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Application of massive laser shock processing for improvement of mechanical and tribological properties

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ABSTRACT

The present paper aims to investigate topographical, microstructural, mechanical and tribological behaviour of precipitation hardened Al alloy subjected to massive laser shock processing (LSP) without protective coating at 2500 pulses/cm^2, using three beam diameters. Wear tests under dry sliding conditions resulted in severe wear, whereas the main wear mechanisms were adhesion accompanied by abrasive wear. Nevertheless, LSP with optimal processing parameters reduce the friction coefficient and wear rate with lower degrees of adhesion and abrasion inside the wear track in comparison to the untreated sample. The enhanced tribological performance is attributed to the positive influence of LSP induced surface topography, surface compressive residual stresses (RS) and dense dislocation arrangements, as the result of high-pressure shock waves. Nonetheless, due to the narrow window of optimal parameters reduced wear resistance as a consequence of undesired thermal/softening effect due to laser ablation and melting was detected with non-optimal processing parameters.

1. Introduction

Despite the fact that laser processing technologies belong to a green manufacturing branch and that aluminium and its alloys are the third most commonly used commercial engineering materials, a constant demand towards higher efficient surfaces, lower and cleaner production costs with lower waste gas emissions remains. Among the products within the 6xxx series aluminium alloys, AA6082 is regarded as a high (medium-high) strength alloy, which contains high numbers of intermetallic second-phase particles, ranging up to 10 μm, i.e. spherical α-$Al_{12}(Fe, Mn)_3Si$, β-Al_5FeSi, and β-Mg_2Si in the form of plates or cubes [1]. However, the predominant nano-precipitate in the peak-aged condition contributing the most to the increase in material hardness and strength is the β″ phase (Mg_5Si_6) [2]. Nevertheless, despite the fact that the age hardenability of Al–Mg–Si alloys is high due to excess amounts of silicon and magnesium, which enhances the precipitation kinetics during heat treatment, the major disadvantage is insufficient wear resistance [3].

According to Sánchez-Santana et al. [4] wear can be regarded (along with fatigue and corrosion) as one of the three most common problems found in industry, leading to the replacement of industrial parts and components, due to reduced operating efficiency, increased loss of power, oil consumption, etc. Ductile materials, such as aluminium alloys under dry sliding conditions, usually experience severe wear; however, it is far from clear which aluminium alloy would offer the best wear resistance [5]. In fact, as Ghazali et al. [6] suggested, it is not clear if the wear resistance scales with the starting hardness of the alloy, which would suggest that a precipitation-hardened matrix would be optimum, or whether it is the work-hardening characteristics that are more important.

Over the previous two decades, laser shock processing (LSP) has been recognized as an advanced, effective, fast emerging severe plastic deformation (SPD) technology, which has been successfully applied to various materials to impart compressive residual stresses, various high-density dislocation configurations, grain refinement, improved fatigue, corrosion and wear resistance [7–14]. Authors [7,10] have confirmed nanocrystalline structures with refined grains, dense dislocation walls and dislocation cells in the material surface as a consequence of laser-induced shock waves propagating into material. Moreover, it has been shown [11] that LSP with a sacrificial protective layer is a reliable and precise surface texturing technique for the fabrication of surface microdents, which may act as lubricant reservoirs to reduce friction and wear in contact applications. Kumar et al. [12] have also confirmed that LSP with optimized laser fluence can improve wear resistance by as

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much as 91% compared to an untreated sample. On the contrary, Hatamleh et al. [14] reported only marginal improvement in wear of laser shock processed stir-welded 2195 Al alloy.

LSP also possess important environmental benefit over conventional SP process, with lower material/energy consumption during the peening process, with as much as 55% lower environmental impacts [15]. Moreover, it was pointed out that LSP has close-to-zero particulate emissions, hence greatly improves the indoor air quality and, thus reduces occupational health risks. However, the same authors argued that with the 'coated' LSP regime the consumption of protective opaque, i.e. aluminium foil present the dominant contributor of energy and material losses across all impact categories.

It should be noted that, according to the availability of different laser sources providing different pulse times and different laser energy over different treatment areas, two main processing regimes for LSP treatments exist, which can be applied either with or without an ablative/protective layer [10]. In the so-called 'high energy + long pulse' regime, pulsed lasers with energy in excess of several tens of joules and interaction times of up to several tens of ns, deliver their energy to broad surface areas (in excess of 10 mm^2). In such way, high thermo-mechanical impulse able to originate the desired residual stress fields on a single pulse-by-pulse basis is provided. This approach demands an additional protective/sacrificial overlay (paint, metallic tape, etc.) at the interaction zone prior to the laser application. The absorbing protective coating enhances the laser radiation absorption and, in turn, prevents thermal effects caused by the relatively long time of contact between the plasma and the treated material.

In contrast to the coated LSP regime, the so-called 'low energy + short pulse' regime was developed in 1995 for nuclear power plants, since the process requires neither surface preparation under radiation environment, nor drainage of water in a reactor vessel [16,17]. In this regime, pulsed lasers with interaction times in the range of several ns and with only mJ-J of energy are applied to smaller surface areas in order to maintain the required threshold energy for the LSP effect. In this case, large areas are covered by a controlled pulse overlapping strategy. At each location of pulse incidence, the effect of pulse overlapping can produce a deep (around or over 1 mm) field of compressive residual stress with very good degree of uniformity and control [18]. In this case (with a comparatively short pulse interaction time), the resulting mechanical and thermal waves applied to the treated material are temporarily uncoupled. With the mechanical wave being applied faster, the residual effects of the subsequent thermal wave are comparatively very small and limited to a narrow zone close to the material's external surface. Hence, the effect of shock waves prevails, producing compressive residual stresses [19].

This is an important feature to be taken into account as it is possible to eliminate the coating layer used in the 'high-energy' approach without any appreciable loss of final surface quality. Moreover, a quality factor due to the stress state uniformity in the component being treated can be provided. Further, protective overlay is a time-consuming affair and it must be applied at the interaction zone prior to the application to prevent the surface from being damaged by the high power laser irradiation. Also, the overlay becomes damaged severely during the LSP process, requiring frequent replacement hence making it slow, less efficient and expensive in industrial applications [20]. It should be noted that the handling system with the low energy, uncoated LSP process to access the target component is simpler, since there is no reactive force against laser irradiation, which has confirmed this process to be very practical not only in nuclear facilities, but also in other harsh environments necessitating full-remote operation [19]. In view of this, low energy, short pulse, laser shock processing without protective coating controlled by a predefined massive pulse overlapping strategy can be regarded as a very promising, cost-effective and cleaner surface treatment technology.

With this in mind and since there are limited reports on the possible detrimental effect of non-optimal LSP process parameters on wear behaviour, the present work describes the investigation of possible improvements of the surface morphology and tribological behaviour of Al 6082 alloy by massive, uncoated low energy LSP with 2500 pulses/cm^2, using three beam diameters, i.e. three laser intensities. Tribological behaviour was evaluated using a ball-on-disc tribometer and the wear tracks characterized using a scanning electron microscope (SEM). In addition, the influence of laser shock processing on the surface morphology was characterized using a 3D confocal laser scanning microscope (CLSM) and transmission electron microscope (TEM), whereas the mechanical state was evaluated by microhardness and residual stress by XRD and hole-drilling measurements.

2. Experimental design

2.1. Material and sample preparation

Test samples were sectioned from a 10 mm thick rolled plate of 6082 Al alloy, using a water jet process. The chemical composition (in wt%) of the material used in this study was 0.87 Si, 0.72 Mg, 0.42 Mn, 0.35 Fe, 0.15 minor elements (Cu, Cr, Ni, Zn, Ti) and Al the rest. The overall heat treatment procedure, T651 (homogenization, solution treatment, aging, etc.), including the subsequent LSP is schematically presented in Fig. 1.

SEM/EDS line analysis (Fig. 2) confirmed the basic Al matrix with fine distribution of intermetallic phases. Results of our previous research [10] confirmed various intermetallic particles in these alloys, i.e. smaller β-Mg_2Si precipitates in the form of plates or cubes and larger α-$Al_{12}(Fe,Mn)_3Si$ intermetallic dispersoids, which are in the length of ~4 µm.

Prior to LSP, no additional machining of the samples was carried out. In order to ensure surface uniformity and proper laser laser-beam interactions with the sample surface all samples were thoroughly degreased with acetone and rinsed with de-ionised water, before performing laser processing.

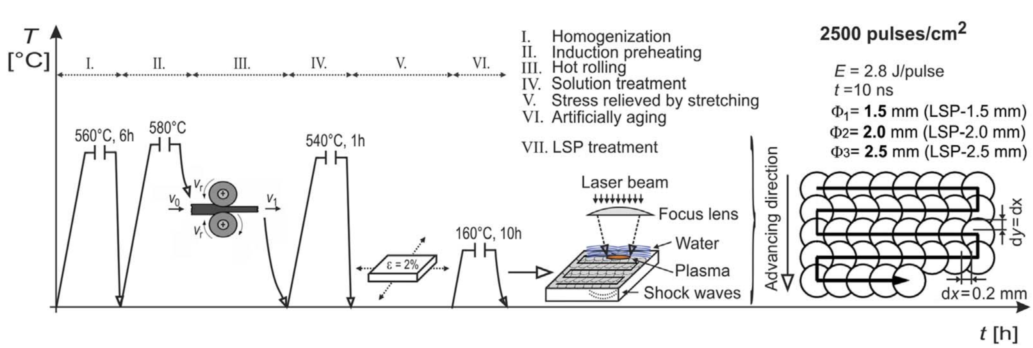

Fig. 1. Schematic presentation of the overall heat treatment and subsequent LSP treatment.