JMEPEG (2010) 19:481–487
DOI: 10.1007/s11665-010-9608-2

1059-9495/$19.00

Thinning Behavior Simulations in Superplastic Forming of Friction Stir Processed Titanium 6Al-4V

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(Submitted December 8, 2009; in revised form January 18, 2010)

A study was undertaken to simulate the thinning behavior of titanium 6Al-4V alloy sheet during Superplastic Forming and to evaluate the feasibility of controlling thinning in areas of interest with Friction Stir Processing (FSP) of the material. The commercially available Finite Element Analysis software ABAQUS was used to execute these simulations. Material properties of the parent sheet and the Friction Stir Processed regions input into the models were determined experimentally by elevated temperature tensile testing. The results of these simulations were compared to experimental test results via Superplastically Forming representative aerospace parts and analytical computations for validation. It was found that numerical simulations can be used to predict the thin-out characteristics of superplastically formed titanium parts and the thin-out can be controlled in desired areas by FSP, locally, prior to forming.

Keywords ABAQUS, finite element analysis, Friction Stir Processing, Friction Stir Welding, simulation, Superplastic Forming

1. Introduction

Friction Stir Welding (FSW), or Friction Stir Processing (FSP), is a solid state joining process that can also be used to alter the grain structure of the parent material. This is a dramatic difference from traditional fusion welding processes where large, coarse grained, cast type microstructures are produced in the weld nugget. Because the microstructural integrity of FSW joints is similar to the parent material, the mechanical properties of the joints will be closer to that of the parent material than for fusion welds. Since its inception in 1991 (Ref 1), FSW has been successfully applied to joining aluminum, magnesium, copper, and even steel (Ref 1-3).

In FSW, a rotating tool is plunged between the abutting faces of two materials under a vertically applied forge load. This rotating tool is then translated along the joint line, as shown schematically in Fig. 1. As the tool surface contacts the workpiece under the downward forge load, an enormous amount of frictional heat is generated. The frictional heat locally softens the material to the point where the flow stress is reduced and work piece material begins viscous flow around the tool pin. Joints are produced by extreme plastic deformation in the workpiece materials. During the process, the temperature of the weld never exceeds the melting temperature of the work piece (Ref 1).

Only recently has FSW, or FSP, been applied to titanium (Ref 3-9) due to the difficulties associated with pin tool wear and survivability, which is because of the high temperatures and forces that are required. Over the past several years, pin tool materials and processing conditions have been identified, most of which are still proprietary in nature, that have been used to produce high quality friction stir welds in titanium. A typical macrograph of a weld made during the course of this study in shown in Fig. 2. In order to successfully FSW high temperature materials such as titanium, it was found that special tungsten alloy rotating pin tools must be used in conjunction with thermal management strategies, such as active water cooling of the tooling and equipment.

The titanium FSW process has sparked much interest in the aerospace industry as it could play a major role in next generation manufacturing techniques. One manufacturing process that FSW will have a dramatic effect on is near net shape superplastic forming (SPF). SPF is an advanced metal forming process which takes advantage of metallic materials to undergo large plastic strains with minimal amounts of necking and strain hardening, Fig. 3 (Ref 5, 10). In SPF highly complex near net shape sheet metal parts can be formed from stock sheet in a single operation. SPF has been successfully applied to many materials, but it is commonly used with aluminum and titanium for industrial applications.

Attempting to SPF sheets with fusion welds generally results in either tearing or severe thinning of the parent material during the forming process because the large grained microstructure in the fusion weld nugget is not superplastic. Superplastic materials require very fine grained microstructures to allow grain boundary sliding. In the coarse grained fusion weld microstructure, strain during SPF is forced into the parent material directly adjacent to the weld nugget causing premature necking and failure as shown in Fig. 4 (Ref 11). In contrast to fusion welds, FSW is capable of retaining the microstructural

This article is based on a presentation at the AeroMat Conference, International Symposium on Superplasticity and Superplastic Forming (SPF) held in Austin, TX, June 23-26, 2008.

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integrity of the resulting joint, and thus, the SPF characteristics of the parent material are retained. Furthermore, the microstructure of the FSW can be controlled with the processing parameters to promote more, or less, forming in the weld nugget compared to the parent material. By using FSW to join multiple sheets of titanium, large blanks can be created for monolithic SPF operations (Ref 12). FSW can also be used to produce local gage reductions or thickness pad-ups as desired in the final part.

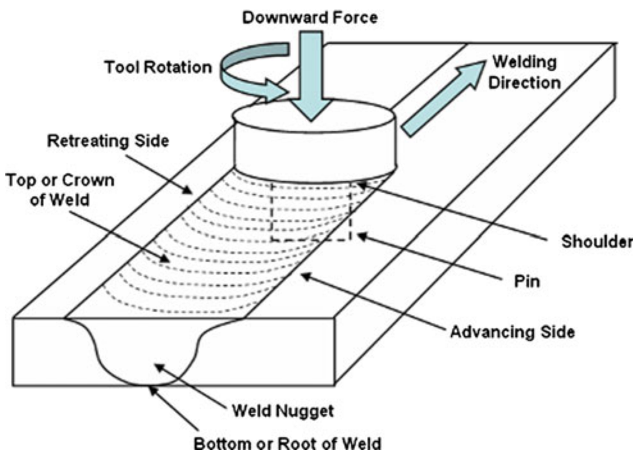

Fig. 1 Friction Stir Welding schematic

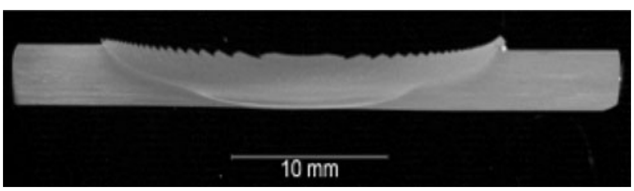

Fig. 2 Typical FSW cross section showing gage thickness reduction in weld zone

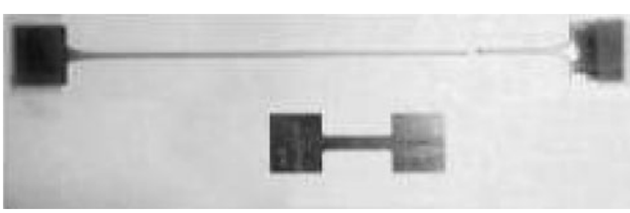

Fig. 3 SPF tensile specimen (Ref 10)

In typical SPF applications, the thin-out of the sheet during forming plays a critical role in the design of the part. In many cases, the thinnest area of the formed sheet must meet the minimum gage requirements of the part. This often results in the rest of the part being too thick, and thus too heavy. It is also potentially too expensive to be economically advantageous. If it were possible to predict and control the thin-out behavior of an SPF part by locally altering the microstructure and the resulting SPF behavior via FSP, it may be possible to achieve more flexibility in the manufacturing process, leading to more efficient part designs.

To date, there has been limited research reported on the combination of FSW with SPF for producing titanium structural components. Recently, a university-industry collaborative FSW-SPF research project was undertaken at the University of Washington. Preliminary experimental evaluations and simulations of the mechanical properties of FSW and SPF-FSW titanium joints have shown promising results (Ref 12-14). However, one of the difficulties associated with superplastic forming of parts that contain friction stir welds is predicting the thin-out characteristics in both the weld and in the parent material. Thus, the goal of this work has been to simulate SPF of titanium sheet containing FSW, or FSP areas, in order to predict and control the final thickness of the welds and base metal in the formed part.

2. Experimental Material Property Evaluations

In order to obtain the material properties of the parent material and FSP areas required for SPF thin-out simulations, extensive elevated temperature tensile testing was conducted on both Ti64 sheet and Ti64 FSW sheet manufactured using various processing parameters at the Edison Welding Institute. Tensile Specimens were fabricated from FSW test panels in such a way that the weld would be located in the center of the gage length. The specimens were also oriented such that the welding direction was perpendicular to the loading direction, or long dimension of the coupon. This facilitated evaluation of the transverse SPF properties of the weldments. The testing was designed to approximate the thermal and forming conditions seen in a real part. A total time in furnace (including bringing

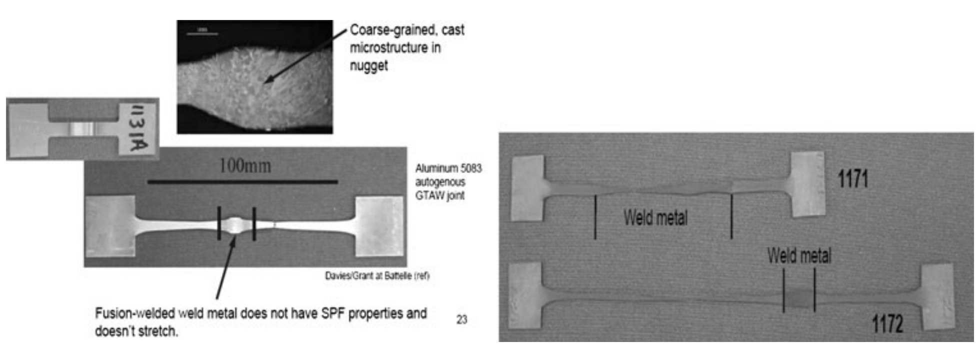

Fig. 4 SPF tensile specimens with Gas Tungsten Arc Weld (GTAW) fusion weld (left) and friction stir welds (right) (Ref 11). Friction stir welds can be made with high (top) or low SPF performance (bottom)

the part up to temperature) of 40 min was used. The test was also run to 50% engineering elongation which was the target total strain. These numbers would be adjusted if the material was to be tested for a part that was expected to have a different forming time or temperature.

All general conditions of the test apparatus, sample preparation, dimensions and method for gripping the sample, and test conditions follow ASTM E 2448-06. Tensile sample dimensions of welds extracted transverse to the welding direction are based on the width of the friction stir tool, or weld width. Samples were tested at 900 °C at a true strain rate of 3.0×10^{-4}. The samples are pulled to a total engineering elongation of 50%. The tests are run at a constant strain rate that is determined by picking a required time at temperature and total elongation, and calculating the strain rate needed to achieve this elongation in the allotted time. All tests had a fixed 10 min in-furnace pretest period for the sample to reach temperature. This time hold is based on temperature measurements taken from thermocouples within the grip and touching the back of the grip section of the actual specimen. After the pretest warm-up, the experiments were run to the predetermined total elongation at which point the test is stopped, the load is removed, and the sample withdrawn from the furnace. Base material tensile specimens are also tested in this fashion to determine the stress and strain relationships under simulated SPF conditions. A typical elevated temperature stress vs. strain curve for Ti 6Al-4V is shown in Fig. 5.

A typical aerospace component was also produced by SPF for comparison and validation of the numerical models, Fig. 6. The starting sheet metal thickness of the formed part was 0.050″. The sheets were formed at approximately 770 °C under a specially designed pressure schedule to maintain a constant true strain rate of 3E−4 in/in per second during the entire SPF processing cycle.

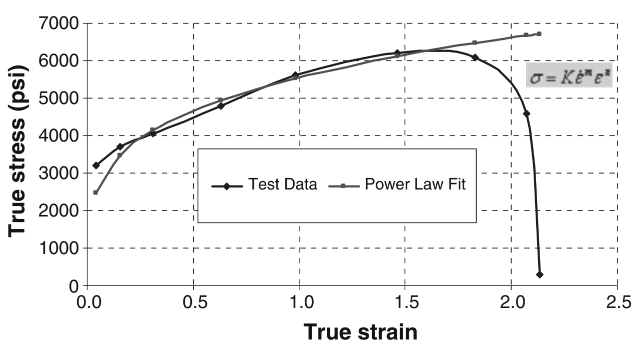

Fig. 5 Typical Ti 6Al-4V stress strain curve under simulated SPF conditions

Fig. 6 Actual SPF part formed for comparison to numerical models

3. Finite Element Modeling Methods and Procedures

The first step in developing a finite element model to simulate the SPF process was to define the material model and the appropriate material properties for input into the numerical analysis code. In experiments, the material model used to define the stress vs. strain behavior is the power law relationship given in Eq 1. The experimental properties for Ti 6Al-4V that fit this material model were empirically found to be $K = 9500$, $n = 0.25$, $m = 0.35$ at a strain rate of 3E−4. In the finite element analysis package ABAQUS, the material model used is a Rate Dependent Creep Plasticity model given by Eq 2. The constants K, m, and n, determined by curve fitting experimental data were translated into the constants A, p, and q by manipulating Eq 1 into the form of Eq 2. The resulting constants that match the ABAQUS material model behavior to the experimental results are $A = 5.612\text{E}{-10}$, $p = 2$, $q = -0.5$ at a target strain rate of 3E−4. These were the material constants that were inputted into the ABAQUS models for Ti 6Al-4V base material which were then subjected to simulated SPF conditions.

$$\sigma = K\dot{\varepsilon}^m \varepsilon^n \quad \text{(Eq 1)}$$

$$\dot{\varepsilon} = A\sigma^p t^q \quad \text{(Eq 2)}$$

where, σ is the stress, ε is the strain, $\dot{\varepsilon}$ is the strain rate, and t is the total time. A, K, p, and q are all material constants.

When inputting the material constants for the Friction Stir Processed areas into ABAQUS, three different cases were evaluated; (1) FSW possessed the same SPF properties as the parent material, (2) FSW has less SPF ability than the parent material, and (3) FSW has more SPF ability than the parent material. These different behaviors were observed experimentally by altering the FSP parameters. "Hotter" processing parameters (relatively high spindle and slow travel speeds) produced welds with significantly less superplastic elongation during testing than "colder" processing conditions (low spindle and fast travel speeds). However, by optimizing the FSP parameters, equivalent superplastic performance could be achieved. An example of this behavior is shown in Fig. 7, where welds made with varying spindle speeds and travel speeds were tested for SPF performance. The y-axis on these graphs gives the "P/W" ratio, which is the ratio between the elongation of the parent material in the test specimen to the elongation of the weld nugget, given as a function of the weld length on the x-axis.

For the purpose of simulating the thinning characteristics of a part containing Friction Stir Processed areas, or Friction Stir Welds, the material constants inputted into the ABAQUS model were varied to produce stress strain curves under SPF conditions that were either less, or more, superplastic than the parent material. Figure 8(a), shows the case inputted into the ABAQUS model for when the FSP material is less, by a factor of 3, superplastic than the parent material. On the other hand, Fig. 8(b) shows the case inputted into the models where the

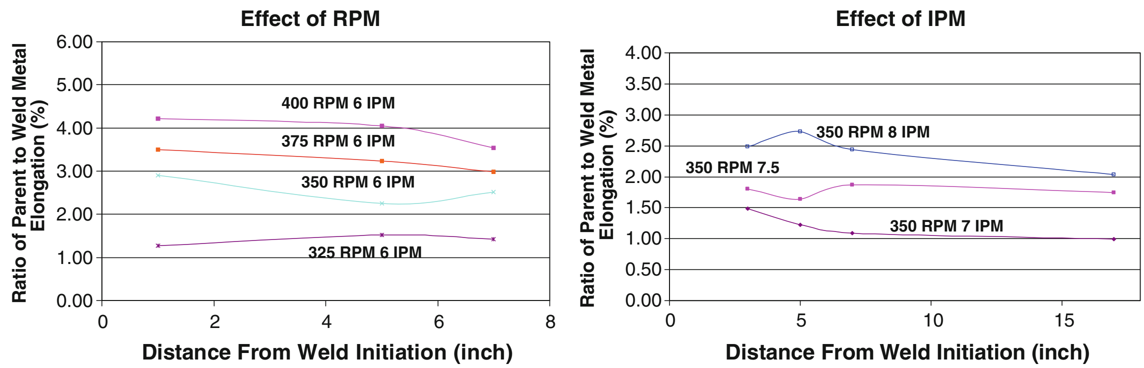

Fig. 7 (left) Superplastic performance of Ti 6-4 Friction Stir Welds as a function of spindle speed at a set travel speed and (right) as a function of travel speed at a set spindle speed

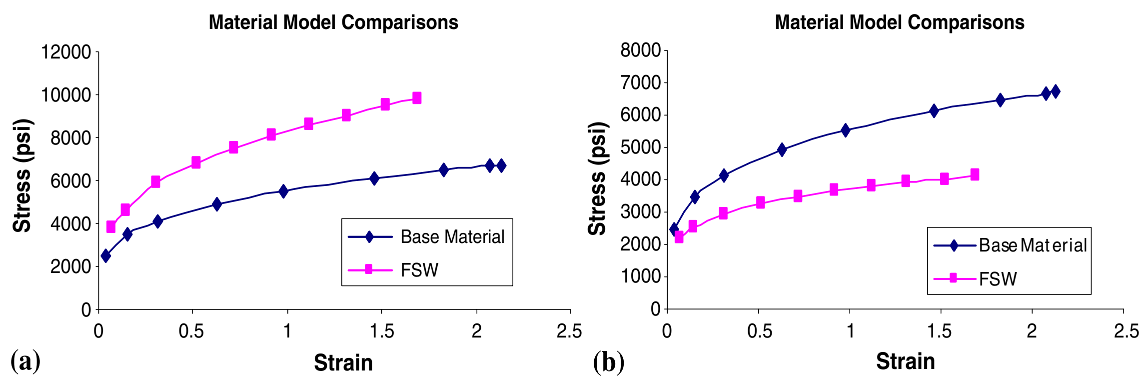

Fig. 8 (a, left) Stress vs. strain curve for FSW which is less superplastic than the base material and (b, right) Stress vs. strain curve for FSW which is more superplastic than the base material

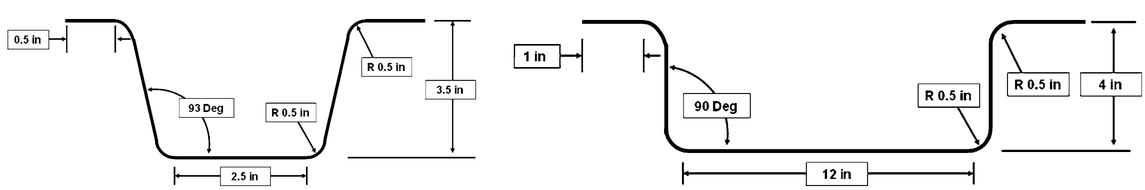

Fig. 9 Die geometries modeled for comparison to experimental test parts, left, and analytical calculations, right

FSP material is more, by a factor of 4, superplastic than the parent material. Both of these scenarios are illustrated in Fig. 8 as follows; at a constant forming pressure of 4000 psi, for the less superplastic FSW case in Fig. 8(a), the base material has elongated to 0.3 while the weld material has only elongated to a strain of 0.1. For the more superplastic FSW case in Fig. 8(b), at a constant forming pressure of 4000 psi, the base material has again elongated to 0.3, but the weld has elongated to a strain of 4.3. The material constants inputted into the ABAQUS material model for the less superplastic FSW case are $A = 5.612\mathrm{E}{-10}$, $p = 2$, $q = -0.6$, and $A = 5.612\mathrm{E}{-10}$, $p = 2$, $q = -0.4$ for the more superplastic FSW case.

Two different die geometries were modeled in ABAQUS for this study. The representative geometries are shown in Fig. 9. Both die surfaces were modeled as fixed, rigid bodies in ABAQUS. The die illustrated in Fig. 9(a) was the geometry used to form actual SPF test parts, shown in Fig. 6, in order to validate the FEA models to experimental forming trials. The second die modeled, Fig. 9(b), was wider so that it could be used to compare the numerical results to analytical calculations. A wider die had to be modeled for comparison to analytical thinning predictions because the analytic formulations required that the sheet being formed contact the bottom of the die before the side walls.

The titanium sheets modeled in this simulation study were either 0.050″ or 0.100″ thick. Friction Stir Welds were modeled as 1.0″ wide sections in the center of the forming blank, Fig. 12(a), with different material properties as outlined above, Fig. 8. It was found in previous studies that the tensile behavior of Friction Stir Welds can be accurately modeled by utilizing a simple Bi-material model (Ref 15). The forming die was defined as a rigid body and the forming sheet was constrained at the edges from being pulled into the die. The interaction between the forming sheet and the die was modeled as contact friction with a coefficient of friction of 0.3. A uniform pressure was applied to the top surface of the forming blank to form the sheet into the die, the magnitude of which was automatically controlled by ABAQUS to maintain a constant true strain rate of 3E−4 in the sheet. S4R elements with 4-node doubly curved thin or thick shell, reduced integration, hourglass control, and finite membrane strains were used for the forming blank. Elements were seeded in 0.1″ increments along the edge of the modeled forming blank. This led to approximately 500 elements on the forming blanks for each of the simulations.

A model was also developed to strategically place two FSW's in the forming blank so that the welds form into the corner of the die, Fig. 10. This model was used to predict and control the thin-out characteristics in the corners of formed parts that contain FSW's. Additionally, during FSW process, the tool pushes a small amount of material out of the weld zone causing the weld nugget to be slightly thinner than the parent material, Fig. 2. These thickness differences can cause complications when trying to achieve uniform forming of a welded blank. Thus, the welds were modeled as being slightly thinner than the parent material.

4. Results

The first simulation conducted was the forming of a 0.050″ thick Ti sheet, with no weld, into the die geometry which reflects the die that the actual test parts were formed into, Fig. 11(a). The model predicts a final part thickness of approximately 0.022″ in the bottom of the die. The actual test part thickness ranged from 0.022″ to 0.024″ in the portion of the part that corresponds to the bottom of the die. In addition to comparing the numerical simulations to actual parts, the model results were compared to analytical computations. Hamilton and Gosh (Ref 16) developed the equations that can analytically predict the forming pressures, stresses, and thicknesses of sheet metal during SPF. Based on these equations, a computer algorithm was developed to calculate the forming pressures, stresses, and thicknesses of a sheet during SPF as a function of the starting sheet thickness and die geometry. A numerical model was run with the wide channel die geometry for comparison to the analytical computations, Fig. 11(b). The numerical model found that final thickness in the part at the

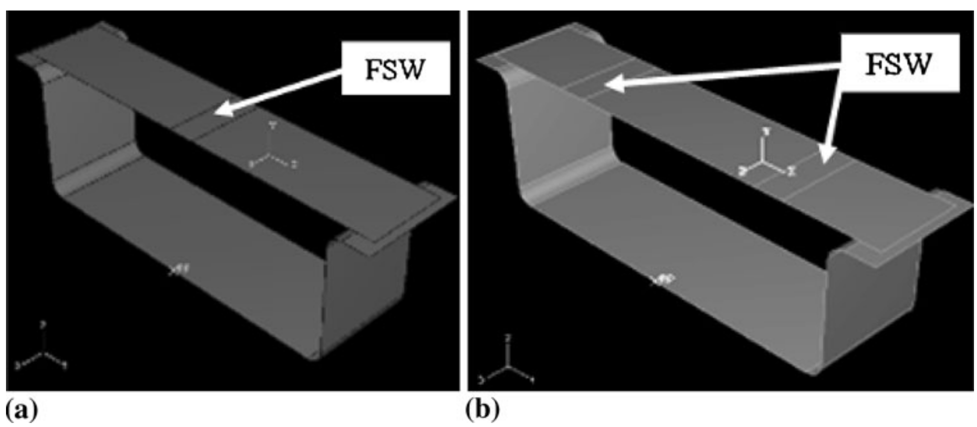

Fig. 10 Typical FEA models with various FSP locations. (a, left) Weld centered in forming blank and (b, right) welds placed to control thickness in corner of formed parts

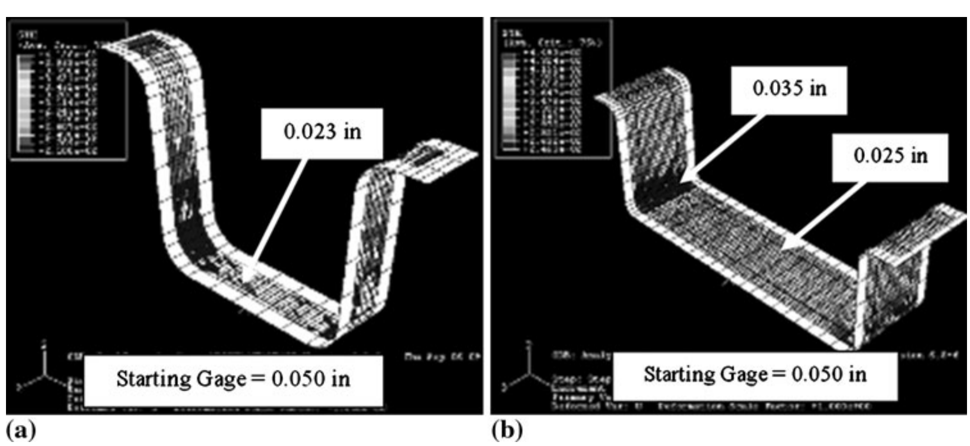

Fig. 11 (a, left) FEA simulation of a 0.050″ starting gage Ti 6-4 sheet being superplastically formed into a die that is representative of a typical aerospace component produced by SPF. (b, right) Simulation of SPF into a die that is compared to the analytical formulation of Hamilton and Gosh

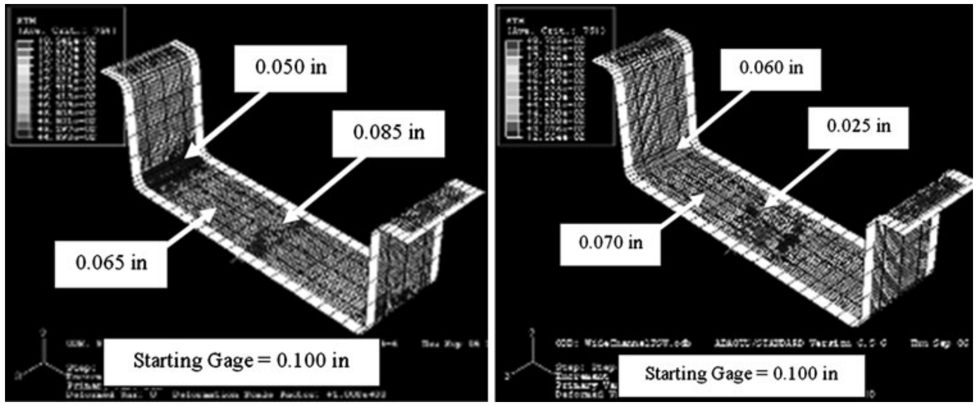

Fig. 12 SPF of FSW simulation where weld is three times less (left) and four times more (right) Superplastic than the base material

bottom of the die is approximately 0.035″ down to 0.25″ in the corners of the die. The analytical computations predict that the thickness in the corner of the die should be 0.017″ and 0.037″ in the center of the part at the bottom of the die.

Once base material SPF numerical simulations had been run for comparison to experimental and analytical results, FSW's were added into the model. The wide channel model was run with a weld in the center of the sheet. Figure 12 shows the post forming part thin-out results when the weld is less superplastic than the parent material and the thin-out results when the weld is more superplastic than the parent material.

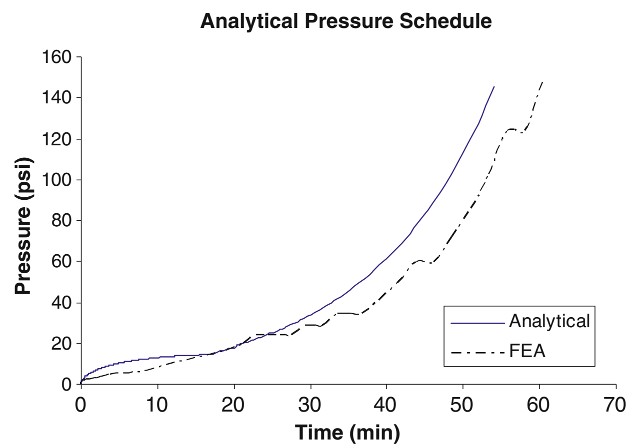

Fig. 13 Analytically and numerically determined pressure schedules to maintain a constant strain rate of 3E−4 in the forming blank during the forming cycle

5. Discussion

It has been shown that the numerical models developed during this study can be used to accurately predict the thin-out characteristics of a SPF part, even in the corner areas. Simulation results were compared to actual aerospace components formed to the same geometry in addition to analytic foliations with reasonable agreement. However, there was some discrepancy between the numerical models and the analytic thin-out formulations in the corners of the part. These differences between the predicted thicknesses at the corner of the part are due to the contact condition differences between the two models. In the numerical model, there is contact friction, but the part can still slip along the die surface, allowing more material to be pulled into the corner of the die. However, the analytical model assumes a no slip contact condition between the part and the die. This condition does not allow the material to be pulled into the corner of the die and causes the final thicknesses in the corners to be thinner than what would be expected in reality. It is common practice in industry to develop SPF pressure cycles based on the Gosh-Hamilton analytic models. Regardless of the differences between the predicted thin-out behaviors between the numeric and analytic models, the pressure schedule required to maintain a constant strain rate in the forming blank during the forming cycle calculated by the numerical model and by the analytical model are in reasonable agreement, Fig. 13.

The results of the FSW SPF simulations show that when the weld is more superplastic than the base material, excessive thinning occurs in the weld nugget. Conversely, when the weld is less superplastic than the base material, the weld zone will be thicker than the adjacent base material in the formed part. Based on these results, it can be shown that when FSW's are correctly placed on the forming blank, the properties of the welds can be adjusted to control the thickness of the final part in areas of interest. For instance, the welds can be placed to produce a more uniform thickness in the corner of the formed part compared to the adjacent parent material thickness, or the thickness of the formed part can be made thicker in the corner than the adjacent parent material, Fig. 14.

6. Summary

It has been shown that finite element modeling can be used to accurately predict the final thicknesses of SPF parts. Furthermore, SPF simulations of parts that contain FSW's, or FSP areas, whose properties may be more or less superplastic than the parent material have also been carried out in order to determine thin-out characteristics in the final part. These modeling procedures can now be applied to the forming simulations of more complex geometry parts to predict how FSW's will affect the final thickness of the part. Follow on studies should be conducted to experimentally SPF parts with

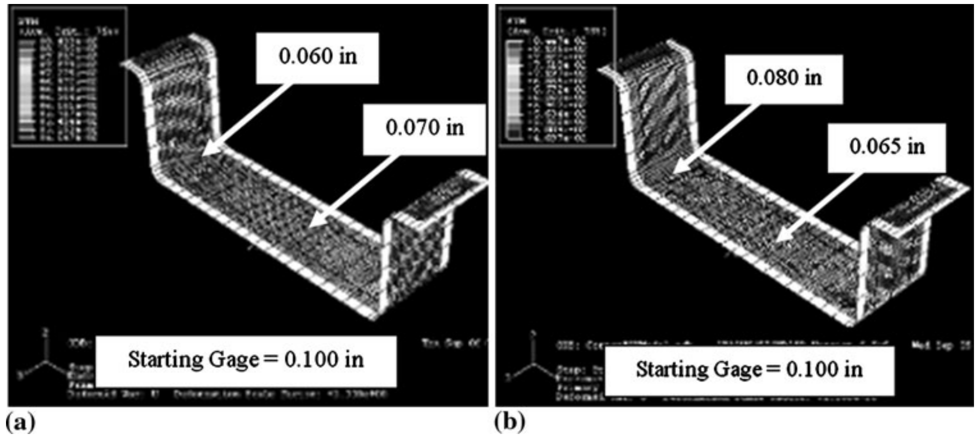

Fig. 14 Forming simulations with a Friction Stir Process blanks (shown in Fig. 12 right) to control the thickness of the formed part in the corners. (a, left) Weld is processed to give it superplastic characteristics that produce a part with more a uniform corner thickness. (b, right) Weld is made to have less superplastic ability than the parent material, creating a part with thicker corners

strategically placed FSW's to attempt and locally control the thickness of the formed part.

Acknowledgments

The authors of this article would like to thank The Boeing Company for their support throughout this research project. Thanks are extended to The Edison Welding Institute for providing the welded specimens and Pacific Northwest National Laboratories for elevated temperature tensile testing of the base and weld materials.

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