Effect of corrosive environment on the fatigue property and crack propagation behavior of Al 2024 friction stir weld

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Abstract: Friction stir welding (FSW) has been used to joint high strength aluminium alloys of aircrafts, however, the fatigue property and crack propagation behavior are still major problems that affect the longevity of aircraft structures, especially when they serve in the corrosive environment. In this investigation, 2024 aluminium alloy plates were friction stir welded, a sequence of experiments was performed including fatigue and crack propagation tests in air, under pre-corrosion and in a 3.5% NaCl solution, in combination with fractography analyses of near-threshold region, Paris region and finial fracture region with the aid of scanning electron microscopy (SEM). Results showed that the corrosive environment caused a dramatical decrease in fatigue lives of FS welds, the corrosion fatigue lives of FS welds were almost a half of the as welded specimens. The crack growth rates in FS welds were higher than their counterparts in base materials, under the corrosive environment, the crack growth rate differences between base materials and FS welds become increasingly apparent with the increasement of ΔK, but the pre-corrosion process had little effect on the FS welds' crack propagation behavior except for shortening the crack initiation lives greatly.

Keywords: friction stir welding; aluminium alloy; fatigue; crack growth rate; corrosion

1. Introduction

High strength aluminium alloys are known to be attractive materials for aerospace industry because of their high specific strengths and low densities. The corrosion fatigue property of high strength aluminium alloys have been widely studied over past few years[1-6]. Nevertheless, according to the famous "wooden barrel effect", the strength of a structure is determined by the weakest position, the weld of high strength aluminium alloy is considered to be the critical site and should be paid more attention, especially when it is subjected to cyclic loads coupled with corrosive environment (termed corrosion fatigue), which plays a detrimental role in longevity of structures and inturn results in premature failure of components in service.

Friction stir welding (FSW) has recently been used to joint high strength aluminium alloys because of its solid-phase welding speciality comparing to traditional fusion welding, resulting in better weld quality and joint strength. The welding zone of aluminium alloy FS weld exhibits susceptibility to corrosion environment[7-9]. Although many fatigue property investigations of aluminium alloy FS weld have been carried out in the past decade[10-17], there are only few researches related to the corrosioin fatigue behavior of aluminium alloy FS weld, especilly for the effect of pre-corrosion defect on the fatigue behavior of FS weld.

In previous work, it was determined that fatigue crack propagation rate was slightly higher in FS weld than the base material counterpart for Al 7050, but it could reach up to two times higher in a 3.5% NaCl solution than that in air both in FS weld and heat affect zone because of the

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Analysis and Modeling of Friction Stir Processing-Based Crack Repairing in 2024 Aluminum Alloy

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Abstract A friction stir processing-based method was used to repair cracks in the 2024 aluminum alloy plates. The temperature field and plastic material flow pattern were analyzed on the basis of experimental and finite element simulation results. Microstructure and tensile properties of the repaired specimens were studied. The results showed that the entire crack repairing was a solid-phase process and plastic materials tended to flow toward the shoulder center and then resulted in the repairing of cracks. Meanwhile, the coarse grain structures were refined in repaired zone (RZ), while the grains in thermal–mechanically affected zone and heat-affected zone were elongated and driven to grow up. Meanwhile, large phases are crushed into small particles and dispersed inside the RZ. Finally, the strength of the repaired specimens can be restored dramatically and their ductility can be partially restored. After heat treatment, the tensile properties of the repaired specimens can be further enhanced.

KEY WORDS: **Friction stir processing; Crack repairing; Aluminum alloy; Microstructure; Hardness; Tensile properties**

1 Introduction

Service reliability of mechanical products is an urgent problem to be solved for their engineering applications [1]. The most dangerous damage that affects service lives of materials and structural components is the cracking occurrence. Generally, the cracking failure has some intrinsic features such as multiplicity, suddenness and repeatability.

Due to external shocks or corrosive environment, many cracks or crack-like damages will appear on the surfaces of the structural components. Moreover, pores and micro-cracks can be introduced in the interior of materials during the manufacturing processes such as welding, hot treating and forging. Then, these defects will gradually develop to macro-cracks and lead to the early failure of the structures. According to the statistics, more than 50% fracture accidents can be attributed to fatigue cracking [2]. With the extension of service time, the cracking probability will increase for the engineering structures. Supposing that cracks could be repaired before final fracture, some catastrophic accidents would be avoided and the service lives of the structures could be prolonged. Unfortunately, so far, the controlling and repairing of the cracks are far from expectation.

Nowadays, studies about crack repairing and healing mainly focused on non-metallic brittle materials such as

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Effect of parameters on fatigue properties and crack propagation behavior of friction stir crack repaired Al2024

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ABSTRACT

Through investigating the effect of parameters on fatigue properties and crack propagation behavior of friction stir crack repaired 2024 aluminum alloy, it demonstrated that the fatigue strength of friction stir repaired Al2024 was sensitive to the repairing parameters and had a “V” type discipline with the rotating speed or advancing velocity. The fatigue crack growth rates of repaired specimens were higher than the base material counterpart, and the crack propagation mechanism in the repaired zone was mainly intergranular. When the improper repairing paramaters were adopted, delamination defect would be formed at the interfaces between repaired layer and base material.

Keywords: Friction stir crack repairing; Aluminum alloy; Fatigue property; Crack propagation

1. Introduction

Since reliability and safety become increasingly important for engineering structures and equipments, cracking issues are considered to play the detrimental key role in the lifetime of engineering materials and structures [1]. It is well known that crack usually initiates from surface or sub-surface because of the plan stress state for

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初稿

二次时效 7055-T7951 铝合金微观组织及力学性能

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摘 要：通过对峰时效与 T7951 二次时效 7055 铝合金力学性能测试、微观组织与断口分析，研究了显微组织、基体析出相、晶界析出相与晶界无沉淀析出带对材料强度与断裂韧性的影响，并分析了断裂机理。研究表明 T7951 二次时效产生的位错强化、细晶强化效应与基体内出现平衡 η 相导致的弱化作用之间的竞争机制导致材料强度较峰时效损失不大；晶界析出相的团聚粗化是造成二次时效 7055 铝合金断裂韧性提高的主因；7055 铝合金室温拉伸断口表明断裂机理为韧脆混合型断裂，二次时效较峰时效表现出更强的韧性断裂特征。

关键词：7055 铝合金；二次时效；强度；断裂韧性；析出相

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飞机的重量是制约其实现超高速与高机动性能的关键。目前，只能通过提高航空材料的比强度和优化结构设计来实现飞机的减重。美国铝业公司开发的 7055 超高强铝合金由于其优异的可成形性、较高的断裂韧性、耐腐蚀性和优良的损伤容限性能，逐渐替代传统的 7075 铝合金用于飞机机身横梁和骨架等关键构件。

热处理制度对 7055 铝合金的显微组织和力学性能影响显著。7055 铝合金热处理包括均匀化、固溶、淬火、时效等工艺，其中时效又包括峰时效、双级时效、回归再时效和形变时效等等。通过峰时效可以得到最高的强度，但断裂韧性和抗应力腐蚀性能较差；双级失效(如 T74 和 T73)可以改善合金的断裂韧性和抗应力腐蚀性能，但会造成强度的损失[1,2]。因此，实现 7055 铝合金强度、断裂韧性、抗应力腐蚀性能和疲劳强度等的良好匹配，始终是重要的工程问题。

国内外针对该问题开展了大量研究，主要期望通过时效过程工艺控制达到提高材料断裂韧性与抗腐蚀性的同时保持材料较高的强度[3-7]。目前，该系合金基本沿着高强—高强高韧—高强高韧耐腐蚀的方向发展，而相应的热处理开发则是沿着 T6—T73—T74—T76—T77—T79 方向发展，但许多关键工艺参数并未公开。

随着我国航空工业的快速发展，对超高强高韧铝合金的需求日益紧迫，而我国目前的高强高韧铝合金研究水平只相当于国外 90 年代中期，大部分牌号处于仿制阶段，相应的加工工艺与热处理制度尚未明确[8]。因此，针对国外同类合金及其热处理制度开展研究，对促进我国超高强高韧铝合金的研发具有重要意义。

目前关于 T7951 状态的 7055 铝合金研究较少，本文通过对比分析峰时效与 T7951 二次时效 7055 铝合金显微组织、拉伸与压缩性能、断裂韧性及断口分析等，研究了 T7951 二次时效过程对材料组织与性能的影响。

1 实验材料与方法

试验选用 7055 航空铝合金，材料成分(质量百分数)为 Zn-7.9%，Mg-2.1%，Cu-2.2%，Zr-0.15%，Fe-0.12%，Si-0.08%，Mn-0.025，余量为 Al。二次时效为 T7951，包括固溶、淬火、预拉伸与人工时效等过程，但具体参数未公开。与 T6 峰时效作对比分析。

利用岛津电子万能试验机进行室温拉伸与压缩性能测试，沿 L 向取样，尺寸如图 1，拉伸与压缩速率分别为 2mm/min 和 10KN/min；断裂韧度 K_{IC} 测试在 MTS-810 电液伺服疲劳实验机上完成，采用 CT 试样如图 2，用计算机与 COD 规分别采集载荷和裂纹尖端张开位移。每组实验各取 6 个平行试样。利用 Olympus GX51 光学显微镜、Philips Tecnai 透射电镜与 Hitachi S-3400N 扫描电镜分别观察 7055 两种状态的微观组织、析出相形貌及分布和拉伸断口。

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Effect of T7951 secondary aging treatment on crack propagation behavior of 7055 aluminum alloy

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Abstract: The crack propagation rates of T6 peak aging and T7951 secondary aging 7055 aluminium alloys were tested under stress ratios (R) of 0.6, 0.05 and −1, respectively. The microstructures and fracture surfaces were analyzed by TEM and SEM. The results reveal that the crack propagation rate is affected by the stress ratio and microstructure such as the distribution, dimension and volume fraction of matrix precipitates, grain boundary precipitates and precipitate free zone. For both heat-treated specimens, crack propagation rate increases with the improvement of R when it is a positive value while crack propagation rate at R=−1 is much similar to that at R=0.06. The crack growth rates exhibit no obvious difference in lower stress intensity factor range (ΔK), while the difference starts to be obvious when ΔK exceeds certain value. The fracture analysis testifies a better fracture toughness for 7055-T7951 with a smaller striation space in Paris region.

Key words: 7055 aluminum alloy; T7951 secondary aging; crack propagation; fracture surface morphology

1 Introduction

Ultra-high-strength 7055 aluminum alloy has a tendency to replace the traditional 7075 aluminum alloy and has been widely applied to aircraft structural materials because of its excellent formability, high fracture toughness, enhanced corrosion resistance and damage tolerance property [1−7]. The microstructures and mechanical properties of 7055 aluminum alloy will be affected by the heat treatment remarkably [4−7]. For 7xxx series aluminum alloys, the heat treatment processes include homogenization, solid solution, quenching and aging, and the aging process can also be divided into peak aging, double aging, retrogression re-aging and deformation aging.

A number of studies about the effect of heat treatment on the microstructure, such as second phases and precipitates and their influences on mechanical properties of 7xxx series aluminum alloys were conducted through the process control during aging process [1,2,5,8−12], and the corresponding heat treatment methods were developed along T6−T73−T74−T76−T77−T79, but some key process parameters were still undisclosed because of the trade secrets.

7xxx series alloys can obtain the highest strength after peak aging, but the fracture toughness and corrosion resistance ability will decrease accordingly [12]. Double aging such as T74 and T73 can improve alloys' fracture toughness and corrosion resistance ability with sacrificing strength. As a result, it is still an important engineering problem to achieve good matching between strength, fracture toughness, corrosion resistance ability, fatigue and damage tolerance property of 7xxx series aluminum alloys.

SCHERIBER et al [1] discussed the cyclic stress- and strain-amplitude-control fatigue response of aluminum alloy 7055-T7751 at both ambient and elevated temperatures. ZHONG et al [10] found that 7449-T7951 alloy had an excellent fatigue property with the fatigue limit of smooth specimens reaching 349 MPa for R=0.5 (R is stress ratio) and 134 MPa for R=−1.0, while it still remained 138 MPa for R=0.5 and 70 MPa for R=−1.0 by using notch specimens with the notch

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盐水环境下2A12铝合金搅拌摩擦焊缝腐蚀速率

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摘 要：采用静态失重法测量了2A12铝合金搅拌摩擦焊缝在3.5% NaCl水溶液中的平均腐蚀速率，结合焊缝腐蚀机理、腐蚀产物成分与腐蚀损伤宏－微观形貌分析了不同腐蚀时间下搅拌摩擦焊缝腐蚀速率的变化规律. 结果表明，焊缝平均腐蚀速率经历了从大幅下降到缓慢回升的过程，这与焊缝的腐蚀经历了由点蚀到沿晶腐蚀，最后发展为剥蚀的腐蚀机理变化密切相关；试件质量去除率表明腐蚀时间越长，焊缝腐蚀越严重；焊缝不同区域腐蚀敏感性不同，焊核区腐蚀严重，前进侧次之，返回侧腐蚀相对较轻.

关键词：搅拌摩擦焊；腐蚀速率；腐蚀机理；二次相
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0 序 言

随着国内对海洋权益的日益重视，对高性能海洋武器装备的需求日益紧迫，尤其是高性能航空装备方面，国家和中央军委高度重视，投入了大量精力和资金进行研发，先后推出了包括预警机、新型四代战斗机、航空母舰与舰载机、大型运输机等一系列高性能先进航空装备. 这些先进装备在近海与海洋环境服役期间所面临的巨大威胁是会受到环境中腐蚀介质的影响，从而导致其性能退化和关键零部件的过早失效，使其服役寿命远达不到设计要求. 国内现役的主要机种也普遍出现了不同程度的腐蚀问题，导致有些机种的出勤率降低，维修工作量及费用大幅增加. 所以，腐蚀损伤已成为国内当前军用和民用飞机所面临的严峻问题.

2系列铝合金是典型的航空高强铝合金，关于其腐蚀机理及腐蚀条件下的力学行为国内外已经进行了较为系统的研究[1-3]，但飞机许多关键结构是通过焊接方式进行连接的，而焊缝往往是导致结构失效的起始部位. 由于焊接过程造成材料组织与成分的改变，必然导致焊缝处材料受腐蚀环境的影响较之母材发生变化. 为人们熟知的“木桶效应”同样适用于航空结构与装备，其寿命往往决定于最薄弱的环节，因此，焊缝的腐蚀行为是我们更需要重点关注的问题.

近几年发展起来的搅拌摩擦焊接技术在铝合金的焊接，尤其是高强铝合金的焊接方面展现了独特的优势[4-6]，已经在航空航天装备制造领域得到广泛应用，其腐蚀行为开始引起人们的关注[7,8]. 针对国产2A12铝合金搅拌摩擦焊缝的腐蚀行为展开研究，重点关注不同腐蚀时间下焊缝腐蚀速率的变化规律，研究结论将为分析一定服役时间下焊缝的腐蚀程度，有针对性的制定结构的防腐措施提供依据，并为后续的搅拌摩擦焊缝应力腐蚀与腐蚀疲劳行为研究奠定基础.

1 试验方法

试验所用材料为4 mm厚航空常用2A12-T4铝合金板，其属于Al-Cu-Mg系硬铝合金，由于塑性成形和机械加工性能良好并具有高强度、耐损伤与耐热性，常用于制造飞机骨架、蒙皮、翼肋、壁板等，其具体成分(质量分数，%)为Cu 4.4，Mg 1.5，Mn 0.6，Si 0.5，Fe 0.5，Zn 0.3，Ti 0.15，杂质0.1，余量为Al.

焊接过程使用型号为FSW-3LM-4012宽幅小型搅拌摩擦焊系统，采用锥形右旋螺纹搅拌针，端部直径4 mm，根部直径5 mm，长度3.7 mm，轴肩直径15 mm. 焊接参数为主轴转速1 200 r/min，焊接速度70 mm/min. 焊接完成后去除飞边，沿焊缝切制成40 mm×25 mm×4 mm待腐蚀试样. 全浸腐蚀试验依

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2A12 铝合金搅拌摩擦焊焊缝表面硬度及微观组织研究

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摘 要：鉴于当前对搅拌摩擦焊接头的研究集中于接头内部而忽略表面的现状，本文针对 2A12 铝合金搅拌摩擦焊接头的表面、内部微观组织形貌和显微硬度展开研究。结果发现：与截面相比，表面热影响区不明显，热机影响区更窄，其晶粒扭曲更严重，且晶粒变形方向相切于焊接方向；截面硬度分布呈 "W" 型，而表面硬度呈 " 犬牙 " 型，表面热机影响区是硬度梯度变化最大、硬度最低的区域，是母材的 68.3%；受轴肩顶锻压力和散热条件影响，表面焊缝中心硬度比截面焊缝中心硬度更高，表面热机影响区是焊缝的薄弱区域。

关键词：搅拌摩擦焊；接头；表面硬度；微观组织
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Study on Surface Hardness and Microstructure of 2A12 Al Alloy Friction Stir Weld Seam

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Abstract: The present research of friction stir welds focuses on the interior of welded joint while ignoring the surface. The study was developed on the microstructure morphology and microhardness of 2A12 alloy not only about the cross section but also on the surface of the weld seam. Compared with the cross-section, the results show that , the HAZ on the surface is misty. The hardness curves on the cross-section generates the type of "W" but "fang" type on the surface. The TMAZ was narrower and the distortions of its grain are severer and the deformation of grains are tangent to the direction of weld seam. The changes of hardness gradient of TMAZ on the surface is largest and the hardness is lowest. The hardness of the zone is 68.3% of BM. Affected by top forging force of the shoulder and cooling conditions, the surface hardness is greater higher than that of cross section at the weld center. The TMAZ on the surface is the weakest zone of weld seam.

Key words: friction stir welding; joint; surface hardness; microstructure

2A12 是 Al-Cu-Mg 系硬铝合金，具有较高的强度、良好的塑性和加工成型性能，已经在航空、机械行业中广泛应用。搅拌摩擦焊(FSW)技术自发明以来，以其优良的焊接特性迅速进入航天、航空、舰船、列车等工业制造领域[1-2]。FSW 接头的力学性能与显微硬度密切相关，国内外许多组织和个人对 FSW 接头显微硬度展开了研究，例如：Ilman 等人研究了 2024-T3 铝合金 FSW 接头的显微硬度，结果发现硬度分布呈“W”型，母材硬度为 160.3 VHN，而焊接区域平均硬度只有 80 HVN，硬度最低点出现在热影响区和热机影响区之间的位置[3]。康举等人对 FSW 接头硬度与腐蚀性关系展开讨论，发现 SAZ 区域晶粒细化，但硬度比母材低，也比母材容易腐蚀[4]。Liang 等人对 2519-T87 铝合金 FSW 接头微观组织展开了研究，发现焊接区域硬度整体比母材低，热机影响区是硬度最低的区域，只有 83 HV[5]。

区别于传统焊接方法的机理，FSW 接头受热循环和机械搅拌力的双重作用，导致 FSW 接头内部形成特殊的“洋葱环”结构，表面微观组织也与其他焊接接头差别显著。微观组织与力学性能密切相关，而焊缝最薄弱的位置有可能出现在接头表面，表面微

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Temperature Numerical Simulation of Friction Stir Welding Process of Radar Cooling Board

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Keywords: Finite element; friction stir welding; radar cooling board; temperature

Abstract. A finite element model of radar cooling board friction stir welding process was built in ANSYS software based on an instantaneous relative linear velocity heat source model. Temporal and spatial temperature distribution disciplinarians were analyzed; results show that the peak temperature is lower than the base material melting point, as a result there is no material melt during the welding process. Temperatures change disciplinarily with the progress of welding process at each point.

Introduction

It is very difficult to measure temperatures at the weld center during friction stir welding (FSW) process because of the exquisite plastic deformation, numerical simulation method was used to predict peak temperature and temperature distribution during the welding process as a result. Early in 1998, Chao et al[1] built a three-dimension heat input model and used it in temperature simulation of FSW process in which the heat flux was assumed as a constant; M. Song and R. Kovacevic et al[2] also built an instantaneous three-dimension heat transfer model in which a moving coordinate system was brought in to calculate the moving heat source, and the heat input of the welding pin was included; Friggard et al[3] divided the FSW process into four states: immovable heating up state, instantaneous heating up state, quasi-steady state and after steady state, they calculated the FSW process temperature distribution by finite difference method and validated them by data from thermal couples.

A finite element model of radar cooling board friction stir welding process was built in ANSYS software based on an instantaneous relative linear velocity heat source model in this work and temporal and spatial temperature distribution disciplinarians were analyzed.

Issue Descriptions

The friction stir welding process of a wind cooling board shown in Fig.1 will be simulated, material of the base board is 6063-O aluminum alloy and the cover board is 3A21-O aluminum alloy. The cooling board is pre-welded by brazing welding, FSW is used to strength the outer rectangle joint lines as shown in Fig.1. Dimension of the cooling board is 396.5×191×32mm with a cavum inside it. Friction stir welding parameters are: rotating speed $\omega = 1200\text{rpm}$, welding speed $\upsilon = 200\text{mm}/\text{min}$, the whole welding process lasts 300 seconds.

Measurement and simulation of temperature and residual stress distributions from friction stir welding AA2024 Al alloy

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ABSTRACT

Finite element (FE) models have been developed to predict residual stress distributions resulting from the friction stir welding (FSW) process. Plates 250 mm × 50 mm × 5 mm in dimension of an Aluminium alloy (AA2024-T4) were butt-joined through FSW. The thermal profiles were monitored *in-situ* during the welding process using thermocouples. Sequentially-coupled thermo-mechanical simulations have been performed using an instantaneous relative linear velocity based heat source. Post weld residual stress measurements have been obtained using the neutron diffraction technique and were used to verify the finite element results. The thermal profiles measured during welding have been simulated in the FE model. Increasing the tool traversal speed is found to reduce the peak temperatures experienced during welding for a given tool rotational speed. The general trends and magnitudes of the residual stress distributions measured along the weld line have been predicted by the FE model. The residual stress distributions measured and predicted are relatively symmetric and uninfluenced by the range of tool traversal speeds for the cases considered. Further refinement of the material and process model may be required to improve the predictions accuracy. However, effective predictions have been obtained in the FE model presented by treating the material as a continuum without additional complexities.

Keywords: AA2024 Al alloy, residual stress, friction stir welding

NOMENCLATURE

ν	Welding speed
ω	Tool rotation speed
r_i	Radial distance between the point 'i' and the tool centre
θ_i	Angle between the axes of rotation and tool traversal
$\vec{F}$	Frictional force
η	Thermal efficiency
γ	Modifying factor
q	Heat flux
λ	Wavelength of the radiation
θ, θ_0	Bragg angle, Bragg angle in a strain free material
d, d_0	Lattice spacing, lattice spacing in a strain free material
h	Convection coefficient
T, T_a	Temperature and ambient temperature
E_{hkl}	Elastic modulus associated with a specific crystallographic plane
ν_{hkl}	Poisson's ratio associated with a specific crystallographic plane

1. INTRODUCTION

Friction Stir Welding (FSW) is a relatively new solid state welding technique invented at TWI in 1991 [1]. It can produce low-cost and high-quality joins without defects since there is no melting of the material during the welding process. FSW involves a (non-consumable) rotating tool with a specially designed pin and shoulder which is inserted into the abutting edges of parts to be joined. The tool is traversed along the line of joint [2] (see Figure 1). The energy input, and thus the peak temperatures experienced in the work piece, is determined by the rotational velocity of the tool piece, ω, and the speed of tool traversal along the weld line, ν. FSW is advantageous since it is capable of joining precipitation strengthened 2000 and 7000 series aluminium alloys, which are not acceptably weldable by fusion welding techniques [3–5] for reasons described in *e.g.* [6].

Friction stir welding is a complex thermo-mechanical process. However, for computational efficiency, a one way coupled model is often performed where the thermal model's results are input into a mechanical model, but the thermal analysis is independent of the mechanical response.

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