CIRP Annals - Manufacturing Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

A study on the influence of surface laser texturing on the adhesive strength of bonded joints in aluminium alloys

L. Romoli (2)[a,*], F. Moroni[a], M.M.A. Khan[b]

[a] *Department of Industrial Engineering, University of Parma, Italy*
[b] *Department of Industrial and Production Engineering, Shahjalal University of Science and Technology, Bangladesh*

ARTICLE INFO

Keywords:
Laser
Surface modification
Adhesive bonding

ABSTRACT

The influence of ns-pulsed laser ablation on the adhesive strength of bonded joints was studied under conservative conditions by tensile stress tests on cylindrical specimens of aluminium alloy. Surface textures were produced by hatching the cross section with concentric grooves and varying the average laser power at fixed repetition rate, the scan speed and the radial hatch distance.

Despite a range of surface activation in which the adhesive strength increases step-wise of about 25% with respect to the non-treated material, the effect of too high roughness values resulted in a decay of the joint strength. Air entrapment into the ablated grooves fixed a limit to the energy density that could be delivered to the surface, establishing an optimal technology range.

1. Introduction

In adhesive bonding the adhesive transmits the load across the joint, therefore its strength depends at first on the mechanical and the chemical properties of adherend and adhesive material. Nevertheless a major role is played by the bonding area as an interface that transfers the load from the adherend to the adhesive. Apart from surface pretreatment to remove all contaminants from the bonding area, changing surface roughness was found to be a keypoint to enhance the quality of an adhesively bonded joint [1]. An increase in surface contact area, coupled with the mechanical locking of the adhesive between micro-asperities, improves the bond strength by shifting the weak point from the interface (i.e. adhesive strength) to the adhesive itself (i.e. cohesive strength) [2]. This approach may also result in favourable modifications of the surface chemistry with a consequent improvement in wettability of adherend/adhesive interface and chemical bonding of the polymer molecules of the adhesive with the metal oxide or other surface layers of the adherend [3].

Several techniques to improve the surface area have been examined in the past, including etching, pitting, blasting with hard particles, and generation of porous surface structures by combination of chemical and physical techniques [4]. Among available techniques, there is a growing amount of published work which testifies the potential of laser irradiation to improve the bonding strength of adhesive joints. Similarly to what was already experienced in the laser texturing of cutting tools [5], lasers can be used to manufacture specifically designed patterns on the contact area in order to improve its adhesive functionalities. The generation of micro-column arrays by laser ablation with high energy pulses at low repetition rate [6] can nowadays find a high throughput upscaling by ns-pulsed fibre lasers [7]. Moreover ns-pulses surface treatment has demonstrated to be an effective technique to improve the cleaning action of the substrate surface and its wettability [8]. The formation of hydrophilic oxide layers may improve the surface wettability to the adhesive with a consequent more favourable disposition into the deepest points of the roughness.

It is worth noting that in addition to the many variables of the laser texturing of the bonding area and of the adhesive bonding process itself, the final strength of the joint also depends on the loading conditions (e.g. tensile, peeling, shear). The orientation of the ablated pattern may have an influence in preventing or delaying cracks propagation while the total roughness of the pattern impacts on the sensitivity of the adhesive to small notch radii. For all the reasons depicted above, a clear technical relationship between adhesive bond strength and surface roughness is not yet available and could be a matter of interest in many industrial sectors and especially in the joining of aluminium alloys for aerospace applications.

The main objective of this study is to investigate the effect of varying surface roughness for aluminium alloy adherends on the adhesive tensile bond strength. Controlling laser parameters may be used to produce textures on the bonding area showing different roughness and peak-to-valley distance and to verify whether the benefits related to the increase of the surface contact area, underlined by the above mentioned literature, increase with increasing the roughness. This is extremely challenging from a

---

[*] Corresponding author.
E-mail address: luca.romoli@unipr.it (L. Romoli).

http://dx.doi.org/10.1016/j.cirp.2017.04.123
0007-8506/© 2017 Published by Elsevier Ltd on behalf of CIRP.

Please cite this article in press as: Romoli L, et al. A study on the influence of surface laser texturing on the adhesive strength of bonded joints in aluminium alloys. CIRP Annals - Manufacturing Technology (2017), http://dx.doi.org/10.1016/j.cirp.2017.04.123

manufacturing point of view since it implies finding a correlation between roughness and laser parameters. Then the optimized condition can be used to produce a tailor-modulated roughness to be exploited for the adhesive bonding process over large areas.

2. Experimental set-up

2.1. Specimens and testing method

Butt joints loaded in tension are commonly used for determining the tensile strength of an adhesive bond system following a conservative approach [9]. In this work aluminium alloy substrates (AA 6082—T4) are bonded together with a two-component epoxy adhesive (Loctite Hysol 9466). The butt joint test is commonly regulated by ASTMD897 [10]. For this kind of test three requirements are essential in order to obtain reliable results: (i) the adhesive thickness should be controlled and kept constant among all the tested specimens; (ii) the two substrates should be, as much as possible, concentric to each other; (iii) the load should be applied axisymmetrically and perpendicular to the bondline. In order to accomplish these targets, an “easy to build” joint was designed as shown in Fig. 1: the axial alignment and the adhesive layer thickness (set to 0.3 mm) were controlled by reference surfaces located in the middle of the specimen. The adhesive layer, therefore, cannot correspond to the entire circular section of the bar, but it consisted of a hollow circular section. A Teflon (PTFE) spacer was placed between the two substrates in order to seal the bonded area. The through hole is required to clamp the specimen during the adhesive polymerization, while the threaded hole was used for the load application. The specimen was connected to the testing machine by means of spherical joints to cope to requirement (iii).

After machining, the two substrates were rinsed with water and soap to roughly remove residuals of machining. When completely dry, the laser surface treatment was performed and within the next hour the adhesive was applied on both the substrates assembled to produce the specimen. The adhesive was cured in oven for 1 h at 80 °C. The specimens were tested using an Instron 4400 electromechanical testing machine equipped with a 30 kN load cell. The test was carried out in displacement control and the crosshead speed was set to 1 mm/min.

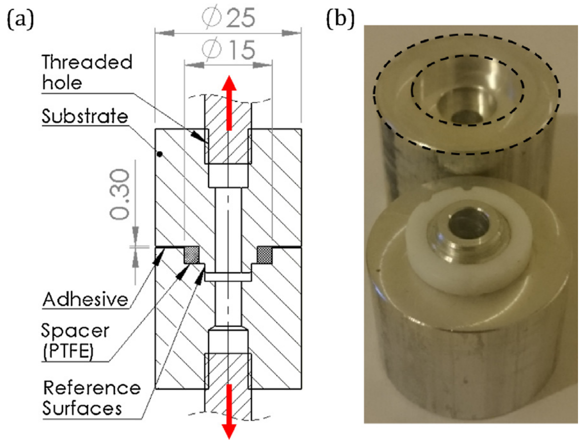

Fig. 1. Panel (a) specimen geometry; panel (b) photo of an adherend textured surface: the dashed line identifies the adhesive bond area.

2.2. Laser texturing and surface characterization

The laser system used in this study consisted of a Nd:YVO_4 laser (λ = 1064 nm), a high precision z-axis positioning system for focus adjustment, and a x–y galvo-mirror scanner. A fixed repetition rate of 20 kHz was used which allowed 5 ns pulses with an associated energy of 0.9 mJ and a measured maximum average power of 18 W. The laser beam was circularly polarized by an adjustable quarter wave plate to avoid unevenness during the change of direction. The beam was focused on the specimen surface to a minimum spot diameter $ø_{spot}$ = 35 μm, with a nearly Gaussian energy distribution.

Each experiment was conducted by performing the laser ablation over the annulus areas of the specimens with a scan strategy consisting of concentric grooves and repeated three times. Surface patterns were obtained by varying, the average laser power (P = 12–18 W) and the tangential scan speed (V = 100–1000 mm/s) and only in a second moment by changing the distance between two adjacent grooves, defined as the hatch distance (H = 0.035–0.200 mm). Considering the pulse overlap at 20 kHz, the ablation process generated by a moving beam can be approached using the concept of Energy Density *ED* expressed in J/mm^2 and defined as the ratio between P and the product of V and the spot diameter [11]. The variation of P and V reported above and the constant $ø_{spot}$, resulted in *ED* in the range of 0.343–6.912 J/mm^2.

The ablated surfaces were characterized using a Taylor Hobson 3D optical profiler having a resolution of 340 nm on the xy-plane and 1 nm on the z-axis. Average surface roughness and surface skewness (S_a and S_{sk}, ISO 25178-2) were derived from the morphology maps. SEM analysis was also undertaken to investigate the textures and the adhesive fractured surfaces.

3. Results and discussion

3.1. Influence of energy density

With the objective to separate the effects of *ED* and H on S_a, a preliminary experimental phase was dedicated to the characterization of single groove width W at the increasing of *ED*. Beyond 2.5 J/mm^2, W reached an asymptotic limit of 0.07 mm and any further increase in *ED* resulted in an increase of groove depth D. In view of shortening process time by a reduced number of concentric grooves it was decided to fix the hatch distance at 0.075 to study the effects of laser parameters.

Fig. 2 illustrates the change in S_a with *ED* input: it is evident that S_a increased almost linearly with *ED* up to a certain level of 3.896 J/mm^2 (Fig. 3 panel b).

Beyond this level it decreased steadily because of the higher *ED* input that caused localized softening of the bulk material and flattening of the crests with a consequent reduction in the peak-to-valley distance over a less uniform pattern (Fig. 3 panel c). All the ablated surfaces showed superhydrophilic behaviour.

Fig. 4 exhibits the variation of the adhesive bond joint strength F with *ED*: surface activation was a step-like process reaching its maximum suddenly at *ED* = 0.438 J/mm^2. Joint strength was potentiated up to 16 kN and failed due to cohesive failure.

This meant an increase of more than 30% with respect to the reference obtainable by the non treated surface, failing due to an interface detachment. Then F showed a U-shaped relation with *ED* having a minimum at the same point in which S_a showed its

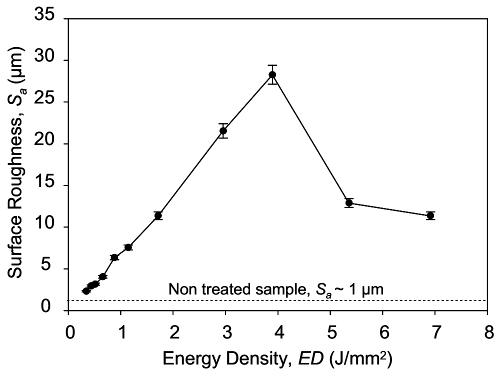

Fig. 2. S_a as a function of *ED* at H = 0.075 mm. Mean values reported with the error bars evaluated on the basis of repeated measurements on the three different specimens.

Please cite this article in press as: Romoli L, et al. A study on the influence of surface laser texturing on the adhesive strength of bonded joints in aluminium alloys. CIRP Annals - Manufacturing Technology (2017), http://dx.doi.org/10.1016/j.cirp.2017.04.123