Materials and Design 160 (2018) 313–324

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Crystal plasticity in fusion zone of a hybrid laser welded Al alloys joint: From nanoscale to macroscale

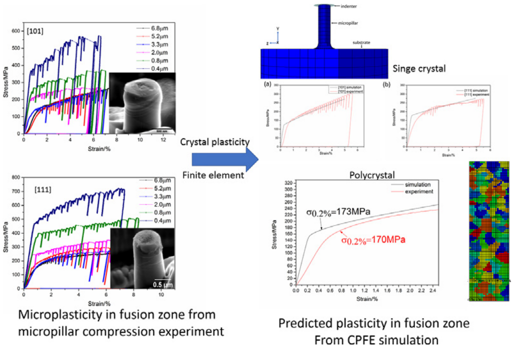
Shaohua Yan [a,b], Haiyang Zhou [a], Bobin Xing [b], Shuang Zhang [b], Li Li [c], Qing H. Qin [a,b,*]

[a] *College of Civil Engineering, Shenzhen University, Shenzhen 518060, Guangdong, China*
[b] *Research School of Engineering, College of Engineering and Computer Science, The Australian National University, ACT 2601, Australia*
[c] *Australia National Fabrication Facility, Research School of Physics and Engineering, The Australian National University, ACT 2601, Australia*

HIGHLIGHTS

- Nano/microplasticity in fusion zone from our experiments can be used to predict the macro-plasticity of the joint.
- The nano/microplasticity in fusion zone depends significantly on sample's size.
- Nano/microplasticity is affected by orientation whose influence deceases in larger samples.
- Numerical models are constructed and used to assess the size and orientation effect.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 20 August 2018
Received in revised form 7 September 2018
Accepted 14 September 2018
Available online 15 September 2018

Keywords:
Size effect
Nano/micropillar compression
Crystal plasticity
Multiscale study
Hybrid laser welding

ABSTRACT

In this paper, we propose a novel approach to predict the plasticity of hybrid laser welded Al alloys joints based on the microplasticity obtained from the micropillar compression test. The micropillar test was performed on the single-crystal pillar with three orientations and various diameters (400 nm to 6.8 μm). It was found that independent of orientation, the yield strength of the pillar increased with the decrease of diameter below a critical length (3.3 μm). A numerical model was successfully built and used to explain the size effect on the pillar's strength. Crystalline orientation did affect the yield strength, the orientation having higher Schmid's factor showing lower yield strength, but the effect was reduced with the enlarged diameter. The macroscale yield strength achieved from crystal plasticity finite element simulation showed was found to have a good agreement with that from the experiment. The results here shed new insights both on the application of the micropillar study of alloys, and on prediction of strength in welded Al alloys joint.

1. Introduction

Hybrid laser welding is increasingly used in joining structures of aluminium alloys, since this welding method has advantages of deep welding penetration, stable welding process, and high welding speed. Because of the quick thermal cycles, the microstructure in the welded joint is often heterogenous. More specifically, fusion zone (FZ) is filled with coarse microstructures (precipitates and grain size) and lack of alloying elements (Mg and Zn) [1–3], while heat affected zone (HAZ) is made of coarsened or dissolved precipitates. The direct outcome of such diverse microstructures is the heterogenous spatial distribution of mechanical properties across the welded joint. Despite the fact that the weakest part of the joint is dependent on several factors (such as

---

* Corresponding author.
E-mail address: qinghua.qin@anu.edu.au (Q.H. Qin).

https://doi.org/10.1016/j.matdes.2018.09.031

filling materials and base metal), the results from existing literatures [1–10] showed that most of the joints are broken in FZ under tensile test, which indicates that the weakest part of the hybrid laser welded Al alloys joint is in FZ. As suggested by Puydt et al. [11], the weakest part of the welded joint would withstand almost all the strains under external loading while other parts remain elastic. Thus, to some extent, the mechanical behaviour of welded joint rest with that of FZ [11], especially at the early-stage plasticity. Thus, knowledge of the plasticity in FZ is crucial to accurately predict the mechanical properties of the hybrid laser welded joint.

To examine and predict the plasticity in FZ, the micro-tensile tests and integrated modelling have been developed [12]. The micro-tensile test sample, with dimensions actually in mm scale, was taken from FZ along the thickness direction and then subjected to tensile tests [11]. Afterwards, integrated modelling was used to predict the mechanical properties of the welded joint based on the macro stress-strain curves. The integrated model was made of several sub-models [12]: a thermal model, a precipitation model, a yield strength and strain hardening model, and a finite element model of a transverse tensile test coupled with a damage model. However, there are several limitations for integrated modelling to apply to the hybrid laser welded Al alloys joint: (a) It is difficult to accurately model the hybrid laser welding due to the complex interaction of laser-arc and laser-materials etc. [13], causing the difficulty to precisely predict the microstructure formed during welding. As a result, the accuracy of this model is not reliable for the hybrid laser welding process. (b) Micro-tensile testing method is based on the macro stress-strain curves as the input, but the information of how the microstructure reacting to the external loading at the grain/micro scale is unknown. (c) The industrial polycrystalline materials usually have crystalline textures, thus show anisotropic mechanical properties, but such model does not tackle this.

Therefore, a new method is needed to accurately and effectively predict the plasticity of FZ in a hybrid laser welded Al alloys joint. Unlike the conventional finite elements [14–16], the crystal plasticity finite element (CPFE) simulation can precisely describe the anisotropic mechanical behaviour of single-crystalline and polycrystalline samples [17]. For instance, Zhang et al. [18] used CPFE to successfully predict the anisotropic yield behaviour of the polycrystalline materials. Pinna et al. [19] employed CPFE model accurately predicting the crystal texture and grain structure in FCC metal under elasto-plastic deformation. These cases prove that CPFE model can give accurate prediction of the plastic deformation of the metal.

The accuracy of the CPFE model is based on the mechanical-deformation data of a single crystal (SC), which determines the material-property parameters used in CPFE simulation. Currently, most of the mechanical experiments for the welded joint have been done using polycrystalline samples, causing difficulty to determine the mechanical properties of SC as the stress in the grains differs from each other [20,21]. One direct way to get the mechanical deformation of SC is to deform a macro SC sample using compressive or tensile test [22,23]. This is mainly applicable for pure metals that can be grown into a macro SC. For alloys, the SC sample may be obtained by Bridgman technique [20]. Nevertheless, the grain size in FZ is only a few tens of micrometres [24] because of the quick solidification process. Such small grains in FZ make it impossible to get mechanical properties of SC utilizing macroscopic testing methods.

Combination of focused ion beam (FIB) milling and nanoindentation [25] provides a way to explore the plastic deformation of a SC sample at submicron/micron scales that is made from bulk polycrystal. In the last decades, extensive efforts have been given to understand the mechanical response of materials in submicron/micron region (see Ref. [26]). The mechanical properties of SC, such as the yield stress, elastic modulus, could be obtained via such advanced testing method. It should be noted that the flow strength of SC depends on the sample's size at micro/submicron scales, known as “smaller is stronger”. Several theories have been proposed to understand this size effect. For nanoscale, the dislocation starvation [27] is applicable, while other models (such as source exhaustion [28], source truncation [29], and weakest link theory [30]) have been used to explain the size effect in the micron region. Although there is a clear size effect in the pure SC of metal, the role of the internal microstructure (such as alloying, precipitation) in the plastic deformation at micro scale is still not well understood. Some researchers reported that the size-dependent strength is still effective for alloys (e.g., FeCrMnNi high entropy alloy [31], austenitic-ferritic stainless steel [32], and aluminium alloys [33,34]), although the size effect is much weaker compared to that of the pure metallic SC. There are also literatures [35,36] arguing that no size effect exists on the strength in the alloying metallic systems. These researches imply that the strength at micro/submicron scale is determined not only by the sample's size but also by the internal microstructure.

The FZ contains aluminium alloys with solute and precipitation strengthening. So, questions are: how would SC with different orientations in FZ perform under uniaxial compressive loading? Does size effect still work? How could we get the mechanical properties (i.e., yield stress) related to the bulk polycrystal sample from the small-scale experiment? How could we accurately predict the mechanical response of the welded joint using CPFE model based on the information obtained at submicron/micro scales? To answer these questions, we conducted micro-compression on pillars with the diameter from 0.4 μm to 6.8 μm with three orientations, [101], [111] and [−301], in FZ. The deformed microstructure is examined through scanning electron microscope (SEM) and transmission electron microscope (TEM). Theoretical modelling and molecular dynamic simulation are used for the explanation of the size and orientation effect in FZ. Finally, CPFE simulation based on the results of micro-compression test is employed to accurately predict the mechanical properties of the hybrid laser welded Al alloy joint. To our knowledge, this is the first time that the microplasticity in FZ has been studied. And this research sheds new insights both on the application of the micropillar study on alloys, and prediction of strength in welded Al alloys joint.

2. Experimental and simulation methods

2.1. Experimental methods

AA6061 aluminium alloys were joined using hybrid laser-MIG welding system, more details about the welding process can be found in Ref. [24]. A rectangular block was cut from the centre of FZ and mounted by resin. The sample was then metallurgically grinded and polished with the last step that was finished by 0.02 μm colloidal silica to remove the deformed layer on the sample's surface. The microstructure of the sample was observed using Zeiss Ultraplus Field Emission Scanning Electron Microscope (FESEM). The chemical composition of the matrix was measured using energy dispersive spectroscopy (EDS). The results of the SEM observation can be found in Fig. S1 in the Supplementary materials. TEM experiment was performed at JEOL 2100F microscope at the acceleration voltage of 200 KV to observe the microstructure of the bulk material and the deformed pillars. The TEM results for the bulk material can be found in Fig. S2 in the Supplementary materials. EBSD test was performed utilizing the same parameters as Ref. [24], and the results about the texture, dislocation density, and the grain size are shown in Fig. S3 in the Supplementary materials.

Cylindrical pillars were made through FIB using FEI Helios 600 Nanolab. All pillars were machined at 30 KV with currents ranging from 9 nA to 0.21 nA for coarse milling and 45 pA for fine polishing to minimize the Ga^+ damage on the surface of the pillar. The pillars' aspect ratios of height-to-diameter were kept between 3:1 and 4:1. To study the orientation effect on the strength, orientations of [101], [111] and [−301], were selected. Since the phases could be etched way during FIB milling, all pillars were made in the phase-free area, as shown in Fig. S1a. Thus, only the solid solution strengthening was considered in the pillar.