A Study on Welding Residual Stress by Numerical Simulation on Friction Stir Welding

H. S. Bang, H. J. Kim, M. S. Go, W. S. Chang and C. W. Lee

Abstract

The Friction Stir Welding (FSW) is a new joining method that was developed at The Welding Institute (TWI) in England in 1991. It applied heating by the rotational friction and material plastic flow. It was developed as a new joining method to solve the problems of epochally in the welding of Al alloys. In the study, 6000series of Alloy composed of Al-Mg-Si, one of the Al alloys that are utilized for shipbuilding and construction, is selected as a specimen and the numerical is executed against the welded zone of FSW. The material used in this study had the unique properties of strength and anti-corrosion, but since the welded joint of this material is easily softened by the welding heat, FSW is executed and the numerical analysis is carried out around the joint. To examine the mechanical behaviors and properties, F.E.M analysis is executed and the developed thermal- elastic-plastic finite analysis are used.

Key Words : Friction Stir Welding (FSW), Plastic flow, Anti-corrosion, Numerical analysis, Mechanical behaviors, F.E.M analysis, Thermal- elastic-plastic finite analysis

1. Introduction

Al-alloy is light and has a good tensile strength, elongation and tenacity to bear heavy load and weight. Also, it is utilized widely as a lightweight material for an automobile, a vessel and many kinds of equipment, due to the properties of hot working, cold working and corrosion-resistance. But the Al-alloy welding done by existing fusion welding have some economical and technical problems. On the other hand, Friction Stir Welding (FSW) that is a new joining method can settle the disadvantage that occur in fusion welding and is being applied and extended into the various industry fields[1]. In this study thermal-elastic-plastic finite analysis program with finite element method was used to accurately analyze the mechanical properties of an area joining by FSW in Al 6061. The size of HAZ and the thermal distribution is simulated and the mechanical properties around the FSW joining area to the Al-alloy 6061 are examined[2].

In general, medium carbon steels are utilized for axle, crankshaft, bolts, gear and parts of machines that require durability and an anti-abrasion property.

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2. The formularization of the finite element method in the thermal- elastic-plastic theory

In the question of the thermal stresses, the unsteady state thermal conduction of the continuous material, the thermal distribution varying with time is to be found out. Since the thermal strain varies with the variation of the temperature, it is called an initial strain. Furthermore, since the physical quality of the material organizing each element varies with the temperature, the relative equation between the nodal force and nodal displacement is to be formulized considering the thermal effect. Therefore, in the program for analyzing the welding residual stresses on the temperature dependency of the material constant (such as yield strength, the elastic modulus, heat expansion coefficient. etc) were considered through the entire elastic -plastic zone considering the material isotropic, depending upon the temperature. Moreover, the yield condition of Von-Mises considering The Linear Isotropic Hardening Rule is used as a yield function in the plastic region. The four-nodal isoparametric elements are used as a usage factor. The relation between the strains and the stresses is expressed as an incremental formula being based on the plastic-flow theory. Therefore the accuracy of the analysis is heightened. The increment of the total strain consists of the resultant of the elastic-plastic and the thermal strains as shown in the equation below[3].

$$\{d\varepsilon\} = \{d\varepsilon^e\} + \{d\varepsilon^p\} + \{d\varepsilon^t\}$$

Where

$\{d\varepsilon^e\}$: Elastic strain,

$\{d\varepsilon^p\}$: Plastic strain,

$\{d\varepsilon^t\}$: Thermal strain

3. Analysis method and welding condition

The principal dimension of the model for the analysis is given in Fig. 1, (L=300mm,B=300mm,T=4mm) respectively.

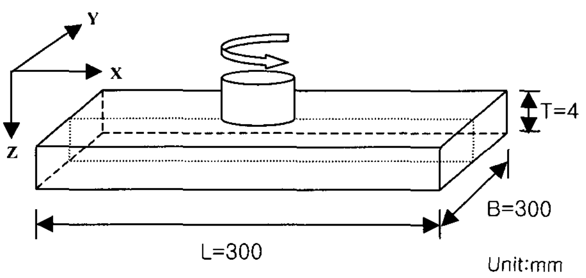


Fig. 1 Configuration of FSW specimen

X, Y and Z indicate the weld line direction, width direction and thickness direction respectively in the analysis model. The material for analysis is Al 6061-T6, and the joining of the specimen is implemented under the conditions that are the rotational speed (1500rpm) and travel speed (500mm/min). Table 1 shows welding condition from the tests[4]. Under constant pressure from the shoulder, the test was carried out repeatedly to get an excellent bead with changing rotational speed and a welding speed among the various process variables. The chemical composition and mechanical properties of the specimen are given in Table 2.

Table 1 Welding Condition

Parameter	Condition
Rotation speed	1500 (rpm)
Welding speed	500 (mm/min)
Shoulder (D)	15mm
Pin (D)	5mm
P	50 (MPa)
Friction Coeff.	0.42
Welding method	Butt

Table 2 Chemical composition and mechanical properties of specimen

Chemical composition (wt%)			
Al	Fe	Si	Cr
98	0.7	0.4-0.8	0.04-0.35
Mg	Cu	Mn	Zn
0.8-1.2	0.15-0.4	0.15	0.25

Mechanical properties		
Yield stress (MPa)	Elongation (%)	Tensile stress (MPa)
55	25	240
Density (g/cc)	Heat conduction Coff.	E (kg/mm^2)
2.7	0.40	7070

To accurately analyze the mechanical characteristics of a welded area by FSW, The Finite Element Method (FEM) introduced the theory of thermal- elastic- plastic. The element and node of the model use the four-nodal Isoparametric element. The welding area regarded as having the largest effects is meshed as shown in Fig. 2 considering tool shoulder and diameter of pin[5]. The minimum size of the elements at joining centerline is 0.3mm×0.3mm in detail and the more distance from welding area the wider mesh is drawn. The element number is 2820 and the node number is 2945 respectively.

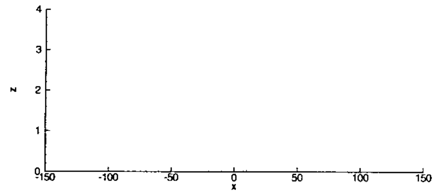


Fig. 2 Schematic mesh generation for analysis of FSW (Unit; mm)

4. Boundary condition

The thermal-elastic-plastic analysis of the FSW welded zone considered thermal history as input data. The boundary condition of thermal elasticity is considerate of the time of shrinkage, expansion and the development of manufacturing. The boundary condition is selected as shown in Fig. 3[6].

Under the considered shrinkage, expansion and a phenomenon while the specimen id fabricated, and the thermal history occurred during the joining specimen is regarded as an input data.

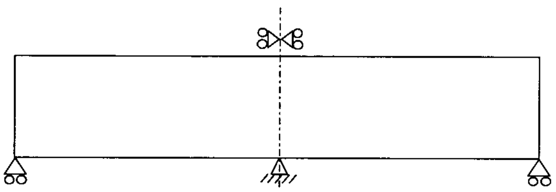
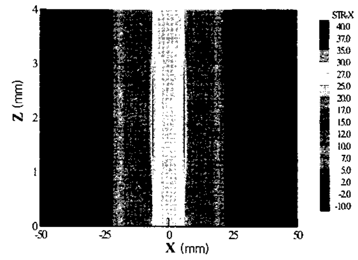
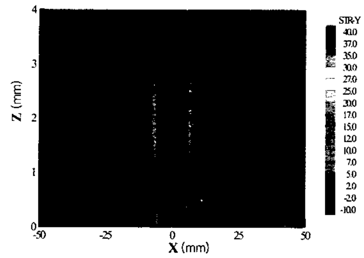


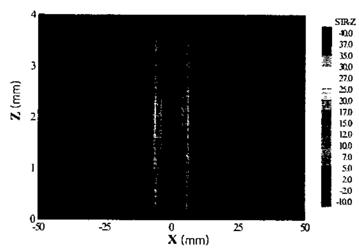
Fig. 3 Boundary condition



(a) Welding residual stress - σ_x (kg_f/mm^2)



(b) Welding residual stress - σ_y (kg_f/mm^2)



(c) Welding residual stress - σ_z (kg_f/mm^2)

Fig. 4 Residual stress distribution of FSW (At Z=1.5mm from the surface)

5. Results and considerations

The thermal distribution history from the analyzing the conduction of the heat is used as input data and the mechanical phenomenon from the result of analyzing the Al 6061-T6 alloy by the thermal-elastic-plastic program is investigated. Fig. 4(a) illustrates the stress (σ_x) in the longitudinal direction and shows that the stress distributes intensively in the SZ, TMAZ and HAZ of welded joint. The maximum tension stress appeared in the friction of the pin at the central area of the specimen (X= -3, 3mm). The compression stress is shown apart from the welded area. Fig. 4(b) and Fig. 4(c) illustrate the stress (σ_y) perpendicular to the longitudinal axes and the stress (σ_z) in the direction of the thickness of the specimen and show that tension stress appears a little around the pin and compressive stress appears apart from the welded area.

Fig. 5 shows the distribution of residual stresses at the upper surface in a widthwise direction. The residual stresses have a differential value around the pin. The component of residual stress in weld line direction that is larger than that in width direction and that in thickness direction, represents compressive stress and tensile stress. The magnitude of residual stress is σ_x > σ_y > σ_z .

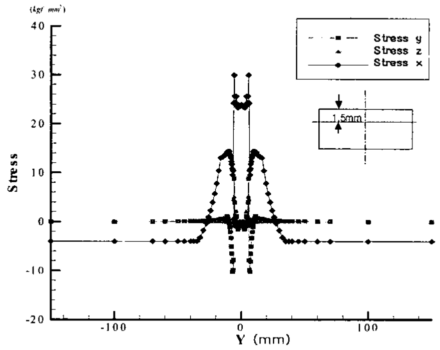


Fig. 5 Residual stress distribution of FSW (At Z=1.5mm from the surface)

Fig. 6 graphs the distribution of the welding residual stress according to the thickness of the specimen (Z=0.2,0.6,1,1.4,2.2,3.3,3.8cm). It presented a welding residual stress that is much bigger at Z=2.2mm, and it shows that the graphs have similar shape but make little differences.

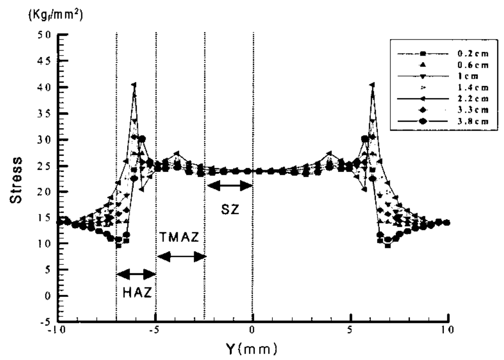
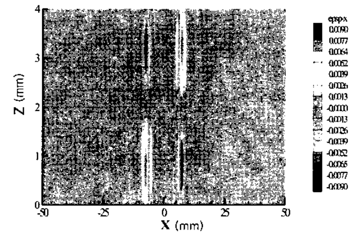


Fig. 6 Residual stress distribution of FSW according to the thickness (At Z=0.2,0.6,1,1.4,2.2,3.3,3.8cm)

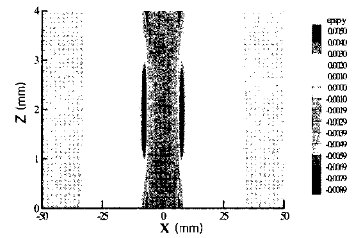
The plastic strains through the entire specimen (in weld line direction and width direction) were shown as contour type graphics in Fig. 7. The compressive strain and the tensile strain in weld direction intersect each other between base metal and around the pin. Also, the plastic strain in weld line direction is larger than that in width direction. The compressive plastic strain is shown between SZ and heat affected zone (HAZ) and the tensile plastic strain is shown at the end in the width direction. Also, The compressive plastic strain and the tensile plastic strain between heat affected zone and base metal rapidly intersect each other.

Fig. 8 shows plastic strain at 1.5mm below the upper surface in the mid-section. The component of plastic strain in weld line direction (ε_x^p) indicates a compressive component in SZ, TMAZ and HAZ and shows a tensile component in base metal.

Furthermore, the component of plastic strain in width direction (ε_y^p) has the opposite appearance, and the compressive component and the tensile component cross between HAZ and base metal. Also, the magnitude of the welding residual plastic strain component is $\varepsilon_x^p > \varepsilon_y^p$.



(a) Plastic-strain along x-direction



(b) Plastic-strain along y-direction

Fig. 7 Plastic-strain distribution of FSW

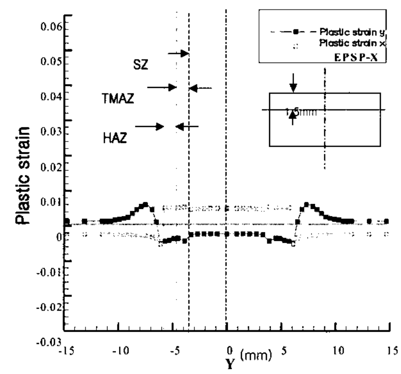


Fig. 8 Comparison of plastic strain distribution (At Z=1.5mm from the surface)

6. Conclusion

The following conclusions are obtained from this study

1. The existing fusion welding is accomplished by the method which melts the base metal over a fusing temperature. But, the FSW is accomplished by friction between the base metal, pin and shoulder below melting point. Characteristics of the welding area from a numerical analysis depend on the rotational speed and joining speed among the various joining process variables.
2. The stress distribution through the numerical analysis is in tension in the central region of joined zone and the magnitude of stress is $\sigma_x > \sigma_y > \sigma_z$. It is considered that this is caused by the stiffness because of the geometrical restriction of the specimen.
3. The intensive stress distribution is discovered at the SZ, HAZ, and TMAZ by the frictional stir action of the pin. The plastic strain distribution crosses rapidly between HAZ and the base metal but has a small-scale magnitude.

In the study, after analyzing the zone joined by FSW in Al-alloy using the F.E.M program through two-dimensional analysis the mechanical characteristic of the joined area is clarified.

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