International Journal of Offshore and Polar Engineering
Vol. 14, No. 4, December 2004 (ISSN 1053-5381)

Grain Structures in Al-alloy Friction Stir Welds Observed by Stop-Action Technique

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ABSTRACT

Experiments have been carried out to freeze the friction stir welding (FSW) process by stopping the tool and immediately quenching the work piece in an Al-2195 alloy welded under typical conditions. This has allowed the grain structure development to be directly observed, as fresh material encounters the deformation field surrounding the rotating pin, by sectioning through the frozen weld keyhole with the tool in place. The mechanisms involved in forming the thermo-mechanically affected zone (TMAZ) and nugget structures are discussed as well as the influence of static annealing in the wake of the thermal field trailing the welding tool.

INTRODUCTION

Friction stir welding (FSW) is being increasingly used to weld Al-alloys because it results in welds with less distorted and superior, more reproducible, joint properties than can be obtained by fusion welding processes. With high-strength Al-alloys it also solves the problem of liquation cracking, which is inherent when fusion welding compositions with wide freezing ranges (Threadgill, 1999). In friction stir welding a rotating tool is plunged into the join line between 2 butted plates. The tool is then traversed under conditions where frictional heating is sufficient to locally raise the temperature of the material so that it can be plastically deformed. The plasticised metal is constrained by the colder surrounding material and between the tool shoulder and backing plate, and it is forced to flow around the tool forming a joint (Reynolds, 2000; Colligan, 1999). The material that flows around the tool undergoes extreme levels of plastic deformation, reaching effective strains in excess of $\varepsilon_{\text{eff}} \sim 40$ (Heurtier, 2002); this normally leads to a very fine 2–10-μm recrystallized grain structure being formed in the centre of the weld (Norman, 2000; Hassan, 2003a). This region of the weld is commonly referred to as the nugget zone and is part of the weld's thermo-mechanically affected zone (TMAZ). The surrounding material that constrains the nugget metal and is deformed by passage of the tool forms the remainder of the TMAZ, and experiences much lower plastic strains ($\varepsilon_{\text{eff}} \sim 0$–5) (Heurtier, 2002; Xu, 2003). The grains in this region are generally rotated and sheared by interaction with the tool. Very large strains are also experienced under the shoulder contact area, where fine grain structures similar to those in the nugget can be produced (Norman, 2000).

Received August 28, 2004; revised manuscript received by the editors October 22, 2004. The original version (prior to the final revised manuscript) was presented at the 14th International Offshore and Polar Engineering Conference (ISOPE-2004), Toulon, France, May 23–28, 2004.

KEY WORDS: Friction stir welding (FSW), thermo-mechanically affected zone (TMAZ), nugget zone, grain structure, dynamic recrystallization, aluminum alloys.

Due to its unusual ultra-fine grain structure, the nugget zone is an interesting feature of friction stir welds, and there has been some debate as to how it forms (e.g. Hassan, 2003b; Jata, 2000; Su, 2003; Bingert, 2003). The nugget zone can also contain flow features composed of concentric, or onion, rings that correspond in width to the incremental advance of the tool per revolution. The formation of these rings has been variously attributed to differences in grain size, particle density, and texture (Norman, 2000; Yan, 2003). The formation of the ultra-fine nugget grain structure has usually been attributed to "dynamic recrystallization" (Threadgill, 1999; Jata, 2000; Su, 2003; Bingert, 2003). However, dynamic recrystallization is generally rare in aluminum alloys, because recovery occurs rapidly at elevated temperatures in high stacking fault FCC metals, lowering the driving force for recrystallization (Humphreys, 1995). Several researchers have proposed that dynamic recrystallization in FSW may occur continuously by progressive subgrain rotation, which arises due to the enormous strains that occur in the nugget (e.g. Jata, 2000; Su; 2003; Bingert, 2003]). On the other hand, research on hot deformation has found that subgrain misorientations generally reach a steady state of only a few degrees at strains >2 (Humphreys, 1995; Blum, 1996; Barnett, 2002). Alternative mechanisms, such as geometric dynamic recrystallization (GDR), could also result in a similar fine-grain microstructure (Humphreys, 1995; McQueen, 1985; Gholinia, 2002a).

To date, all published results on the grain structures of FSW have been obtained from postmortem studies of completed welds. Recrystallization and recovery can occur very rapidly at elevated temperatures, and there is a considerable time lapse after the nugget material has been deformed until the weld has cooled. Thus the static annealing phenomenon cannot be ruled out and may have confused previous microstructural interpretation. For example, attempts to compare the grain sizes found in weld nuggets with those from torsion tests suggest that they are coarser than might be expected from the high strain rates found in FSW (Hassan, 2003a). Further, postmortem studies do not show how the grain structure develops as the material interacts with and flows around the tool.

In order to try to better understand the formation of the interesting grain structures seen in FSW, observations will be reported