行政院國家科學委員會專題研究計畫　成果報告

摩擦攪拌焊接製程之有限元素模擬

計畫類別：個別型計畫
計畫編號：NSC94-2212-E-041-001-
執行期間：94 年 08 月 01 日至 95 年 10 月 31 日
執行單位：嘉南藥理科技大學資訊管理系

計畫主持人：徐宏修
共同主持人：黃永茂
計畫參與人員：康宗瑋，周培家

報告類型：精簡報告
報告附件：出席國際會議研究心得報告及發表論文
處理方式：本計畫涉及專利或其他智慧財產權，2 年後可公開查詢

中　華　民　國 95 年 10 月 31 日

行政院國家科學委員會補助專題研究計畫 **☑ 成果報告**
□期中進度報告

摩擦攪拌焊接製程之有限元素模擬

計畫類別：☑個別型計畫　　□ 整合型計畫
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行政院國家科學委員會專題研究計畫成果報告
摩擦攪拌焊接製程之有限元素模擬

An FEM simulation on during Friction Stir Welding

計畫編號：NSC 94-2212-E-041-001
執行期限：94 年 8 月 1 日至 95 年 10 月 31 日
主持人：徐宏修　嘉南藥理科技大學醫療資訊管理研究所
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一、中文摘要

摩擦攪拌焊接中銲道上的熱傳及機械特性的變化是由於工具頭在工件上移動所產生的，而熱傳及機械性質的變化相當複雜。本文利用一個三維的熱機械模式，使用有限元素分析來模擬摩擦攪拌中溫度與應力之變化。焊接的熱源來自於工具頭及肩部在工件上的摩擦，及工件本身受到工具旋轉所產生的塑性變形功率。本研究利用套裝軟體有限元素 Deform 3D 來做有限元素模擬，研究範圍包含摩擦攪拌的熱傳分佈歷程及溫度變化對攪拌旋轉過程中材料機械性質之影響，研究結果可提供使用者被加工板材在製程中之機械性質變化、熱機性質變化、溫度歷程及應力變化及應變分布。在實驗方面，以立式銑床、萬能試驗機，實行 FSW 實驗，並一一探討工具頭轉速，前進速度，加工溫度與產品之關係，做為未來實施 FSW 最佳化設計參考依據

關鍵詞：FSW, HAZ, TMAZ, FEM

Abstract

The heat transfer and mechanical characteristics on the welding line of a workpiece sheet due to the tool pin moving are quite complicated. In this paper, a thermal-mechanical model for friction stir welding (FSW) along with three dimensional finite element analyses is proposed. The heat generated from the tool pin and shoulder is considered as the heat source in the friction stir welding process. A software package – DEFORM 3D is used to simulate the temperature, strain and stress distributions of the sheet in FSW. The simulation results can provide a useful knowledge for designing the FSW process.

The numerical simulation is preformed by Deform 3D, the research scope includes the effect of heat conduction and temperature change upon the mechanical properties of stirred material during FSW. The mechanical properties, thermo-mechanical properties, heat history and stress and strain distribution of sheet are discussed in detail. The experiments is carried by using milling machine to investigate the effect of forming parameters such as rotating speed of pin, advance speed. The result can offers a useful knowledge for optimal designing the friction stir process.

Keywords: FSW, HAZ, TMAZ, FEM

二、前言

摩擦攪拌焊接可應用在飛機機身骨架之接合與製造。在汽車工業中，鋁擠形車體骨架可減少車體骨架的零組件數，且精確鋁合金製的車體骨架可經由 FSW 的接合。FSW 也可用於建築物外觀壁板的接合與窗戶骨架的接合、管路的組建、在造橋所運用到的鋁合金之接合、鋁合金擠製物的接合與熱交換器和空調系統等。，摩擦攪拌焊接中最大的特徵就是焊道外觀有洋蔥環出現。在摩擦攪拌焊接後，使得不同晶粒大小的三維片狀橢圓面間隔的出現在攪拌區。焊道區的微觀組織可分為熱機械影響區(Thermo-mechanical affected zone)，熱影響區(Heat affected zone)，礦塊(Weldingnugget)等。

Rhode 等人[3]將工具頭旋轉插入 7075 鋁合金，隨即拔出並急速冷卻，以探討在 FSW 過程中微細晶粒結構的演變。在鋁合金焊道攪拌區中所得的細晶粒，是重覆變形所產生的成核逐漸成長而來，非原先存在的次晶粒旋轉所形成[3]。

摩擦攪拌製程(FSP)為美國的 Mishra 教授研究團隊所提出[4,5]，並應用於母材的改質、金屬基複合材料的製作、以改變母材材質使具備超塑性變形等。因此摩擦攪拌製程用於創造均勻的材料微觀組織及延性，常用於金屬基複合材料的製造，具有使材料晶粒細化能力，已逐漸成為新興的晶粒細化技術。

Kwon 等[6,7]在 1050 鋁合金、Su[8]在 7075 鋁合金與 Charit[9]在 2024 鋁合金以摩擦攪拌製程研究時，皆能在攪拌區形成良好的晶粒細化結果至 10 μm 以下，甚至可達奈米尺度。

以摩擦攪拌製造微細晶粒材料的優點有：

(a)在單次製程中可得到高晶角界奈米晶粒，達到晶粒細化目的。

(b)改變製程參數與冷卻速率來控制最終微結構組織。

(c)無需複雜機器設備、低消耗能量、操作簡單。

(d)提供製造大尺寸奈米結構金屬或合金之工業材

料。

Su[8]在 7075 鋁合金上進行單趟摩擦攪拌製程，利用經工具頭攪拌過後立即急速冷卻材料，減少不連續動態再結晶粒核在熱循環中的晶粒成長過程，在動態再結晶區製造出 30~180nm 的等軸晶粒。

應用摩擦攪拌製程於2024 鋁合金[9]、2095 鋁合金[10]、AL-Mg-Zn 鋁合金[11]等，皆有良好超塑性質的表現。摩擦攪拌在表面製造具有均勻的奈米粒子分佈與良好鍵結的金屬基複合材料。因此製程是一非常有效的應用技術，對於製造具粒子良好分散且與金屬基質有良好鍵結的表面金屬基複合材料，具有更高的延性與拉伸強度。

Lee 等人[12]在鑄造 A356 與鍛造 6061 鋁合金異質接合的實驗中發現，焊道攪拌區的微觀組織主要是由退出邊的物質所構成，即退出邊的物質對焊道的微觀組織與機械性質影響較大。

Webster[13]研究 AP7108 之 FSW 製程，利用 X-ray 技術，得到長軸方向殘留應力之分布在-60 至 140MPa 之間。

Sutton[14] 利用中子繞射技術探討兩塊 2024-T3 板在焊接製程中之殘留應力分布，並指出最大殘留應力發生在焊道的冠狀區。

Sony 等人[15,16]利用有限差分法，探討 FSW 中之熱傳問題。Chao[17]提出一個數學模式，忽略了工具對板材機械性質之影響，來預測熱應力及工作的時變過程。Dong[18]同時考慮了 FSW 中之熱傳，材料流塑性流等因素。

Chen[19]分析鋁合金 6061-T6 雙板焊接過程，對不適用傳統方式焊接的合金，FSW 是一種可減少畸變的選擇，而藉由固態間的焊接來改進機械性質。Chen 認為主要熱源來自工具頭和材料間的摩擦，用 FEM 套裝軟體 ANSYS 模擬 6061-T6 實施 FSW 之板材的溫度變化歷程及熱機影響區域的機械性質變化，分析模式包括工具頭的機械力學反應及焊道附近的熱機效應，並獲得長軸，板材及板厚方向的應力及溫度變化的數值模擬結果。

四、FEM 分析

本研究中，利用套裝軟體有限元素Deform 3D 來模擬摩擦攪拌焊接的熱傳分佈歷程及溫度變化對攪拌旋轉過程中材料機械性質之影響。其中熱源來自於肩部及凸梢，可提供使用者瞭解被加工板材在製程中之機械性質之變化、熱機性質之改變、溫度歷程及長軸方向、橫軸方向及板厚方向之數值模擬。同時探討殘留應力和製程參數如工具轉速，前進速度之關係，延伸至未來實施製程時最佳化設計之參考依據。

為了解FSW 之物理現象，有必要以數值模擬方式探討材料在製程中之塑性變形過程，減少實施 FSW 製程中之嘗試錯誤次數。首先考慮SKD 工具鋼，肩部的半徑R ，凸梢部的半徑 r ，被加工板材的延性材料具彈性塑性及動態硬化等特性。在 FSW 中的熱傳模式如下：

$$\rho c\frac{dT}{dt}=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \quad \text{in} \quad \Omega \qquad (1)$$
$$-h_c \cdot T+\dot{Q}$$

從整個製程觀點而言，工具的機械效應是應該納入數學分析模式中。Deform 3D 原是為了金屬成形加工的套裝FEM 分析軟體，特別應用於鍛造加工的分析上，本研究使用Deform 3D 來模擬工具頭的轉動及長軸方向的移動，來模擬Al6061-T6，鋁合金AZ91，AZ61等在FSW 時之塑流變化、溫度分佈及加工後之機械性質。

模擬時，利用三維的Lagrange 有限元素分析模式。以及多重線性應變硬化效應來模擬三維固態結構，以四面體元素來快速重建網目分割，應用於 FSW 的大變形特性。雖然四面體比六面體元素的計算耗時，受惠於電腦的運算速度大幅進步，使用四面體元素來分析FSW仍是最佳的選擇

實驗方面，使用材料為6061鋁板材，以改變板寬、轉速、前進速度，得到在各種組合下摩擦攪拌焊接製程的熱應力、熱傳時變過程及塑性流，來獲得6061鋁板之基本摩擦攪拌製程的實驗數據。

五、結果與討論

6061 鋁板材 FEM 模擬之結果, Step 478 的溫度分布如圖 1, 2 所示，最高溫在 Pin 的周圍。

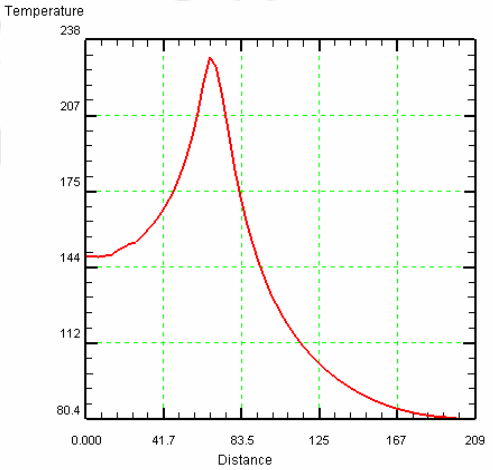

圖 1　底面溫度分布 (step 478, x=5, z=0)

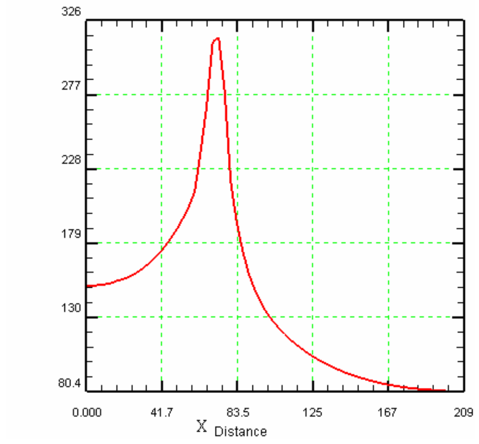

圖 2　頂面溫度分布

圖 3 表示等溫線分布圖，為 6061 鋁板材 FEM 模擬之結果。 Step 478 的溫度分布如圖 3c 所示，等溫線以 Pin 為中心呈同心圓狀分布。

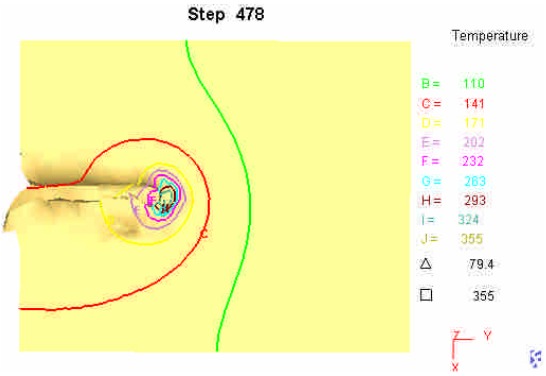

圖 3a 頂面等溫線分布圖 (step 478)

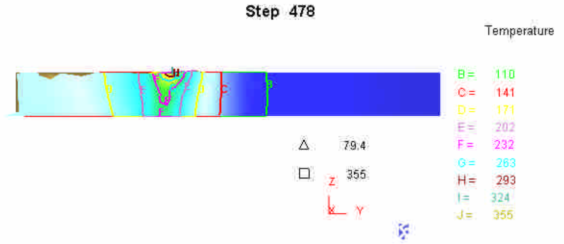

圖 3b 前斷面等溫線分布圖 (step 478)

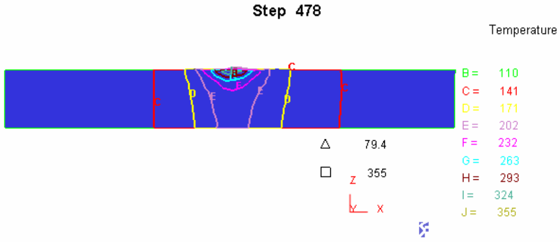

圖 3c 側斷面等溫線分布圖 (step 478)

圖 4 表示等效應變分布圖。如圖 4 b 所示，等溫線以 Pin 為中心呈對稱分布。

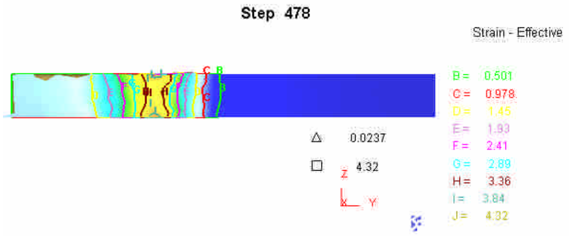

圖 4a 前斷面等效應變分布圖 (step 478, x=5)

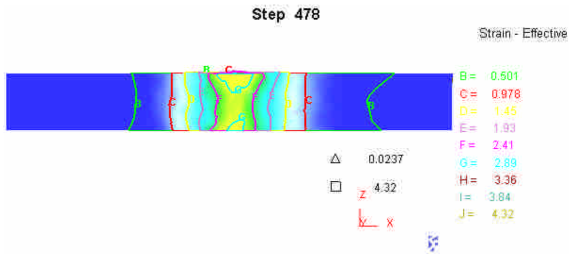

圖 4b 側斷面等效應變分布圖 (step 478, x=5)

圖 5 表示等效應變率分布圖。如圖 5b 所示，等溫線以 Pin 為中心呈對稱分布。

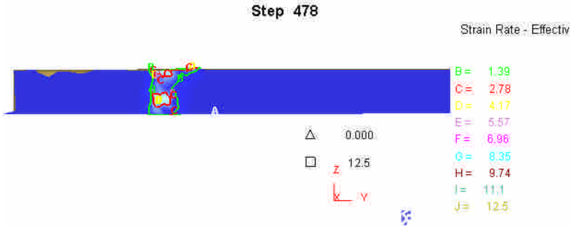

圖 5a 前斷面等效應變率分布圖(step 478, x=5)

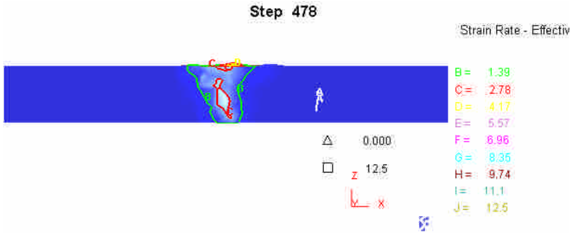

圖 5b 側斷面等效應變率分布圖 (step 478, x=5)

圖 6 表示 Damage 分布圖。如圖 6b 所示，等溫線以 Pin 為中心呈對稱分布。

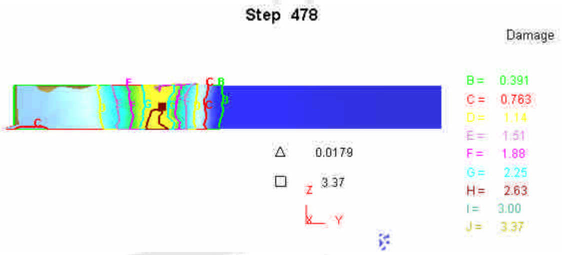

圖 6a 前斷面等 Damage 分布圖(step 478, x=5)

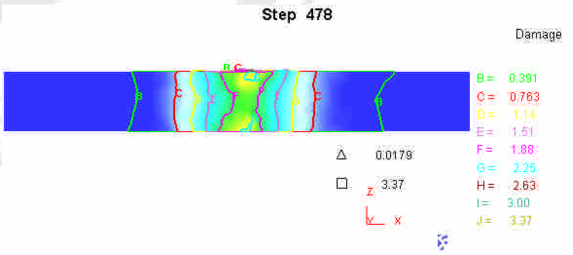

圖 6b 側斷面 Damage 分布圖(step 478, y=80)

圖 7 表示頂面 Flow net 分布圖。如圖 6b 所示，大部分塑性流動來自於中央焊道及其鄰近周圍材料。

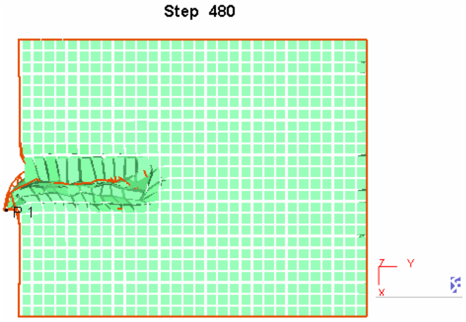

圖 7 頂面 Flow net 分布圖

圖 8 表示殘留應力分布圖。X,Y,Z 方向的殘留應力各不相同，尚需實驗證明。

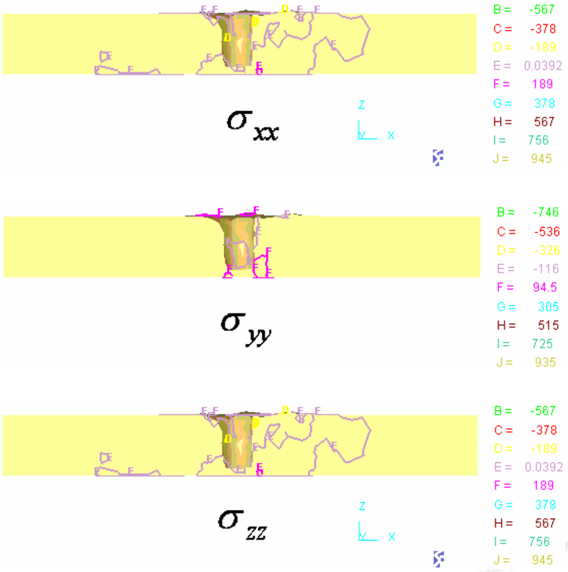

圖 8 殘留應力分布圖 (step 478, x=5)

在理論研究上，利用套裝軟體 DEFORM-3D 對摩擦攪拌之製程技術作深入探討，充分瞭解工具頭進給深度、摩擦係數、工具頭轉速、工具頭前進速度等加工參數對應力分佈、應變分佈及溫度分佈等之影響。

在有限元素法的分析，分析鋁合金 6061-T6 雙板焊接過程，對不適用傳統方式焊接的合金，FSW 是一種可減少畸變的選擇，而藉由固態間的焊接來改進機械性質。用 FEM 套裝軟體 DEFORM 模擬 6061-T6 實施 FSW 之板材的溫度變化歷程及熱機影響區域的機械性質變化，分析模式包括工具頭的機械力學反應及焊道附近的熱機效應，並獲得長軸，板材及板厚方向的應力及溫度變化的數值模擬結果。

另外在實驗中獲得如下成果。當轉速提升時而前進速度保持不變的情形下，工具頭每轉一圈的前進距離縮短，因此焊道表面的半圓形環距減少。此現象與等溫度線分布相似，與 Deform 3D 的模擬結果相似。

未來可應用一系列模擬結果於摩擦攪拌焊接製程之開發設計上。預計在可摩擦攪拌製程焊道之橫切面上，計算模擬所需工作功率和材料焊道區的塑性變形狀態。

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行政院國家科學委員會補助國內專家學者出席國際學術會議報告

95 年 10 月 10 日

附件三

報告人姓名	徐宏修	服務機構及職稱	嘉南藥理科技大學
會議時間地點	9 月 25 日~9 月 29 日 日本名古屋	本會核定補助文號	NSC94-2212-E041-001
會議名稱	(中文)第八屆亞太塑性工程暨應用學術研討會 (英文)The 8th Asia-Pacific Symposium on Engineering Plasticity and Its Applications		
發表論文題目	(中文)鎂合金板 AZ31 的摩擦旋轉製程之研究 (英文)A Study on Friction Stir Process of Magnesium Alloy AZ31 Sheet		

一、參加會議經過

本人自 9 月 24 日上午搭華航班機赴日本名古屋，行程達 3 小時。當地氣候非常溫和。名古屋為中部大城，新幹線與地下鐵以名古屋車站為中心向外延伸到市區和其它大都市，有許多國內外游客選擇名古屋為觀光據點。抵達名古屋之後，經一夜的休息，9 月 25 日下午抵達會場－日本國立名古屋大學。在現場註冊後得知，許多學者選擇 26 日以後註冊，只能與少數學者交換研心得。值得一提的是看到許多大陸學者與會，並且有年輕化和內陸化趨勢，近年來中國大陸逐漸推廣高等教育，積極參與國際會議，國內主管單位多多推動與鼓勵。

二、與會心得

選擇Tuesday, September 26, 13:30-15:00, TS 1F, Welds場次，Chair: H. Kimura。所觀察發表之論文，首篇由Osaka Prefecture University的Kenji Higashi報告Superplastic Properties and Microstructure of Friction Stir Welded Joints Zn-22wt.%Al Alloy，內容為鋁鋅合金的Friction Stir Welded之熔接處的超塑性特性與微觀結構。Kenji Higashi表示，熔接處的伸長量及抗拉強度在室溫下比母材要來得更低，熔接處的會產生更多的細晶粒及等軸晶粒。

其次為 Tokyo Metropolitan College of Technology 的 Shigeru Aoki 發表 Reduction of Residual Stress of Welded Joint using Local Plasticity Caused by Ultrasonic Vibration, 為在 Welding 時利用超音波達到 Welds 局部塑性，以降低殘留應力的方法。Shigeru Aokiu 以數值模擬方式來探討殘留應力降低的比例，作為以超音波輔助設計 Welding 的參考依據。

第三位為本人所報告的 A Study on Friction Stir Process of Magnesium Alloy AZ31 Sheet, 以 Deform 3D 來探討鎂合金板 AZ31 的摩擦旋轉製程之研究，分析其溫度、應變率、應力等之分佈，以了解 Friction Stir Welding 塑性流動之概況及 TAZ,TMAZ,HAZ 與 Nugget 分佈。

第四位為 Technology Research Institute of Osaka Prefecture 的 T. Hirata 發表的 Formability of Friction Stir Welded and Arc Welded 5083 Aluminum Alloy Sheets。探討鋁 5083 合金板的 Friction Stir Welded 與 Arc Welded 後之板材的機械性質，包含伸長量、抗拉強度，以及熱生成量對上述機械性質之影響。結論指出經 Friction Stir Welded 後，板的延性增加，改善了鋁 5083 合金板的成形性。

9 月 27 日選擇 Wednesday, September 27, 13:00-14:40, TS 3A, Metal Forming(3)場次，Chair: C G. Kang。第一篇為同行參加研討會的國立中山大學機電系 Y.M.Hwang 所報告 Adaptive Simulations of T-Shape Tube Hydroforming Processes.為有關 T-Shape Tube 液壓成形之有限元素模擬。

第二篇為 Toyohashi Unversity of Technology 的 K.Mori 所發表的 Development of PC Cluster Parallel Processing Scheme of 3-D Rigid-Plastic Finite Element Method using Diagonal Matrix，為利用叢集電腦進行 3D 有限元素法的平行運算，以提昇運算效能，用來模擬較複雜的成形加工，縮短計算時間。

第三篇為 Noshirvani Insitute of Technology 的 M. Loh-Mousavi 發表的 3-D Finite Element Simulation of Pulsating T-Shape Hydroforming of Tubes. 利用震動加壓的液壓裝置，提供 T-Shape 液壓成形的所需，以改善 T－SHAPE 的成形性。

第四篇為 Toyohashi Unversity of Technology 的 C. J. Tan 所發表的 Increase of Wall Thickness around Corner of Multi-Stage Drawn Cup with Flange using Conical Punches,利用錐形模來加壓，使得轉角處更易於成形，Tan 利用此法得到以 25 度的錐形角可增加 9%厚度。

第五篇為 Pusan National University 的 Seong-Chan Heo 所發表的 Automatic Approach on Derivation of Loading Path using Adaptive Finite Element Analysis Simulation Method。以負載路徑和有限元素法來探討板材的成形極限圖。翔實的討論 Diffuse necking 和 Local necking 發生的狀況。

下午另選擇 Wednesday, September 27, 15:10-17:00, TS 3A, Metal Forming(4)場次，Chair: K. Mori。此 Session 延續前一場,所研究的為有關流變鍛造與板金成形方面的題目。共計有 Pusan National University 的 C. G. Kang 所發表 Computer Aided Simulation of the Rheology Forging Process for Aluminium Alloys and Experimental Investigation, 以 CAE 來探討改良 Aluminum 合金的流變鍛造。Koyto University 的 Takayuki Hama 所發表 Effect of Tool Modeling Accuracy on Sheet Metal Forming Simulation 來探討板金成形。Tsung-Chia Chen 來自台灣，所發表的 An Elasto-Plastic Finite Element Simulation of the UO-Tube Processes of Sheet Metal 為有關 UO-Tube 的板金成形。Yong-Ming Guo 來自 Kagoshima University，所發表的 Hot Forging Comparative Analyses by using a Combined Finite Element Method 為結合 volumetrically elastic 與 rigid-plastic 的 FEM 分析。來自大陸的 Yingshe Luo 發表 The 3D Modeling of Dies Based on UG and Numerical Simulation of the Heat Rheological Forming of Titanium Alloy Vane Disk，以 UG 及 Deform 3D 分析 Titanium Alloy Vane Disk 的流變鍛造。

三、考察參觀活動(無是項活動者省略)

本人參與 9 月 26 日與 27 日的論文發表—Metal forming 以及 Welds。得到許多寶貴收獲。9 月 27 日下午參觀名古屋大學 Takashi ISHIKAWA 的 Deformation Processing of Materials Laboratory 研究室，內有 CNC、機械手臂以及高倍數的電子顯微鏡，以尖端設備從事基礎和應用研究，值得國內學者效法。

四、建議

希望國科會能多補助類似的國際會議，以此次會議而言。來自大陸、韓國的與會者明顯地比國內多出許多學者。意即相關研究上，我國尚落後周遭的國家，這些鄰國也有心效法日本的相關研究，如此積極的作法值得我國學習。若能邀請 AEPA 來台舉辦更能加強與鄰國在 Engineering Plastic 研究上的交流。

五、攜回資料名稱及內容

Final Program and Abstracts, AEPA2006, The 8th ASIA-PACIFIC Symposium on Engineerign Plasticity and Its Applications.

六、其他

無

A Study on Friction Stir Process of Magnesium Alloy AZ31 Sheet

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Keywords: FSP, HAZ, TMAZ, FEM, AZ31.

Abstract. Friction stir processes (FSP) are important for enhancing mechanical properties of metal sheets, such as the tensile strength, the elongation, etc. The stress distribution of the tool pin is affected by the thermo-mechanical characteristics of the workpiece in FSP. Recently, magnesium alloy AZ31 is widely used in machine industries due to the light-weight material property. In this paper, a thermo-mechanical model for FSP using three dimensional FEM analyses is proposed for exploring temperature distributions, strain distributions and stress distributions of the workpiece. The heat generated from the plastic deformation and the friction between the head tool and workpiece is considered as the heat source in the simulation of the FSP process. A commercial finite element code – DEFORM 3D is used to carry out the simulation of the plastic deformation of AZ31 sheets during the FSP. The analytical results of temperature, strain and stress distributions of the workpiece and head tool can provide useful knowledge for tool pin design in FSP

Introduction

Friction stir welding (FSW) was developed for solid state joint technology, which is first proposed from The Welding Institute(TWI) in 1991[1]. Many papers [2-8] have proved that FSW is useful in the aluminum sheet joint technology. Furthermore, friction stir welding is also suitable for joint of nickel, magnesium and carbon steel alloy sheets.

The mechanical properties of a welded sheet material have various advantages such as improved strength, finer grain size, better fatigue strength and anti corrosion property. Welded sheets with a FSW process are generally used as the outer sheet of shuttle and aircraft. The thermal-mechanical affect zone (TMAZ) and thermal affect zone (TAZ) occurred under the welding path, i.e. the rotating tool pin causes a TMAZ and TAZ. The FSW process is a kind of solid state welding, the heat flux is assumed to be zero when the temperature reaches the material melting temperature.

In the FSW, the temperature history of sheet material is under the melting temperature. The flow pattern around the tools pin and shoulder is very complex [2]. Tang [3] investigated the heat input and temperature distribution during friction stir welding. He found the highest temperature in the welding seam less $0.8T_m$ and the temperature dose not change appreciably in the sheet thickness.

Khandkar[4] proposed a three dimensional model to study the transient temperature distributions during the friction stir welding of aluminum. The moving heat source was corrected with the actual machine power input. Comparison between simulated temperature and experimental data has been demonstrated. Chen[5] developed a three dimensional model by considering the heat derived from the friction between the welding tool and welded material. The thermal history and evolution of longitudinal, lateral and through-thickness stress in the friction stirred weld are simulated numerical.

Chao[6] used ABAQUS to develop FEM heat transfer model by formulating the heat transfer of FSW process into two boundary value problem-a steady state BVP for the tool and a transient BVP for the workpiece. The detail temperature distribution in the workpiece and the tool was presented.

Song[7] proposed a three dimensional heat transfer model for FSW by using a moving coordinate. A non uniform grid mesh is generated for calculating the temperature distribution. Fratini[8] determine the average grain size due to continuous dynamic recrystallization phenomena in friction stir welding of AA6082 T6 aluminum alloys. The gain size can be obtained by taking into account the local effects of strain, strain rate and temperature. Fratini used an inverse identification approach based on a linear regression procedure to develop the material properties.

Chang[9] investigated the grin size refinement in AZ31 magnesium alloy by friction stir processing. The dimension of AZ31 sheet is $10\times 85\times 100mm$. Chang illustrated the grain size refinement is effective means of dynamic recrystallization. The relationship between the resulting grain size and the working strain rate and temperature for the friction stir processing in AZ31 magnesium need to be examined. Chang determined the relationship of grain size and the Zener-Hollomen parameter.

In above papers[2-8], due to reduce the difficulty during establishing FEM model, heat flux input from the friction between tool and sheet material are assumed. It is not reasonable for analysis the FSW procedure in detail and entirely. In this paper, a FE analysis on friction stir welding of magnesium AZ31 sheet is developed with software package-Deform 3D. Without estimating heat flux equation, it calculates the generated heat flux input from the friction caused by rotating motion during FSW.

In this paper, three dimensional thermal mechanical FE analysis used to investigate FSP of magnesium alloy AZ31. The plastic deformation of material around the tool pin can be simulated, the temperature distribution, the strain and stress field can be obtained through the entire FSP process.

Numerical Model

The Bessel function is often used to determine the possibility of modeling the temperature distribution around the FSP tool. It includes the advantage that temperature of sheet can be investigated theoretical without numerical technology. But it use single heat source to replace the generated heat source due to the friction between the tool and workpiece. Several different simplified generated heat equations are employed as the amount of single heat source and the temperature distribution fields of the workpiece can be calculated.

The FSP of magnesium steel is investigated by a three dimensional thermal mechanical model. This model is established by sing commercial code Deform 3D[10]. In this paper, the welding phenomenon of FSP is neglected and it assumes the tool pin is moving along the central line of whole sheet. Furthermore only one single sheet is used as the workpiece in FSP simulation without welding behavior.

Fig. 1 shows the schematic drawing of friction stir welding. It is isometric drawing, i.e., it is three dimensional drawing. For a three dimensional numerical simulation, the geometric shape drawing of workpiece for FEM meshed is shown in the Fig. 2 The FSP is considered in two main motions, first the rotation behavior of tool pin and shoulder. Second, the magnesium alloy sheet moves at a fixed speed.

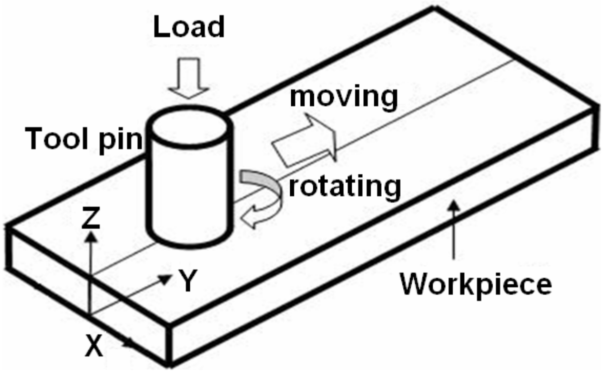

Figure 1 Illustrated schematic drawing of Friction Stir Welding.

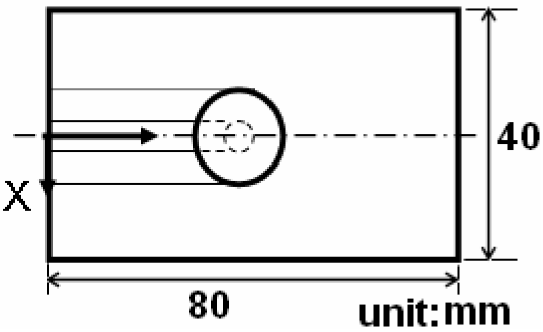

Figure 2 Geometric shape drawing of workpiece for FEM simulation (top view)

The heat transferred of friction between the tool pin stir and workpiece during FSP includes two main parts as follows:

(1) Heat source generated by the friction on the surface of the tool pin;

(2) Heat source generated by the plastic work due to the shear deformation of workpiece;

The heat transfer equation is a parabolic PDE and the heat equation of tool and workpiece in the FSP is defined as the following:

$$\rho c\frac{dT}{dt}=k(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2})-h_c\cdot T+\dot{Q} \quad \text{in} \quad \Omega \tag{1}$$

where Ω is the domain in workpiece, $\dot{Q}$ is the heat generated by stir friction between the tool and the workpiece. ρ , c , k and T are the material density and the heat capacity, the conductivity and the temperature, respectively. h_c is the convective heat transfer coefficient. There term $h_c \cdot T$ represents a model of transversal heat transfer the surroundings. $\frac{\partial T}{\partial x}$, $\frac{\partial T}{\partial y}$ and $\frac{\partial T}{\partial z}$ denotes the temperature gradient with x, y and z, respectively.

According to the friction between tool with workpiece, the total heat generated rate at the workpiece/tool interface, $\dot{Q}$ is be obtained by following the below equations:

$$\dot{Q}=\int_S \Delta\vec{V}\cdot\mu(T)\cdot P(T)\mathrm{d}S \tag{2}$$

Where $\mu(T)$ is the coefficient of work transmitted to heat source, $P(T)$ is the pressure, both are dependent on the temperature, T . The heat generated rate is caused by the shoulder of tool pin. The frictional work at the interface between tool pin and shoulder with workpiece are considered in this model.

The FSP of magnesium alloy sheet of 8 mm thickness (Z-direction) and 40mm in width (X-direction) and 80mm in length (Y-direction). The strength of magnesium AZ31 is setup according to the Deform 3D material database. The material of tool is use Din-D5-1U, which is also a pre stored in the Deform 3D material database. Because the friction factor between the workpiece/tool is more complicated, it is no clear statement until now. For convenience, the friction factor, is assumed to be a constant value, which is 0.4. The room temperature during performing FSW is assumed to be $20°C$. The flow stress of AZ31 is according to experiment of Chang[11] on the hot working flow stress of Mg-3Al-Zn. A three-dimensional FE analysis for temperature distribution of workpiece is proposed to investigate the thermal distribution and history of magnesium alloy sheet during the FSP.

Calculation Results and Discussion

The magnesium AZ31 is fixed on the table of machine. The tool pin is forced downward with a constant rotating angular speed $800rpm$. After the shoulder touch the top surface of workpiece, the magnesium AZ31 moves on the Y-axis of sheet with a fixed speed, $V = 1.5mm/s$. This paper includes 45 seconds for the entire simulation for AZ31 friction stir process.

Fig. 3 shows the line contour of calculated temperature of workpiece ($24.75s$). The high temperature is around the tool. The higher temperature is near the center of tool pin and the temperature gradient is steeper at front side of tool. The higher temperature is concentrated on the interface between the tool and workpiece. It is because that the shear deformation of workpiece is larger on the sheet. The material is easily yielded due to the shear deformation of workpiece. Fig. 4 shows the line contour of effective stress of workpiece ($25.43s$). The effective stress near the tool pin is larger than that near the shoulder. Due to the material of workpiece is constrained by the material around the tool, the plastic flow near the pin needs larger effective stress to be yielded.

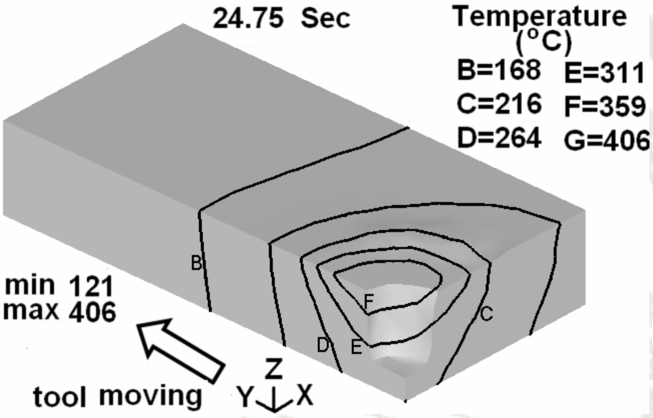

Figure 3 Line contour of calculated temperature of workpiece.

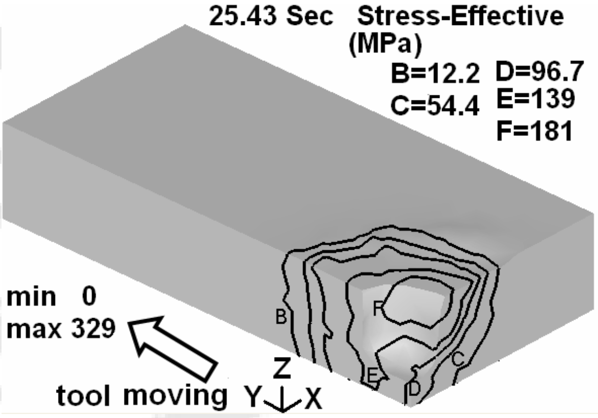

Figure 4 Line contour of effective stress of workpiece.

Fig. 5 shows the line contour of calculated effective strain of workpiece ($24.75s$). The effective stress gradient near tool is similar the nugget and the temperature distribution under the shoulder. The effective stress near the pin is larger than that of base material of workpiece. The plastic flow near the pin is easily drugged due to the interface friction of tool/workpiece. Fig. 6 shows the line contour of calculated effective strain rate of workpiece ($24.75s$). Those illustrate the strain rate distribution are like those in Fig. 5. The strain rate gradient is concentrated on the tool pin. It is because the shear deformation of workpiece is more obviously due to friction between tool/workpiece.

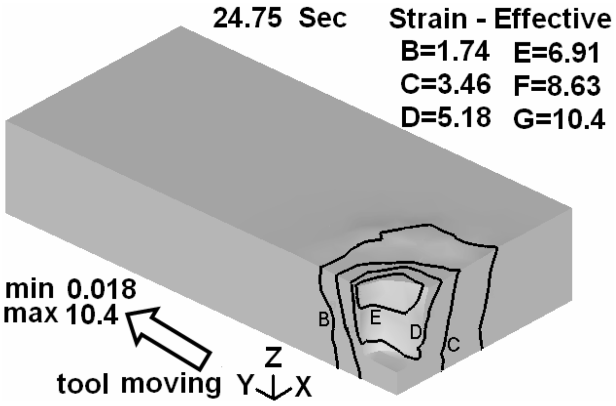

Figure 5 Line contour of effective strain of workpiece.

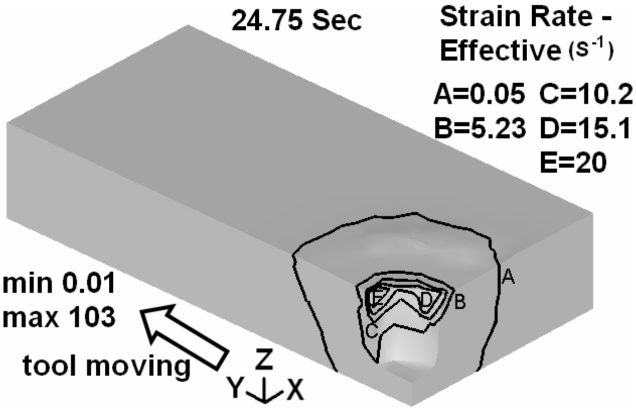

Figure 6 Line contour of calculated effective strain rate of workpiece.

The line contour of damage is shown in Fig. 7. Beside the thermal mechanical model for calculating the temperature distribution of workpiece, the damage can be also obtained by using this FEM model. The damage is identification parameter illustrate the possibilities of workpiece failure during FSW procedure. As shown in Fig. 7, the most possibly fracture occurs near the central line of the tool pin. Avoid the tool or workpiece fracture can enhance the life of tool pin and increase the product of workpiece of FSW. The design of the tool shoulder and tool pin also can be modified by experimental work but it costs much. The fracture phenomenon of workpiece during is important information for designing the tool pin. It causes the larger damage parameter near the tool shoulder. The maximum damage of workpiece may cause material or tool failure during Friction Stir Process. The modification of tool pin geometric profile can avoid the fracture of material and tool.

Fig. 8 shows the line contour of direction of total velocity of workpiece. The plastic deformation is almost near the welding path as tool pin moving. It is because the friction between tool with workpiece and straight moving of tool pin. On the other word, the distortion of workpiece near the tool is more obvious as the tool pin rotates. The maximum of total velocity occurs near the tool pin, it similar to the effective strain rate distribution of workpiece in Fig. 6. From Fig. 3, 5, 6and 8, is can be obtained the similar distribution of temperature, strain, strain rate and total velocity. The TMAZ caused by the friction between the rotating tool and workpiece can be identified. It proves the existence of TMAZ by using FEM simulation.

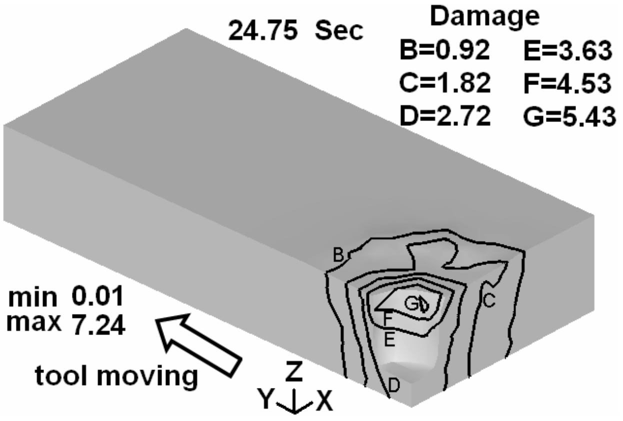

Figure 7 Line contour of damage of workpiece.

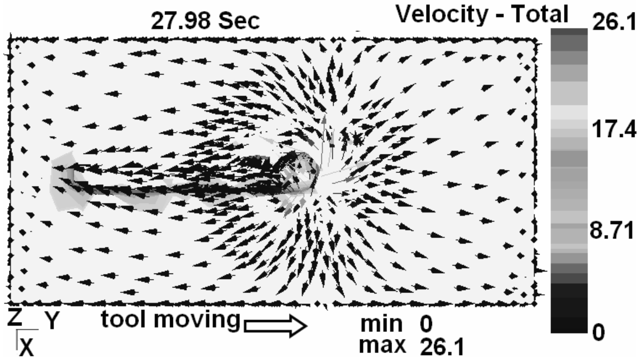

Figure 8 Total velocity distribution on the workpiece.

Fig. 9 shows the position of temperature points of T1, T2, T3 and T4. T1, T2 and T4 are located on the center line on workpiece. T1 and T3 are located on the middle of length of the workpiece.

The Z-direction value are 1mm in T1, T2 and T3 but 8mm in T4. Fig. 10 shows the temperature history diagram of T1, T2, T3 and T4. Because the temperature gradient near the pin tool is steeper, the peak temperature of each curve is occurs when the tool pin pass by the temperature point. The maximum temperature is located at T4 when the FSP is finished.

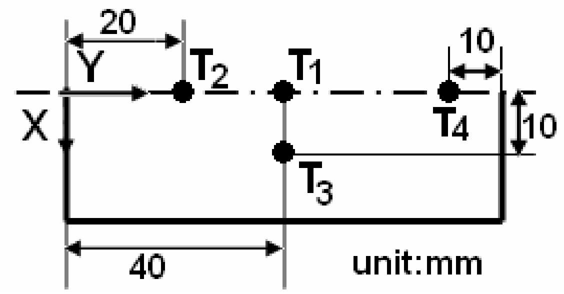

Figure 9 Position of temperature points of T1, T2, T3 and T4.

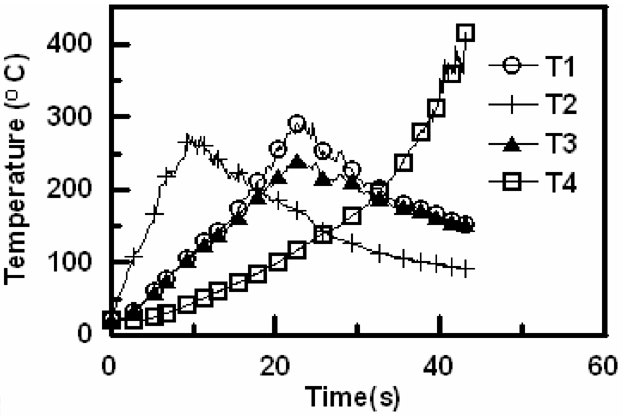

Figure 10 Temperature history diagram of T1, T2, T3 and T4.

Conclusion

A numerical study on the thermal mechanical model of FSW in a three dimensional coordinate and meshed by rigid-plastic elements has been developed by using a commercial code Deform 3D in this paper. The workpiece of magnesium AZ31 is the simulated results offer knowledge of the heat transfer process for the workpiece in the friction stir welding process. It provides useful data for designing the friction stir welding process. Several conclusions can be obtained as followings:

(1) This thermal mechanical model of FEM is useful for simulating the heat transfer process in FSW. The distribution of temperature, strain, strain rate and damage around the tool pin during FSW has been obtained. It can help design the FSW process and prevent the workpiece from being damaged during FSW.

(2) The temperature distribution fields, strain and stress fields obtained at each step are significantly useful for estimating the TMAZ and TAZ of workpiece under the tool pin. These numerical simulation results can provide a useful knowledge of designing the tool dimension in a FSW process.

In the future, the three dimensional FEM analysis of FSW with the material properties such as grain size model will be investigated. The microstructure model due to strain, strain rate and temperature needs to be included in a three dimensional FEM simulation to determine the grain size of workpiece in FSW

Acknowledgements

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