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Micro-friction stir welding of titan zinc sheets

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Aim of this research is first to evaluate the applicability of micro-friction stir welding (μFSW) to wrought zinc alloy sheets and then to improve the structural integrity of such joints. μFSW tool design was based on an algorithm that considers material and process limitations. Joining trials were performed at different feed rates. It is proven that joining by μFSW thin ZnTiCu sheets is possible and it offers extremely fine microstructures and β-phase distribution due to the mechanical fragmentation which is the outcome of the stirring. The β-phase particles were homogenized and precipitated inside deformed zinc grains and not at the grain boundaries, where they used to be in fusion welds. Electron microscopy showed that its size was limited to 150 nm, which is in average 13 times smaller than the size of the 2 μm that they get when sheets are TIG welded. Macroscopically, the μFSW joint mechanical properties are comparable with industrially fusion-welded material. The relative low elongation achieved, similar to fusion-welded sheets, is explained by the occurrence of three main defects: root opening, thinning and kissing bond.

1. Introduction

Friction stir welding (FSW) is, a solid state joining technique, invented by The Welding Institute (TWI), United Kingdom in 1992 (Thomas et al., 1992). Although initially developed for Al-alloys, soon it was applied successfully to many other metals and materials, especially to metals hard to weld using the given fusion welding techniques.

In FSW frictional heat is generated between the wear-resistant welding tool shoulder and pin, and the material of the work-piece. The frictional heat and surrounding temperature cause the stirred materials to be softened and mixed avoiding their melting. Thus, the bonding is a solid state process. However, the grains are transformed and relocated. Material flow patterns under the shoulder are similar to the forging process, while these around the tool pin are like an extrusion process as stated by (Mishra and Ma, 2005). Weld quality is strongly affected by the tool geometry as shown in detail by Sued et al. (2014) and Groche et al. (2014).

Groche et al. (2014) in their review paper described in detail methods of joining by forming, among others FSW, which seems to be of paramount importance. In general, regarding the process, during FSW the rotational movement of a tool is overlapped by the feed speed. The tools are primarily machined from tool steels such as H13 and subsequently hardened. In research settings, these tools would typically exhibit little wear and would be considered practically non-consumable. The side aligning the directions of both speeds is called the advancing side, whereas the other side is called the retreating side. Plastic flow and frictional heating create a characteristic stir zone. Friction stir welded microstructures consist of four zones: the dynamically recrystallized zone (DXZ) or nugget, the thermo-mechanical affected zone (TMAZ) and the heat affected zone (HAZ). The DXZ or nugget is located where the pin is in contact with the base material. This zone is characterized by sufficient values of thermal and strain energy for recrystallization to occur leading to fine grains of equal size. The thermo-mechanically affected zone (TMAZ) is located at the side of the nugget, is affected by high strains and heat, but the energy provided is insufficient for a complete recrystallization. The heat affected zone (HAZ) consists of undeformed base metal and is thermally affected by the heat produced by the stirring of the tool.

As Groche et al. explicitly point out during FSW the material near the top of the work piece is stirred under by the threads and is deposited in the weld nugget, if fusion welding, melting and homogenization would take place. However, larger concentration differences can be found in the welding zone, with diffusion couples at the edge. The joining mechanism can be described as

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a combination of cold pressure welding, diffusion welding and mechanical alloying at the same time (Groche et al., 2014).

Defects in FSW might be of any orientation, size, or shape. Groche et al. describe and categorize very well the defects in FSW. Like arc welding, the process moves in a linear fashion, usually at a constant rate along the joint line, and therefore has a similar tendency to produce defects, which propagate for some length and have their major dimensions parallel to the travel direction. Defects are divided into inclusions, volumetric defects, and non-volumetric (laminar) defects. Flash is produced by displacement of material from the face (tool-side surface) of friction stir welded components. Root flaws are surface-breaking discontinuities that are present on the material surface which is opposite of the tool. The mechanical effect of a root defect is dependent primarily on its through-wall height and degree of bonding or width. Changes in root defect orientation also change mechanical properties. Especially in thin sheets root defect is detrimental for the joint's structural integrity.

According to Kim et al. (2006) the defects which occur during FSW can be caused by an overheating or insufficient heating of partial areas. Overheating can lead to the formation of an excess flash. Furthermore, the grain structure can be affected by exceeding a certain temperature value. Cavities can be formed due to an inadequate material flow, which can be caused by a disadvantageous rotational speed to travel speed of the tool.

Thus, from all the above it is clear that the FSW process can be influenced by the tool design, the travel speed and the rotational speed, the vertical pressure of the tool, the tilt angle of the tool and the material characteristics.

Mishra and Ma (2005) underline the difficulty of creating high integrity welds of aerospace aluminium alloys able to withstand high-strength and fatigue loads, not to crack due to the poor solidification microstructure and porosity in the fusion zone and the very significant loss in mechanical properties as compared to the base material. These aluminium alloys (e.g. highly alloyed 2XXX and 7XXX series) are generally classified as non-weldable as these factors make the joining of such alloys by conventional welding processes unattractive. It is known that some aluminium alloys can be resistance welded, but the surface preparation is expensive, with surface oxide being a major problem. Thus, FSW is an alternative joining process to fusion welding. It is a suitable joining technique for sheet metals to be welded by butt, lap or fillet joints. The rapid development of FSW in aluminium and its successful commercial implementation has motivated its application to other non-ferrous materials (Mg, Cu, Ti, as well as their composites), steel, dissimilar alloys/metals, and even thermoplastics. As many metals are welded using given fusion techniques, it is not only important to show the feasibility of FSW, but also to delineate its advantages over existing fusion techniques. Additionally, FSW gains potential engineering importance due to the absence of problems associated with conventional welding such as distortion, grain growth in the heat affected zone and porosity.

As previously stated a defining characteristic of FSW is that the joint is created by a non-consumed cylindrical rotating tool, mechanically traversed through the materials. The pin though that might be threaded or polished, can be consumed. Especially threaded pins are usually altered (polished) during processing as Gibson et al. (2014) describe in their review paper. Lorrain et al. (2010) state that material flows during FSW are very complex and not fully understood. Given the fact that most of the studies describe the use of threaded pins and that the initially threaded tools may become unthreaded due to tool wear (Gibson et al., 2014; Lorrain et al., 2010), the material flow becomes even more complex. Lorrain et al. have shown that the material flow with unthreaded pin undergoes the same features with classical threaded pins; material is deposited in the advancing side (AS) in the upper part of the weld and in the retreating side (RS) in the lower part of the weld; a rotating layer appears around the tool.

Nishihara and Nagasaka (2004) successfully adapted the FSW process to materials with thicknesses of 1000 μm or less. The authors named this modified technique micro-friction stir welding (μFSW). μFSW could be applied as well in thin walled structures, electrical, electronic and micro-mechanical assemblies.

Significant challenges related to tool design and critical procedure parameters are to be overcome when μFSW is applied. Different materials with various tool geometries and process parameters are to be tested before excellent joints with optimized conditions can exist. Teh et al. (2012) achieved homogeneous microstructure distribution after μFSW of thin aluminium sheets; even 180° bend was carried out without cracking. This technique could be appropriate for special welding uses requiring properties such as high flexural strength, ductility and durability, combined with smooth joint appearance.

Béré et al. (2000) indicated the importance of the c/a ratio in relation to formability. Zinc with its hexagonal close packed crystal structure and with lattice parameter c/a ratio 1.856, which is higher than the ideal 1.633, has a very limited formability, an important factor that needs to be taken into consideration when designing new techniques that involve high degree of deformation. FSW up to now has mostly been applied in easily deformable metals like aluminium and steel. But when materials with limited formability (such as metals with hexagonal crystal structure e.g. magnesium, zinc) are to be joined, literature and industrial experience are limited. Unfortunately, especially for welding of zinc alloys the available scientific literature, even with current fusion welding techniques, is very limited. Furthermore, FSW of zinc alloys has not been industrially applied yet and experimental results are not published (if available).

Copper (Cu) and titanium (Ti) are the main alloying elements in the ZnTiCu alloy, from which rolled zinc obtains its desired mechanical properties. Their chemical composition is defined by the standard EN 988:1997. ZnTiCu alloy contains usually 0.06–0.20% Ti. Titanium has very little solubility in Zn (0.02%), and it also reacts with Zn and forms a hard intermetallic phase with chemical composition $TiZn_{15}$ called β-phase. Copper is in solid solution, forming α-Zn solution.

The presence of the intermetallic β-phase is of high importance, as it refines the cast Zn grains and prevents grain growth during hot rolling. The β-phase precipitates very close to zinc's melting point (m.p. = 421 °C; β-phase forms 2–3 °C below the m.p.), and forms stringers along the rolling direction in the α-Zn matrix. Their size and distribution are crucial for the alloy's mechanical properties as they can be responsible for precipitation hardening based on their size, but also they can act as stress raisers and crack initiation points, especially when they are enlarged and placed at the grain boundaries.

Zinc is easily joined with fusion techniques such as TIG/MIG (Squillace et al., 2004) and/or ultrasonic welding (Patel et al., 2014) but the structural integrity of such joints is easily deteriorated. Especially, when very thin zinc sheets are to be welded for construction purposes, such as gutters, industrial roofing systems and other architectural applications, both suppliers and applicants face severe brittle fracture occurrences even at low loading conditions leading to cracking within the weld zone.

After fusion welding, β-phase redistributes and is totally concentrated at the grain boundaries. The precipitation hardening effect is thus cancelled and the overall structural integrity of the welded part can be compromised.

Pantazopoulos and Sampani (2007), in a case study of a zinc tube failure, found that zinc wrought alloys can suffer from failure caused by crack formation initiated at such hard intermetallic β-phase precipitates.