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Microstructure modifications induced by a laser surface treatment in an AA7449 aluminium alloy

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ABSTRACT

This work investigates the modification of the precipitate microstructure induced by laser surface treatments in an AA7449 aluminium alloy in T7651 temper. Microhardness maps in the cross-section below the laser lines, as well as maps of the precipitate size and volume fraction obtained by Small-Angle X-ray Scattering, show that a significant precipitate dissolution and coarsening has been induced by the laser treatment. Integrated modelling is carried out to quantify this effect, including a thermal finite element model, a size class precipitation model and a precipitation hardening model. The precipitation model is calibrated using separate reversion experiments, and then coupled to the thermal and mechanical models, allowing a quantitative description of the modification of the microstructure.

1. Introduction

Laser surface treatments for aluminium alloys have experienced extensive development in the past 10 years, aiming at modifying the shape and properties of aluminium components, particularly in the aerospace industry. Three types of laser treatments have emerged as practically viable. The first is Laser Shock Peening (LSP), sometimes simply called Laser Peening [1–8]. It consists of sending very short athermal laser pulses (a few tens of ns) that induce a shock wave in the material and result in significant compressive surface internal stresses, which may notably improve the fatigue resistance of the alloys. The second is Laser Surface Melting, which aims at melting a small depth of the alloy (typically 10–300 μm) in order to obtain a solute-rich microstructure and improve the stress corrosion cracking performance of the material [9,10].

A third technique, which has received less attention, is Laser Beam Forming, which uses the laser operation as a tool for modifying the component shape, by the plastic flow that follows the non-uniform thermal dilatation of the material [11–15]. Such treatments, where the material stays in the solid state, provide an attractive solution for correcting the distortion of aerospace components, which is often found in thin walls after machining of thick plates, due to the presence of quench induced internal stresses [16].

Laser Beam Forming (LBF) is a complex process, where the shape modification of the alloy is the result of highly inhomogeneous, non-isothermal temperature paths, and depends in detail on the thermo-mechanical response of the material in a wide range of temperatures and strain rates. The temperature field induced by such laser treatments has been modelled by Hu and co-workers [13] and Ji and Wu [11]. More recently, Labeas [15] has included the mechanical response of the material to reach a thermo-mechanical description of the process. However there is little evaluation in the literature of the effect that this laser treatment may have on the alloy's fine scale microstructure, and on the related in-use properties. Chan and Liang [12] and Geiger and co-workers [14] have reviewed the influence of LBF on microstructure in aluminium alloys of the 6000 series (AA6013 and AA6082). They indicate changes in dislocation density, grain structure, and precipitate structure. No study is available on the microstructure modifications in 7000 series aluminium alloys, although they are direct potential candidates for part distortion correction in aerospace components.

High strength 7000 series aluminium alloys gain their mechanical properties essentially by precipitation hardening [17]. It is known that the precipitates present in peak strength tempers of these alloys are very sensitive to a sudden heat input, which can be for instance met in MIG welding [18], friction stir welding [19] or electron beam welding [20]. Due to the sudden increase of tempera-

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ture, precipitates can either be dissolved or experience coarsening, and this can be adequately described by appropriate modelling of non-isothermal precipitation kinetics [21].

Characterising the evolution of the nanoscale precipitation state during non isothermal, non homogeneous heat treatments requires the use of tools which make it possible to perform microstructure mapping, and which can be performed in situ during customised heat treatments. Small-Angle X-ray Scattering (SAXS), particularly when performed with a synchrotron source, is a characterisation technique compatible with these requirements [22]. It provides a quantitative measure of precipitate size and volume fraction, can be applied to microstructure mapping with a spatial resolution typically in the range of 200 μm, and can be performed during rapid non isothermal temperature paths.

The aim of the present paper is first to provide a quantitative assessment by SAXS of the microstructure changes and related microhardness distribution due to laser treatments performed on plates of the high strength AA7449 alloy in the T7651 temper. In order to make the problem simpler, the laser treatments will be performed on relatively thick plates (5 mm), in order to minimise the sample deformation and therefore to study mainly the thermal processes related to the laser treatment.

Secondly, SAXS measurements carried out during reversion experiments (rapid heating of the alloy to a prescribed temperature) will be performed in situ to assess the material response to sudden temperature changes. A combined thermal and microstructure model will then be used to predict the microstructure after the laser treatment. The model parameters will be adjusted to the reversion treatments and then applied on the temperature fields predicted by the thermal model. A simple model for precipitation hardening will then be applied to the predicted microstructure maps and compared to the experimental hardness maps.

2. Materials and experimental methods

The studied material is an AA7449 alloy, a wrought aluminium alloy of the Al–Zn–Mg–(Cu) family. The specific composition of the received plate, provided by Alcan – Centre de Recherches de Voreppe (France), was 8.3% zinc, 2.2% magnesium and 1.9% copper (all in wt%). The as-received temper was T7651, i.e. pre-strained and over-aged. The industrial ageing treatment consists in a water quench from the solution treatment temperature, a plastic deformation of about 2%, a few days of natural ageing, and a two step ageing treatment: 6 h at 120 °C and 10 h at 160 °C.

The laser treatment was applied on the Long/Short Transverse plane of rolled plates of dimension 170 × 76 × 5 (mm). Five consecutive laser lines were performed with a diode pumped solid state Nd:YAG laser (λ = 1064 mm), as shown in Fig. 1, in order to investigate the effect of plate heating when repeating the process. At the end of the first four lines the laser was shut off for 10 s to allow for a distribution of the heat within the plate before proceeding with the subsequent line. The beam was defocused to a diameter of 5 mm, the beam power was 3000 W and the velocity of the beam was 10 mm/s. Within about 3 s after the last line was finished, the samples were kept in liquid nitrogen until further investigation to prevent any evolution of the microstructure.

Hardness maps were performed on mirror polished surfaces using a semi-automatic micro-indenter with a weight of 100 g. Hardness line-scans across the lines on the plate surface (slightly polished) gave access to the properties of the outermost surface, while cross-section maps gave access to the in-depth hardness evolution.

Mapping of the precipitate microstructure in the laser treated material was achieved using Small-Angle X-ray Scattering. Slices parallel to the plate surface and of thickness 100 μm were prepared by cutting and mechanical polishing. Line scans were then performed on these slices across the laser line while recording the SAXS images with a CCD camera. X-ray measurements were performed on the D2AM/BM02 beamline of the European Synchrotron Radiation facility (ESRF), at a wavelength of 1.3 Å. The accessible range of scattering vectors was [0.007–0.4] $Å^{-1}$, and the beam diameter was 200 μm. CCD camera data was corrected for read-out noise, distortion, flat-field, background noise. It was normalised using a reference sample and transmission measurements through calibrated filters.

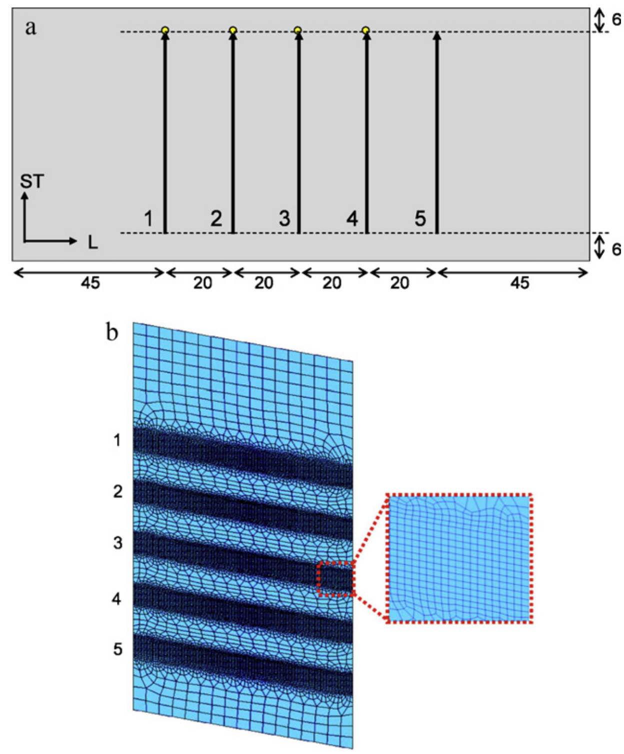

Fig. 1. (a) Scheme of the 5 laser lines realised on the AA7449 plates (units are in mm); the circles indicate a pause of 10 s to distribute the heat within the plate before proceeding. (b) Scheme of the FE mesh for thermal modelling.

Reversion experiments were also carried out while measuring in situ the SAXS images. Samples of originally T7651 temper material were inserted in a rapid heating furnace and heated in the range of 200–400 °C with a heating rate of 10 °C s^{-1}. SAXS recordings were made every 5 s during these heat treatments.

3. Results: hardness maps

Fig. 2 shows the hardness maps realised on the lines #1, 3 and 5. Fig. 3 shows in more detail the hardness profiles for the same lines. The "top" labelled line was measured on the plate surface after slight mechanical polishing. The other lines were measured on the plate cross-section.

From these measurements, the heat-affected zone, as defined by the zone where the hardness is affected as compared to the base material, can be evaluated to approximately 4–5 mm wide, namely comparable to the beam size. It is approximately 500 μm deep. In this HAZ, the hardness drops by up to 65 HV. The hardness drop is monotonous as a function of the distance with respect to the beam centre.

The three lines show qualitatively the same behaviour. However, one can observe that when going from the 1st line to the line #5, the minimum drop in hardness is slightly more pronounced.