peritectic reactions and can not appear directly from the liquid phase, in contrast to results reported by Tsai et al (5).

V - Conclusion :

Laser cladding is a useful technique to produce sound and hard surface layers. In this paper, it has been demonstrated in aluminium alloys. By adjusting powder injection parameters (composition of the mixture, feeding rate...) and laser processing conditions (power, scanning rate, defocusing distance...), a sound coating is achieved. As a small amount of the substrate is also melted, a good metallurgical bonding is produced, without any deleterious dilution effect.

Al-Cu-Fe base alloys (QC) are achieved ; their main features are as follows :

- thickness of the cladding can be up to 1 mm thick, in a single pass,
- microstructure is mainly dendritic ; both crystalline phases (Al_5Fe_2 and $\text{Al}_{13}\text{Fe}_4$, with dissolved copper) and quasicrystalline phases are observed ; this last type of component is found mainly in the interdendritic zones.

The influence of this protective and hard layer on the mechanical and tribological properties of the sample is now in progress.

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