

Accepted Manuscript

A novel method for improving fatigue life of friction stir spot welded joints using localized plasticity

Soran Hassanifard, Masoud Mohammadpour, Hossein Ahmadi Rashid

PII: S0261-3069(13)00732-2

DOI: <http://dx.doi.org/10.1016/j.matdes.2013.07.098>

Reference: JMAD 5718

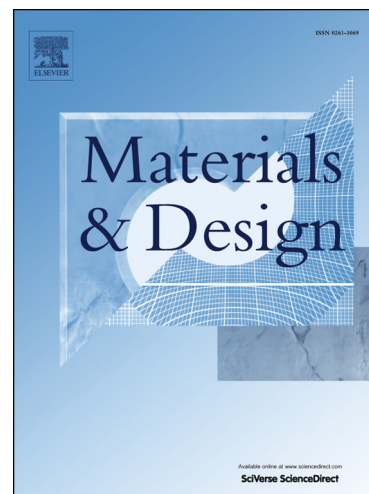
To appear in: *Materials and Design*

Received Date: 18 March 2013

Accepted Date: 31 July 2013

Please cite this article as: Hassanifard, S., Mohammadpour, M., Rashid, H.A., A novel method for improving fatigue life of friction stir spot welded joints using localized plasticity, *Materials and Design* (2013), doi: <http://dx.doi.org/10.1016/j.matdes.2013.07.098>

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.



A novel method for improving fatigue life of friction stir spot welded joints using localized plasticity

Soran Hassanifard¹, Masoud Mohammadpour^{2*}, Hossein Ahmadi Rashid³

1,3- Faculty of Mechanical Engineering, University of Tabriz, Tabriz, Iran

2- Mechanical Engineering Department, Faculty of Engineering, Urmia University, Urmia, Iran

Email: st_m.mohammadpour@urmia.ac.ir

Tel: +98 411 5276756

Abstract

This study introduces a new method for enhancing the life and strength of friction stir spot welded (FSSW) joints using a localized plasticity process. The aim of this investigation is to evaluate the effect of cold expansion on the improvement of fatigue life of FSSW joints in aluminum alloy 7075-T6 plates through conducting experimental and numerical procedures. In the experimental section, the fatigue tests were carried out using constant amplitude load control servo-hydraulic fatigue testing machine on the as-welded and cold expanded FSSW joints with cold expansion level of 3.3%. In the numerical part, three-dimensional finite element models were implemented to calculate stress and strain distributions in two batches of specimens using two multi-axial fatigue criteria: Smith-Watson-Topper and Fatemi-Socie. The obtained experimental and numerical S-N data revealed that the cold expansion method could improve the fatigue life of FSSW joints in all load ranges so that in high cycle regimes, it could improve the fatigue life up to six times. Although the results revealed that there is a relatively good agreement between estimated fatigue lives and experimental data in reasonable fatigue life regime, considering the fatigue crack growth life can lead to better estimation.

Key words: Multi-axial fatigue criteria, Finite element, Residual stress, Friction Stir Spot Welding.

1. Introduction

Friction Stir Spot Welding (FSSW) technology is being targeted at modern automotive and aerospace industries in order to resolve the significant issues such as: energy saving, environmental preservation, fuel economy improvement, and performance. One of the efficient procedures is through replacing conventional iron based alloys with light and high strength materials such as aluminum, magnesium and reinforced polymer composites in fabrication of vehicles, as reported by Blawert et al. [1], and Davies [2]. These mentioned alloys are difficult to fusion weld, and their mechanical properties are drastically attenuated by fusion welding process, as reported by Cavaliere et al. [3]. The resistance spot welding (RSW) with some privileges like high tolerance to poor part fit up compared with fusion welding techniques is commonly employed for joining steel sheets; however, this method leads to poor mechanical performance [4, 5]. Generally, friction stir welding (FSW) is a revolutionary joining method which was introduced by TWI in 1991[6] with various advantages such as good retention of baseline mechanical properties, little distortion, and low residual stresses in comparison with traditional welding techniques. German factory GKSS [7] has recently applied friction welding process for spot welding, called friction stir spot welding (FSSW). In this new generated solid-state joining process, the specimens are connected to each other based on friction heating on the facing surfaces of predesigned special tool and sheets. The stirring process plays an important role in producing a plastically deformed zone around the pin. This new invented technology has been adopted by Mazda Motor [8] in mass production of hood and rear door of the sport model Mazda RX-8. In FSSW the whole process of welding occurred under the melting point of welded alloys. That's why it is appropriate for low melting point materials such as Al and Mg. Due to overwhelming development in application of this welding technique, many researchers have been allured to study the several aspects of this technology.

The main issues are micro-structural and mechanical characteristics of the joints, optimization of welding process parameters, capability in joining dissimilar materials, strength of the joints which are influenced by deviations in process parameters, and fatigue life and failure modes of spot friction welded joints. Most of the previous studies investigated the spot friction welds between similar and dissimilar aluminum alloys.

Smith et al. [9] proposed a review on the advantages of using FSSW in transportation industry. Merzoug et al. [10] experimentally determined the optimal parameters of FSSW process in order to enhance the mechanical properties of Al 6065-T5 welded joints. Da Silva et al. [11] investigated the effect of joining parameters on the mechanical properties and micro structural features; and described the material flow of dissimilar intermixing during FSSW into different aluminum alloys. Rodrigues et al. [12] studied the influence of welding parameters such as conical and flat shoulders, on the microstructure and mechanical characteristics of joints to get non defective welds. Most of the previous studies have focused on determining the influence of welding parameters on the microstructures, failure modes of SFW joints under quasi-static loading conditions. In another study by Lin et al. [13], the microstructures and failure modes of spot friction welds in lap-shear specimens of aluminum 6111-T4 sheets were studied using optical micrographs. Wang and Chen [14] predicted fatigue lives of FSSW in AL 6061-T4 lap shear specimens under cyclic loading conditions based on Paris law and local stress intensity factors as functions of the kink length. Rash Ahmadi et al. [15] investigated the fatigue life of single friction stir spot welds by performing finite element analysis and strain-based modified Morrow's damage equation considering hardness distribution, assuming the cyclic material constants and mechanical strength of different zones around the FSSW are proportional to the base material hardness value. A new technique has been recently proposed to improve the strength of friction welded joints which results in enhancement of static load capacity and fatigue life. In this method, a number of actions are used such as adding some particle reinforcement during the friction welding process, refilling the joints by using a special designed double-acting tool to remove the created cavity in welded zone, and applying thermal annealing to friction welded structures. Some of the relevant studies have been done by Miller et al. [16]. They studied addition of metal particles during the spot friction welding process to create a localized Metal Matrix Composite (MMC) for the improvement of lap shear strength in AL 6111-T4 alloys; and experimental procedures revealed that the MMC reinforcement improved the lap shear strength of Spot Friction Welded (SFW) joints by about 25%. Uematsu et al. [17] investigated the effects of refilling probe hole and increased effective cross sectional area of the nugget on tensile and fatigue behavior of FSSW joints. Although experimental results revealed that tensile strength of refilled

joints was higher than the as-welded joints, the fatigue strength of the refilled joints was almost the same or in some cases lower than the joints with probe hole.

In parallel with our mentioned goal, a process has been proposed to improve the fatigue life of FSSW joint in this research. This process generates compressive residual stresses at the periphery of the joints via passing a designed concave pin with larger size than the created hole in the center of the weld. The main objective of the present study is to evaluate the performance of the proposed method through investigating its effects on fatigue behavior of FSSW joints of aluminum 7075-T6 and therefore some reliable strain based multi-axial fatigue criteria have been selected to predict fatigue lives of specimens based on finite element analysis.

2. Theoretical background

Fatigue failure is commonly seen in many mechanical components. Although many spot friction welded work-pieces are under uni-axial loads but multi-axial stress-strain states are often observed at critical areas around the weld zone. Numerous methods have been implemented to predict the real life services of mechanical components with uni-axial and multi-axial states. Generally multi-axial fatigue theories can be categorized into stress, strain and energy based approaches. As previously mentioned, multi-axial fatigue state may occur in the welded zone. This is because of the nature of spot friction welded joints.

In this regard, a number of well-known critical plane multi-axial fatigue criteria have been employed to estimate the fatigue life of welded structures. The first inevitable step in predicting the fatigue lives of FSSW work-pieces is to build a Finite Element (FE) model. Through using FE analysis, it is possible to find the critical planes and also the local and principle stresses and strains in the regions of high stress gradients. In addition, the number of cycles for failure of the specimens, N , can be calculated by substituting the obtained values in damage equations.

Two prominent multi-axial fatigue criteria Smith-Watson-Topper (SWT) and Fatemi-Socie (FS) were chosen for estimating the fatigue lives.

2.1. Smith-Watson-Topper (SWT)

According to this criterion proposed by Smith et al. [18], a critical plane approach is appropriate for materials with tensile crack nucleation [19]. This relationship is based on the product of first principal stress and principal strain ranges, commonly referred to as SWT parameter. In this study, the maximum value of SWT parameter is calculated for any nodes during cyclic loading using FE simulations.

$$\left(\frac{\sigma_1 \Delta \varepsilon_1}{2}\right)_{\max} = \varepsilon'_f \sigma'_f (2N_f)^{b+c} + \frac{\sigma_f'^2}{E} (2N_f)^{2b} \quad (1)$$

In this equation, σ_1 , $\Delta \varepsilon_1$, ε'_f , σ'_f , b , c , E are the first principle stress, first principal strain range, fatigue ductility coefficient, fatigue strength coefficient, fatigue strength exponent, fatigue ductility exponent and the modulus of elasticity, respectively.

2.2. Fatemi-Socie (FS) criterion

This critical plane approach was proposed by Fatemi and Socie [20] as a multi-axial fatigue criterion. They conducted a combination of tension and torsion tests with a constant shear strain range and finally ended up with a shear fracture parameter to describe the fatigue process. This fracture parameter is a function of maximum shear strain amplitude $\frac{\Delta \gamma_{\max}}{2}$

and maximum normal stress σ_n^{\max} acting on the critical plane, as follows:

$$\begin{aligned} \frac{\Delta \gamma_{\max}}{2} \left(1 + n \frac{\sigma_n^{\max}}{\sigma_y}\right) &= (1 + \nu) \frac{\sigma_f'}{E} (2N_f)^b + \frac{n}{2} (1 + \nu) \frac{\sigma_f'^2}{E \sigma_y} (2N_f)^{2b} \\ &+ 1.5 \varepsilon'_f (2N_f)^c + \frac{n}{2} 1.5 \frac{\sigma_f' \varepsilon_f}{\sigma_y} (2N_f)^{b+c} \end{aligned} \quad (2)$$

Where n equals 0.6, a material constant which can be achieved from uni-axial and pure torsional fatigue test data, σ_y is the material yield strength, and ν is Poisson's ratio.

3. Experimental procedures

3.1. Material and specimen configuration

An aerospace grade Al alloy 7075-T6 is selected as a parent material to fabricate spot friction welded joints. The chemical compositions in mass percentage, tensile properties and fatigue parameters of parent material are listed in **Table 1** and **Table 2** [21].

In this study, a method is provided for improving the fatigue life of FSSW joints. To achieve this goal, a series of residual compressive stresses were induced in the weld zone to have all samples with same size. The specimens for experimental set up were made of two 2mm thick sheets, with a length of 150mm and a width of 30mm. Upper and lower sheets overlapping area was $30 \times 30 \text{mm}^2$ as shown in **Fig 1**. Two spacers with a length of 50mm were attached to both ends of the lap-shear specimens.

Table 1: Chemical composition (wt.%) of 7075-T6 aluminum alloy.

Table 2: Mechanical properties of Al 7075-T6.

Fig 1. Dimensions (mm) of specimen for tensile and fatigue tests, the highlighted section represents the region used in FE simulation.

3.2. Welding conditions and tool geometry

Generally, in friction welding techniques, the tool geometry, rotational speed, holding time, and shoulder plunge depth are vital parameters which affect joints quality. All in all, any changes in these parameters could influence the strength of FSSW connections. The only parameter which needs to be changed is the applied load in fatigue tests. That's why all the friction stir spot welding process parameters are same. The processing conditions employed in this study are tool rotational speed of 1500rpm, tool holding times of 10s, travelling speed of 19 mm/min, and shoulder plunge depths of 1mm.

We managed to achieve a fine weld, by employing a flat tool with a shoulder of 16mm in diameter and a pin of 6mm in diameter with length of 2.5mm as shown in

Fig 2.

Fig 2. Welding tool of friction stir spot welding (Note: dimensions are in mm).

3.3. Fatigue life improvement set up

As previously mentioned, the inherited holes at the center of welded joints are one of the main objections in friction stir spot welding process. Although it has been shown that the deeper penetration produces high strength joints, sometimes it might lead to the perforation of plates. Therefore, it is generally accepted that the existence of holes at the center of welds is inevitable in order to have high strength connections. To do so, in this study a new process is introduced to enhance the strength of joints through applying the cold expansion method and a series of reforms in the created hole at the center of weld. According to the previous studies, the great impact of this process on increasing the fatigue life of joints and perforated plates is quite clear [22, 23].

Technically, the following main steps are needed to prepare the cold expanded specimens. In first step, an inherited blind hole in the middle of joints that was left by the probe, transferred to open hole by means of drilling with the same dimension of pin's probe ($D=6\text{mm}$). All welded specimens had a 6mm diameter central hole which was drilled and reamed in order to eliminate possible surface scratches. **Fig 3** shows a schematic view of as-welded and perforated FSSW welded specimens.

Fig 3. A photo of (A) as-welded and (B) open hole FSSW joint.

In second step, after initializing the open hole samples as the fatigue test specimens, all of them were allocated for cold expansion process. The main purpose in this section was to subject the perforated specimens to direct cold expansion in order to induce compressive residual stresses by means of an oversized tapered pin. The pin used in this study as shown

in **Fig 4** was made of steel with an outer diameter of 6.2mm to create a 3.3% cold expansion level according to Eq. (3).

$$I = \frac{D - d}{d} \times 100 \quad (3)$$

Where I is the level of cold expansion, D is the pin outer diameter and d is the welded specimen hole diameter.

Fig 4. Dimensions (mm) tapered pins used for cold expansion.

This process was carried out by inserting the pre-lubricated tapered pin into the created holes in the middle of welded joints. To do this, a Zwick 6-Ton capacity tension-compression test machine and a designed steel support were employed to supply the penetration process of tapered pin by means of opposite movements in test machine's vices, as depicted in **Fig 5**.

Fig 5. A schematic view of cold expansion process.

3.4. Fatigue tests and results

Fatigue tests were carried out for two batches of specimens: first one includes as-welded joints and second batch includes cold expanded specimens. These tests were conducted at 6 levels of load starting from 1.5kN to 4kN by means of a load controlled 250kN Zwick/Amsler fatigue test machine with a frequency of 10 Hz and a load ratio of $R=0.1$ (load ratio= P_{min}/P_{max}) in air laboratory. A buckling guard was employed for specimens in fatigue tests. The Japanese industrial standard JIS Z 3138 [24] method of tensile-shear fatigue testing for spot welded joints was used. **Fig 6(A)** depicts the specimen position in the test machine. **Fig 6(B)** depicts a close-up view of the as-welded specimen in fatigue test machine.

Fig 6. (A) Fatigue test stage and specimen of FSSW, (B) a close-up view of as-welded specimen and (C) a close-up view of cold expanded specimen in fatigue testing machine.

As mentioned, both types of the specimens were subjected to the same load amplitude. The applied load versus the number of cycles to failure (S-N) are presented in semi-logarithmic plot (**Fig 7**). As illustrated, there is a distinction between the fatigue lives of specimens. This states that the cold expansion causes a significant improvement in the fatigue lives of spot friction welded joints especially at lower load levels. However, the life improvement is not appreciable at low cycle regimes.

Fig 7. Experimental (S-N) data obtained from fatigue tests, at $R=0.1$.

3.5. Fatigue fracture approach

The failure modes of two mentioned welded joints with a special attention to the fatigue fracture mechanisms were investigated. The ordinary induced parameters are sheet thickness, nugget diameter, and applied load levels. In fatigue tests of spot friction welded structures, three common failure styles were observed: nugget fracture, crack propagation in thickness, and button plug nugget fracture. **Fig 8** and **Fig 9** depict the fatigue failures of as-welded and cold expanded joints at different load levels. These figures reveal that for both types of specimens, nugget fracture has occurred in low-cycle regime; and fracture through the sheet thickness perpendicular to the load direction has come up at low load levels.

Analysis of these results shows that the cold expansion only enhances the fatigue life of joints without altering their failure modes. On the other hand, the created hole at the center of weld only increases the fatigue strength of welded joints without any destructive effects.

Fig 8. Different fracture mechanisms of as-welded specimens in various load range: (A) Sheet fracture through the thickness at low load level, (B) Nugget fracture at high load level.

Fig 9. Different fracture mechanisms of cold expanded FSSW joints in various load range: (A) Sheet fracture through the thickness at low load level, (B) Nugget fracture at high load level.

4. Finite element simulation

4.1. Finite element model

The single spot friction welded joints of 7075-T6 Aluminum alloy sheet with thickness of 2mm were investigated. The stress and strain distributions in periphery of welded zones were required to predict the fatigue lives of specimens (as-welded and cold expanded). Since obtaining the precise values of stress and strain distribution around the weld is theoretically impossible, finite element model was to resolve this problem. A brief explanation of the FE models was presented here, however, the more details could be found in [15] and [25].

In both types of the specimens, a non-linear 3D finite element model based on hardness distribution was employed to obtain the local stress and strain values. In conducting the simulations, a multi-linear kinematic hardening model was chosen to represent the aluminum alloy 7075-T6 stress-strain behavior and a linear elastic model was selected for the pin with the Young's modulus of 210 GPa and Poisson's ratio of 0.3. To do so, two types of work pieces were modeled by ANSYS finite element package considering gap effects and specific values for actual boundary diameter of the welds. According to the symmetric structure of model with respect to XY plane, only half of the actual model was created in order to obtain an optimum model with less computational time. All parts were meshed with eight-node structural solid elements (Solid45). The size of the elements was refined sufficiently in order to obtain more realistic results. **Fig 10** and **Fig 11** depict the finite element models and the local elements near the stir zone of as-welded work pieces and cold expanded types, respectively.

Fig 10. Finite element meshed model of FSS as-welded specimens.

Fig 11. 3D finite element meshed model of cold expanded specimens.

As seen, in the cold expanded cases, a tapered pin was also added to the finite element model in order for inducing compressive residual stress fields. To do this, mandrel should pass through the created hole at the center of weld. Generally, in the cold expanded models, a set of elements was introduced as the contacting surfaces. These elements would allow the pressure to be transferred between the contact surfaces without piercing to each other. In this study, contact 174 and target 170 elements [26] were employed between the hole and pin. The friction effect between the contact pairs was selected as Coulomb friction model with coefficient of 0.1[27].

The simulation process of FSS as-welded joints was organized in one main step by applying different cyclic loads which were similar to the experimental conditions. In contrast, the numerical analysis of cold expanded cases was carried out at two different load steps. In the first load step, to perform the cold expansion, the mandrel was penetrated into the hole and removed from the other side applying displacement increments on it. In the second load step, the welded structure was subjected to particular stresses to resemble the process of cyclic loading during the fatigue tests.

4.2. Finite element analysis results

In order to investigate the fatigue life of specimens, the experimental setup should be similar to the boundary conditions of finite element model. The specimens in fatigue test are under tensile-shear loading or multi-axial stress state. Therefore, to predict the fatigue life of an improved spot friction welded joint based on multi-axial fatigue criteria the numerical data such as principal stresses and strains are required especially near the critical zones or high stress concentration areas. The longitudinal stress distribution for a typical loading of as-welded model under loads of 1.5kN and 4kN are depicted in **Fig 12** and **Fig 13**. Contour plots of tangential stresses before and after the cyclic loads were constructed

showing the residual stress distributions around the hole of cold expanded specimens (Fig. 14 and 15). As expected, the maximum stress values occurred around the TMAZ zones. The circumferential residual stress distributions around the hole of welded joint are demonstrated in Fig 14 and Fig 15. As illustrated, stage (A) refers to cold expanded state before applying the repetitive load, and stage (B) represents the cold expanded FSSW joints after applying the cyclic load.

Fig 12. Distributions of longitudinal stress (σ_x) in MPa under load 1.5kN.

Fig 13. Distributions of longitudinal stress (σ_x) in MPa under load 4kN.

Fig 14. Tangential residual stress (MPa) contours for: (A) 3.3% cold expansion; (B) after applying 1.5kN remote load.

Fig 15. Tangential residual stress (MPa) contours for: (A) 3.3% cold expansion; (B) after applying 4kN remote load.

The data from FE models were then substituted in multi-axial fatigue damage equations. The experimental and critical plane approach results are summarized in Table 3. As depicted, the predicted fatigue lives of specimens with specific multi-axial criteria based on the finite element models are in a good agreement with the experimental fatigue test data.

Table 3: Comparison of estimated results by two multi-axial criteria with experimental data for two batches of specimens.

5. Results and Discussion

Among the technical literature and surveys which are available in the field of spot friction welded joints, a few studies have been performed to investigate the effect of weld improvement on the fatigue behavior of the joints. According to Ref. [16], a localized metal matrix composite (MMC) was created during the spot friction welding process for the improvement of lap shear strength in AL 6111-T4 alloy, and static tests results revealed that the MMC reinforcement improved the lap shear strength of SFW joints about 25%. On the other hand, according to Ref. [17], refilling probe hole of the welded specimens, despite increasing in the tensile strength, has no major impact on the fatigue strength of FSSW joints. Shen et al. [28] investigated the effects of heating process on the microstructures and tensile properties of a FSSW welded AZ31 magnesium alloy by microstructural observations and tensile tests. Experimental results revealed that the width of the bonded zone and merely the tensile strength of the heated FSSW joint increased remarkably. Bakavos and Prangell [29] studied the effects of employing zero pin length and anvil insulation on the strength of the FSSW joints during the welding process. Results revealed that insulate anvil in the case of the pinless tool, enhanced the peak temperature in bottom side by 45°C. Therefore successful joints without a retained weld keyhole were produced, however, advantages of this method in improving fatigue strength of the joints has not been reported. Senthil et al. [30] investigated the applications of compressed Ancorsteel metal particles, around the axial center-line of the tool between the upper and lower sheets, in spot friction welding in order to create localized metal matrix composite. Results revealed an aluminum-ferrous solid formation around the steel particle and aluminum matrix interfaces which increased the maximum lap-shear by 20%. Sun et al. [31] introduced a novel two-step process of spot friction welding in order to improve the mechanical property of the joints by eliminating the keyhole. In the first step, a conventional method of spot FSW was applied above a round dent previously made on the back plate. In the second step, the welding process was conducted on a smooth back plate employing a pinless rotating tool with the purpose to remove the protuberance on the back side and the keyhole on the front side. Results indicated that the final joints had a smooth surface with no defects and improved mechanical properties. Uematsu et al. [32]

investigated the effect of two kinds of post heat treatment, namely aging and T6 treatment, on fatigue behavior of as-welded FSSW joints. Although their experimental observations exposed that fatigue strength was little influenced by post heat treatment, fatigue fracture phenomenon was dependent inextricably on load level, and post heat treatment. The only merit of this procedure was affecting the fracture mode without any enhancement in tensile or fatigue strength of the joints.

In the present study, the stress and strain distributions obtained from the FE models were employed to extract the critical values of parameters for each multi-axial fatigue criterion in the work pieces model. Furthermore, at any nodes in the FE models, the left hand side of SWT damage equations of multi-axial fatigue criteria was calculated to find the maximum value. The calculated $\Delta\gamma_{\max}$ and σ_n^{\max} was then used to find the numerical value of fracture parameter. Finally, by employing these values and material constant parameters, the estimated fatigue lives were obtained.

Although, it has been proved that in higher cold expansion levels, the improvement of fatigue life is noticeable, but applying a large amount of cold work might cause damage or even failure of the FSSW joints. So, to overcome this difficulty, the cold expansion level of 3.3% was employed in this study. The distribution of longitudinal stress due to 1.5kN remote load for the as-welded and cold expanded welded joints (see Fig 12 and Fig 14) shows that the cold expansion considerably reduce the stress around the weld zone. Fig 13 and Fig 15 depict the longitudinal stress distribution due to 4kN remote load for both batches of models are close to each others in critical regions. These facts are in line with the experimental results (Fig 7) which express that the cold expanded specimens have longer fatigue lives at lower load levels in comparison with high load levels.

Life prediction results based on these two multi-axial fatigue damage equations for both types of spot friction welded specimens are presented in Table 3. The results indicate that all predicted lives obtained from the local stress-strain methods are in a good agreement with the experimental results particularly at low-cycle fatigue life regime. Generally, SWT criteria results in an accurate estimation of fatigue lives; however, FS criteria underestimates the fatigue lives. Nevertheless, these critical plane approaches have best efficiency in comparison with biaxial fatigue damage equations in spot friction welded

cases. However, in fatigue science, a unique multi-axial fatigue criterion cannot be suggested to supply whole fatigue life regime with good level of accuracy for different specimen types with various loading ranges.

6. Conclusions

The present study has proposed a new method to improve the fatigue life of friction stir spot welded (FSSW) joints through applying a cold work process. The estimated lives of two different joints were evaluated by employing Smith–Watson–Topper and Fatemi-Socie multi-axial fatigue criteria. The finite element method was used to find the principle stress, strain, and critical plane in order to evaluate the values of SWT parameter and FS shear fracture parameter.

By taking all above-mentioned arguments into consideration the following conclusions can be drawn out:

The cold expanded FSSW joints have longer fatigue life compared to as-welded joints and the life enhancement is more considerable in high cycle fatigue life regimes.

Application of cold expansion process to FSSW joints improves the fatigue life of specimens without altering their failure modes.

Results obtained from the multi-axial critical plane approaches are in a good agreement with the experimental fatigue test data for FSSW joints.

There was no considerable difference between the obtained results of SWT and FS multi-axial fatigue criteria.

References

- [1] Blawert C, Hort N, Kainer KV. Automotive applications of magnesium and its alloys. *Trans Indian Inst Metal* 2004; 57:397–408.
- [2] Davies G. Future trends in automotive body materials. *Materials for Automobile Bodies* 2003; 8:252–69.

- [3] Cavaliere P, Nobile R, Pannella FW, Squillace A. Mechanical and microstructural behaviour of 2024–7075 aluminium alloy sheets joined by friction stir welding. *Int. J Mach Tools Manuf.* 2006; 46:588–94.
- [4] Gean A, Westgate SA, Kucza JC, Ehrstrom JC. Static and fatigue behavior of spot-welded 5182-O aluminum alloy sheet. *J. Weld* 1999; 78:80–6.
- [5] Thornton PH, Krause AR, Davies RG. The aluminum spot weld. *J. Weld* 1996; 75:101–8.
- [6] Thomas M, Nicholas J, Needham J, Murch M, Templesmith P, Dawes C. Friction Stir Welding. GB Patent Application No. 9125978.8 Dec. 1991, US Patent No. 5460317.
- [7] Schilling C, Dos Santos J. Method and device for joining at least two adjoining work pieces by friction welding. US Patent Application; 2002.
- [8] Sakano R, Murakami K, Yamashita K, Hyoe T, Fujimoto M, Inuzuka M, et al. Development of spot FSW robot system for automobile body members. In: Proceedings of the 3rd international symposium of friction stir welding, Kobe, Japan; 2001.
- [9] Smith CB, Hinrichs JF, Ruehl PC. Friction stir and friction stir spot welding. Lean, mean and green. In: Sheet metal welding conference, vol. XI; 2004. Paper 2–5.
- [10] Merzoug M, Mazari M, Berrahal L, Imad A. Parametric studies of the process of friction spot stir welding of aluminium 6060-T5 alloys. *J Mater Des* 2010; 31:3023–28.
- [11] Da Silva A, Arruti E, Janeiro G, Aldanondo E, Alvarez P, Echeverria A. Material flow and mechanical behaviour of dissimilar AA2024-T3 and AA7075-T6 aluminium alloys friction stir welds. *J Mater Des* 2011; 32:2021–27.
- [12] Rodrigues DM, Loureiro A, Leitao C, Leal RM, Chaparro BM, Vilaça P. Influence of friction stir welding parameters on the microstructural and mechanical properties of AA 6016-T4 thin welds. *J Mater Des* 2009; 30:1913–21.
- [13] Lin PC, Lin SH, Pan J, Pan T. Failure modes and fatigue life estimations of spot friction welds in lap-shear specimens of aluminum 6111-T4 sheets. Part 1: welds made by a concave tool March. *Int J Fatigue* 2008; 30:74–89.
- [14] Wang DA, Chen CH. Fatigue lives of friction stir spot welds in aluminum 6061-T6 sheets. *Int J Mater Proc Technol* 2009; 209:367–75.
- [15] Rash Ahmadi S, Hassanifard S, Mohammad Pour M. Fatigue life prediction of friction stir spot welds based on cyclic strain range with hardness distribution and finite element analysis. *Acta Mech* 2012; 223:829–39.

- [16] Miller SF, Arul SG, Kruger GH, Pan TY, Shih AJ. Effect of localized metal matrix composite formation on spot friction welding joint strength. *J. Engineering materials and technology ASME* 2011; 133/031009-1.
- [17] Uematsua Y, Tokajia K, Tozakib Y, Kuritac T, Muratad S. Effect of re-filling probe hole on tensile failure and fatigue behaviour of friction stir spot welded joints in Al-Mg-Si alloy. *Int. J Fatigue* 2008; 30:1956–66.
- [18] Smith KN, Watson P, Topper TH. A stress strain function for the fatigue of metals. *J Engng Mater Technol* 1970; 5(4):767–78.
- [19] Socie D. Multiaxial fatigue damage models. *J Engng Mater Technol* 1987; 109:293–97.
- [20] Fatemi A, Socie DF. A critical plane approach to multiaxial fatigue damage including out of phase loading. *Fatigue Fract Engng Mater Struct* 1988; 11:149–65.
- [21] Dowling NE, *Mechanical behavior of materials. engineering methods for deformation, fracture and fatigue.* 2nd Ed. Prentice Hall ; 1999.
- [22] Liu J, Shao XJ, Liu YS, Yue ZF. Effect of cold expansion on fatigue performance of open holes. *J Materials Science and Engineering A* 2008; 477:271-76.
- [23] Pasta S. Fatigue crack propagation from a cold-worked hole. *J Engineering Fracture Mechanics* 2007; 74:1525-38.
- [24] Japanese Industrial Standard (JIS). JIS Z 3138-1989: method of fatigue testing for spot welded joint [released on 1989 March 1].
- [25] Hassanifard S, Rash Ahmadi S, Mohammadpour M. Weld arrangement effects on the fatigue behavior of multi friction stir spot welded joints. *J Mater Des* 2013; 44:291–302.
- [26] ANSYS Release 11.0 Documentation. ANSYS Inc.; 2008.
- [27] Chakherlou TN, Abazadeh B. Estimation of fatigue life for plates including pre-treated fastener holes using different multiaxial fatigue criteria. *Int. J Fatigue* 2011; 33:343–53.
- [28] Shen J, Min D, Wang D. Effects of heating process on the microstructures and tensile properties of friction stir spot welded AZ31 magnesium alloy plates. *J Mater Des* 2011; 32:5033–37.
- [29] Bakavos D, Prangnell, PB. Effect of reduced or zero pin length and anvil insulation on friction stir spot welding thin gauge 6111 automotive sheet. *J Science and Technology of Welding & Joining* 2009;14: 443-56.

- [30] Arul SG, Kruger GH, Miller SF, Pan TY, Shih AJ. Spot Friction Welding Joint Strength Improvement Using Localized Metal Matrix Composite Formation. ASME International Manufacturing Science and Engineering Conference, Volume 2 West Lafayette, Indiana, USA, October 4–7, 2009.
- [31] Sun YF, Fujii H, Takaki N, Okitsu Y. Novel spot friction stir welding of 6061 and 5052 Al alloys. J Science and Technology of Welding & Joining 2011;16: 605-12.
- [32] Uematsu Y, Tokaji K, Tozaki Y, Kurita T, Murata S. Effect of post-heat treatment on the fatigue behaviour of a friction stir spot-welded Al–Mg–Si alloy. Int.J Welding 2009; 23: 481-89.

Table captions:

Table 1: Chemical composition (wt.%) of 7075-T6 aluminum alloy.

Table 2: Mechanical properties of Al 7075-T6.

Table 3: Comparison of estimated results by two multiaxial criteria with experimental data for two batches of specimens.

Figure captions:

Fig 1. Dimensions (mm) of specimen for tensile and fatigue tests, the highlighted section represents the region used in FE simulation.

Fig 2. Welding tool of friction stir spot welding (Note: dimensions are in mm).

Fig 3. A photo of (A) as-welded and (B) open hole FSSW joint.

Fig 4. Dimensions (mm) tapered pins used for cold expansion.

Fig 5. A schematic view of cold expansion process.

Fig 6. (A) Fatigue test stage and specimen of FSSW, (B) a close-up view of as-welded specimen and (C) a close-up view of cold expanded specimen in fatigue testing machine.

Fig 7. Experimental (S-N) data obtained from fatigue tests, at R=0.1.

Fig 8. Different fracture mechanisms of as-welded specimens in various load range: (A) Sheet fracture through the thickness at low load level, (B) Nugget fracture at high load level.

Fig 9. Different fracture mechanisms of cold expanded FSSW joints in various load range: (A) Sheet fracture through the thickness at low load level, (B) Nugget fracture at high load level.

Fig 10. Finite element meshed model of FSS as-welded specimens.

Fig 11. 3D finite element meshed model of cold expanded specimens.

Fig 12. Distributions of longitudinal stress (σ_x) in MPa under load 1.5kN.

Fig 13. Distributions of longitudinal stress (σ_x) in MPa under load 4kN.

Fig 14. Tangential residual stress (MPa) contours for: (A) 3.3% cold expansion; (B) after applying 1.5kN remote load.

Fig 15. Tangential residual stress (MPa) contours for: (A) 3.3% cold expansion; (B) after applying 4kN remote load.

ACCEPTED MANUSCRIPT

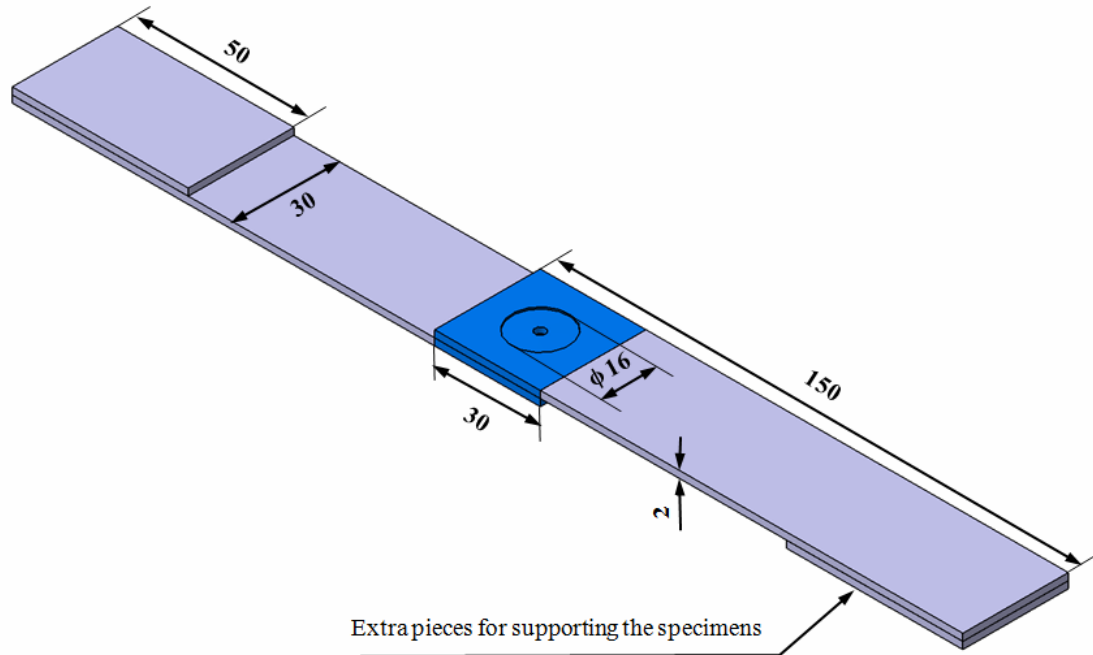


Fig. 1. Dimensions (mm) of specimen for tensile and fatigue tests, the highlighted section represents the region used in FE simulation.

ACCEPTED MANUSCRIPT

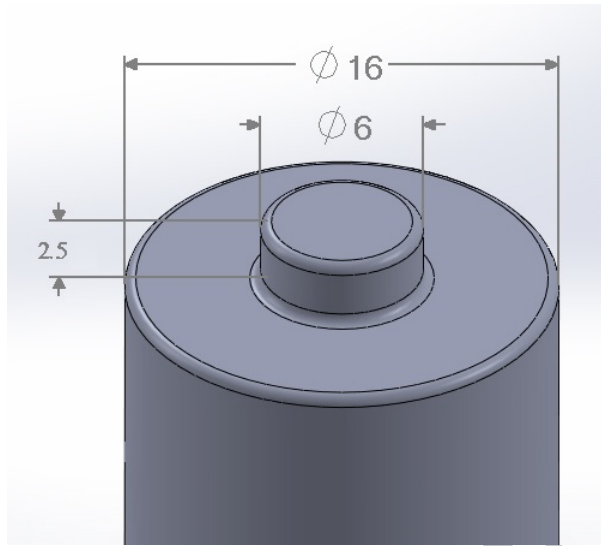


Fig. 2. Welding tool of friction stir spot welding (Note: dimensions are in mm).

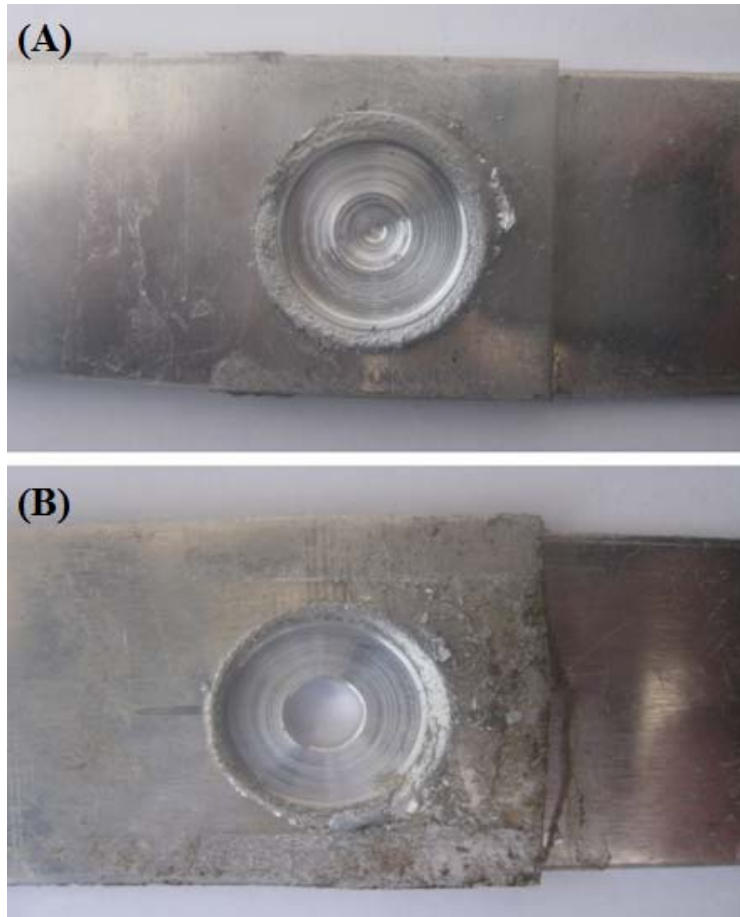


Fig. 3. A photo of (A) as-welded and (B) open hole FSSW joint.

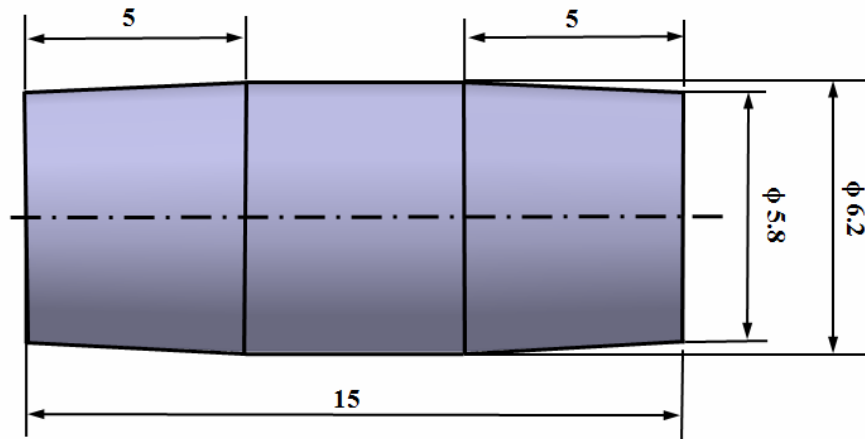


Fig. 4. Dimensions (mm) tapered pins used for cold expansion.

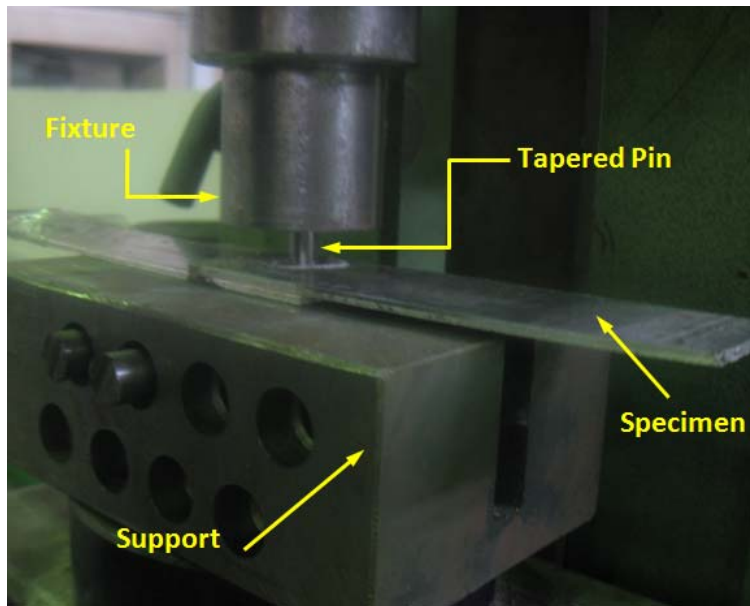


Fig. 5. A schematic view of cold expansion process.

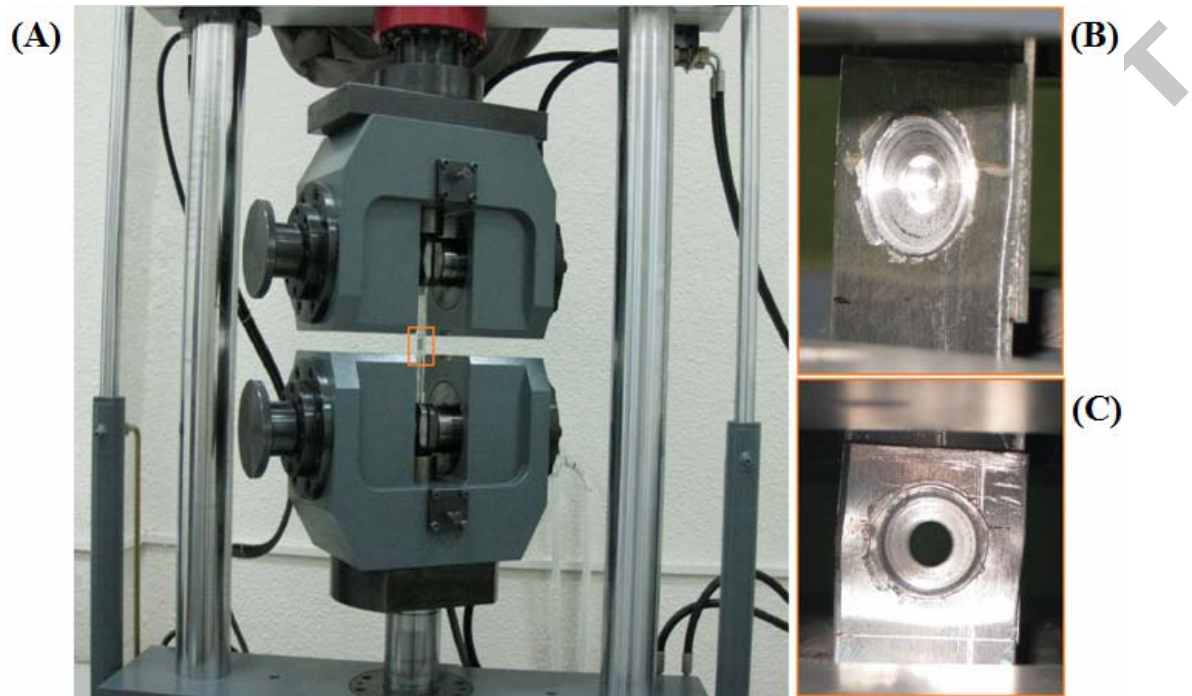


Fig. 6. (A) Fatigue test stage and specimen of FSSW, (B) a close-up view of as-welded specimen in fatigue testing machine and (C) a close-up view of cold expanded specimen in fatigue testing machine.

ACCEPTED

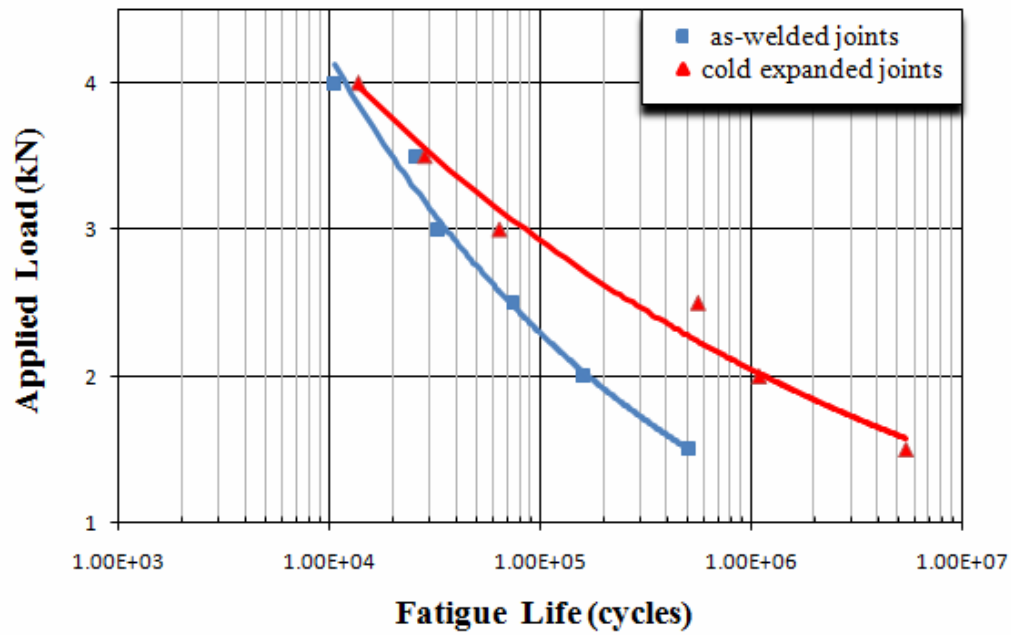


Fig. 7. Experimental (S-N) data obtained from fatigue tests, at R=0.1.

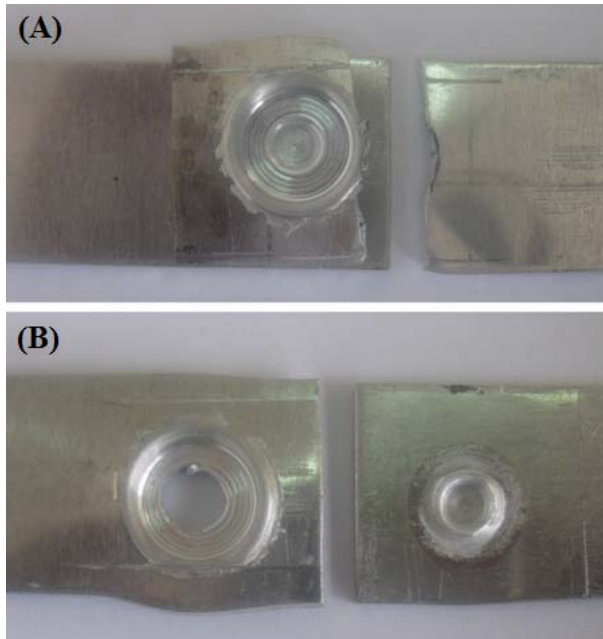


Fig. 8. Different fracture mechanisms of as-welded specimens in various load range: (A) Sheet fracture through the thickness at low load level, (B) Nugget fracture at high load level.

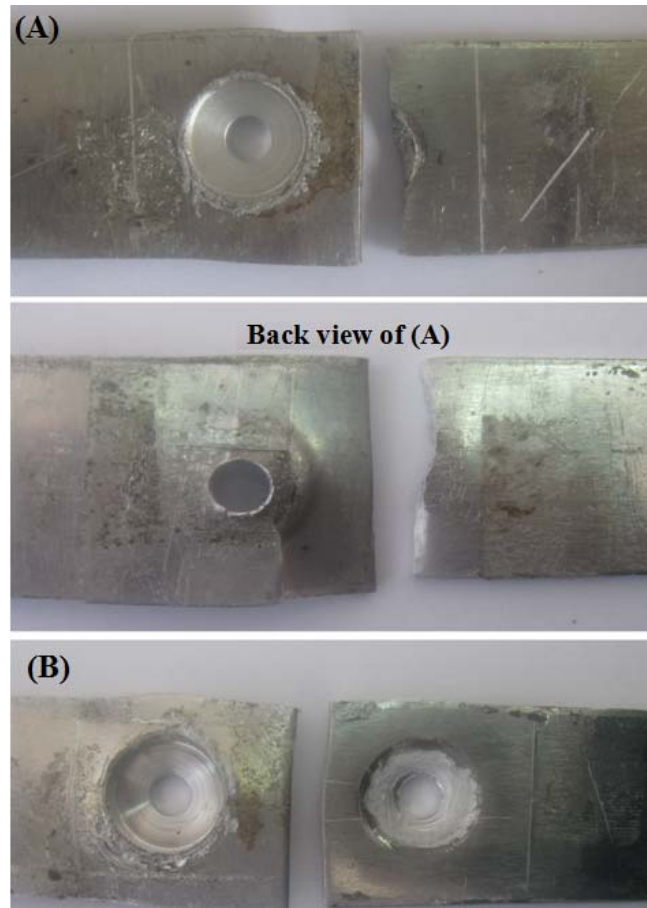


Fig. 9. Different fracture mechanisms of cold expanded FSSW joints in various load range: (A) Sheet fracture through the thickness at low load level, (B) Nugget fracture at high load level.

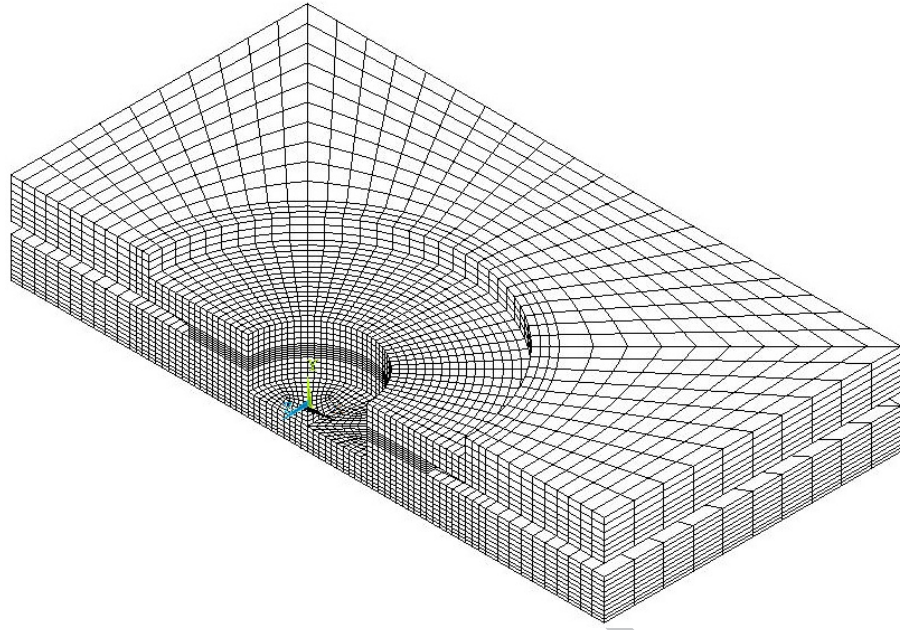


Fig. 10. Finite element meshed model of FSS as-welded specimens.

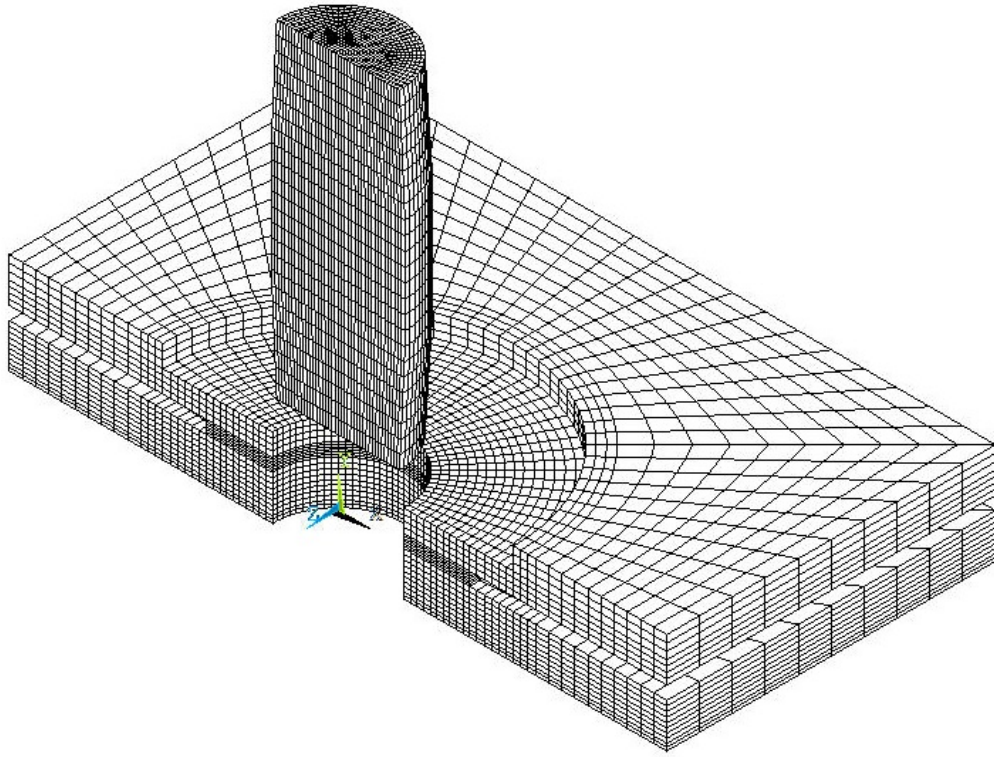


Fig. 11. 3D finite element meshed model of cold expanded specimens.

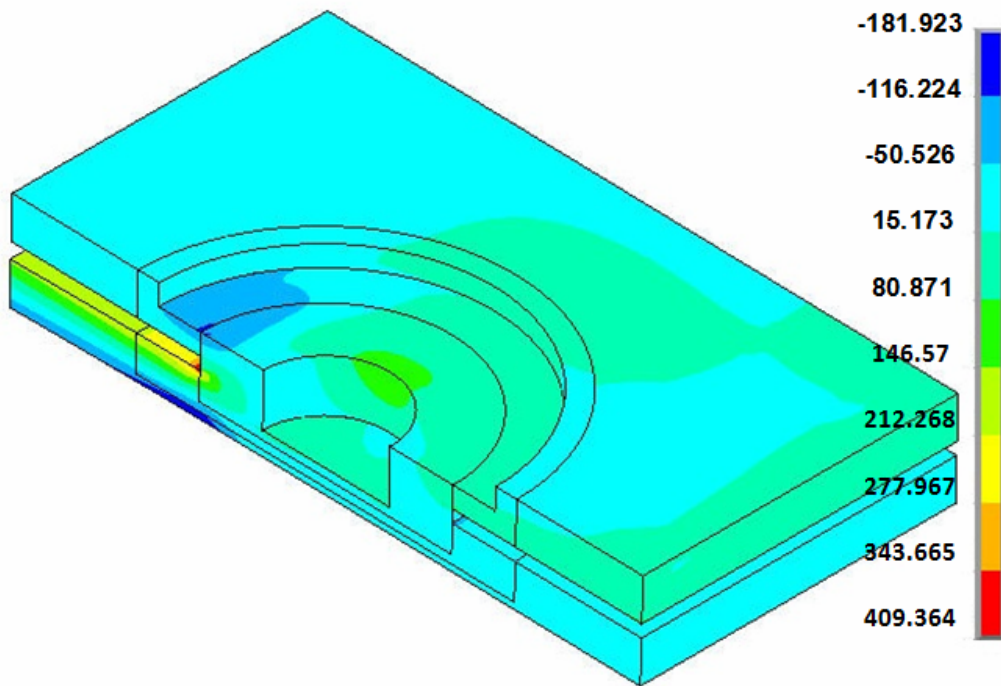


Fig. 12. Distributions of longitudinal stress (σ_x) in MPa under load 1.5kN.

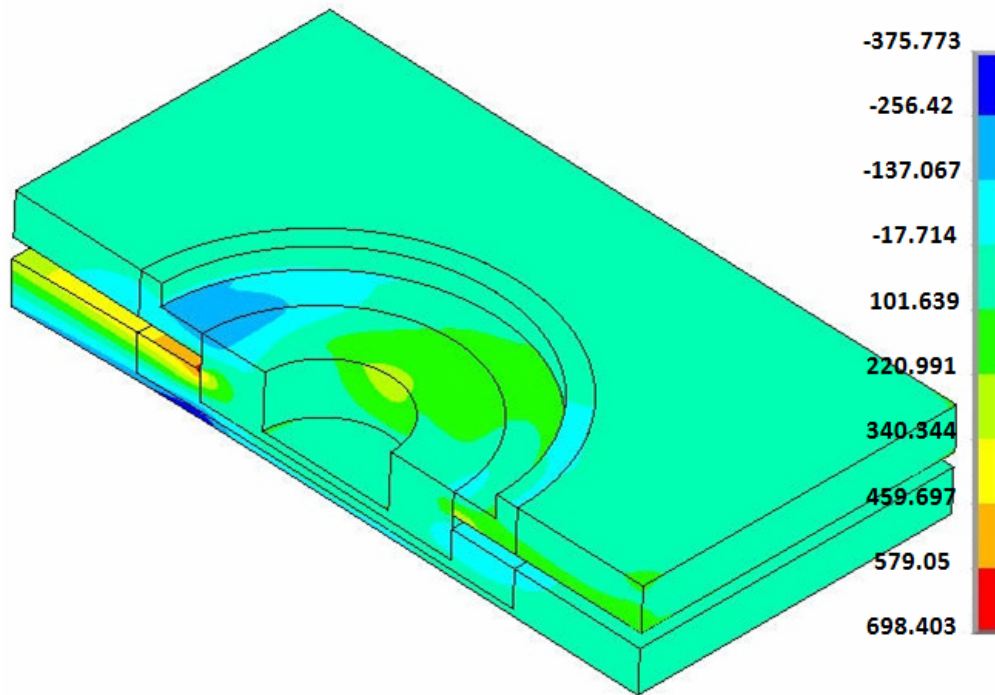


Fig. 13. Distributions of longitudinal stress (σ_x) in MPa under load 4kN.

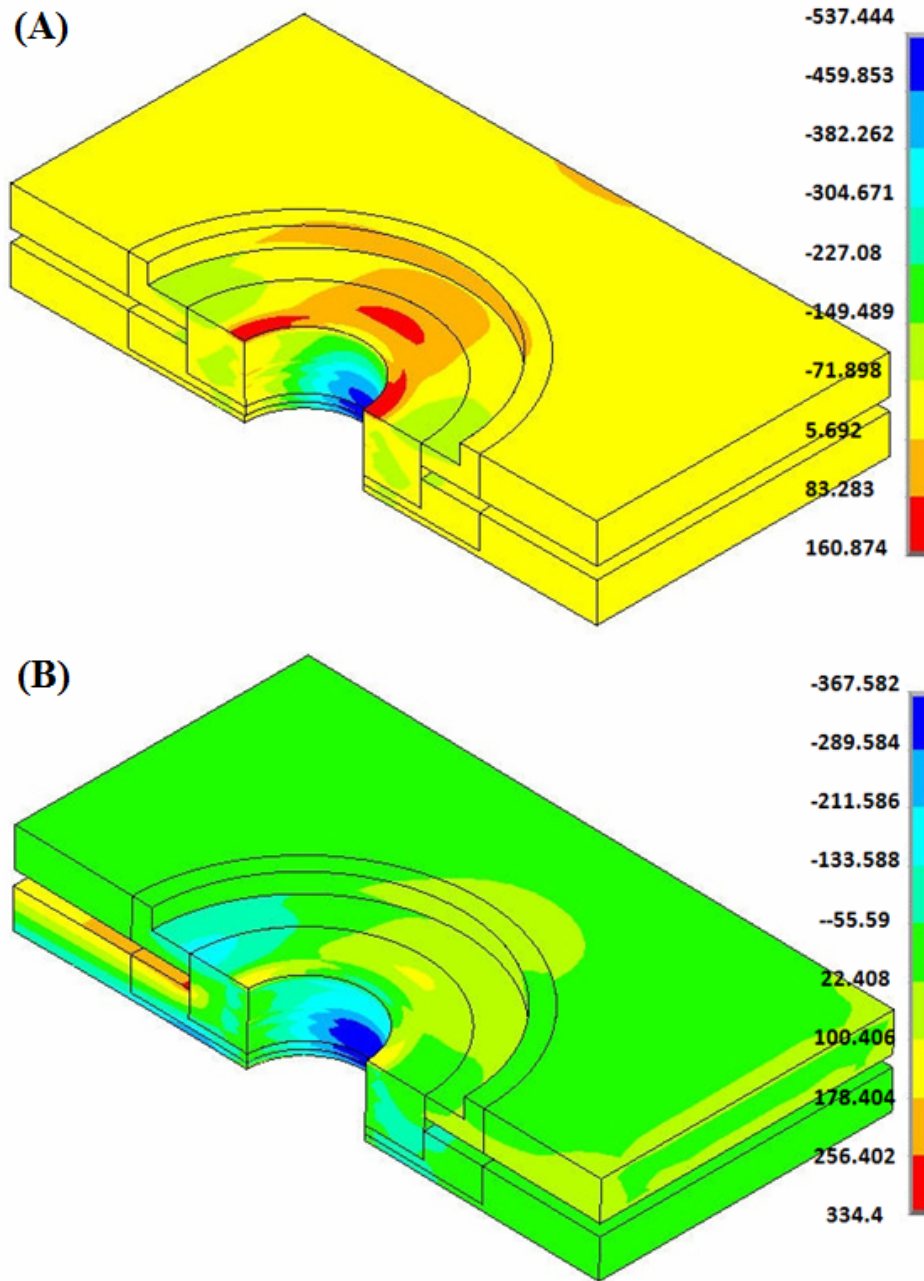


Fig. 14. Tangential residual stress (Mpa) contours for: (A) 3.3% cold expansion; (B) after applying 1.5kN remote load.

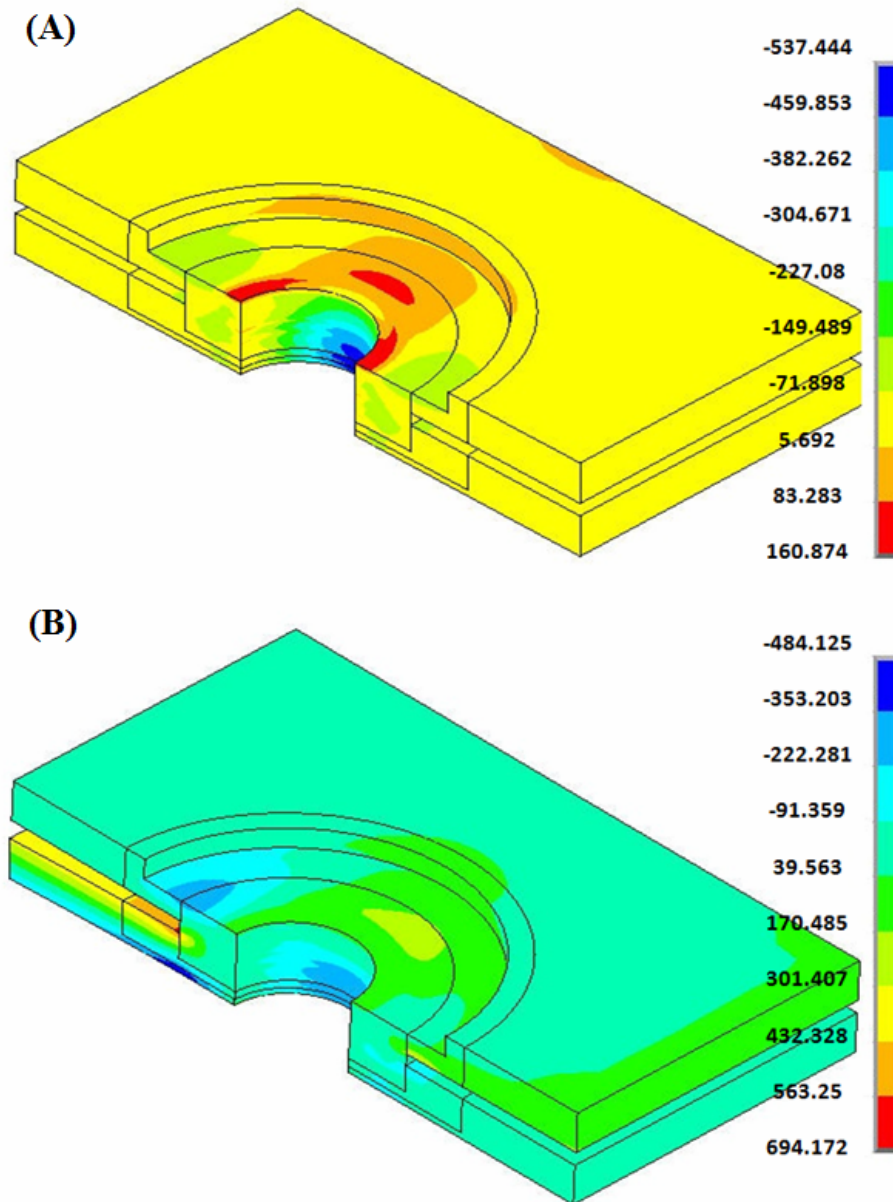


Fig. 15. Tangential residual stress (Mpa) contours for: (A) 3.3% cold expansion; (B) after applying 4kN remote load.

Table 1: Chemical composition (wt.%) of 7075-T6 aluminum alloy.

Alloys	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
7075 -T6	≤0.4	≤0.5	1.2 - 2	≤0.3	2.1 - 2.9	0.18 - 0.28	5.1 - 6.1	≤0.2	rem

ACCEPTED MANUSCRIPT

Table 2: Mechanical properties of Al 7075-T6.

Property	Value
Modulus of elasticity (GPa)	71
Yield strength (MPa)	469
Ultimate tensile strength (MPa)	578
Elongation (%)	33
Poisson's ratio	0.33

ACCEPTED MANUSCRIPT

Table 3: Comparison of estimated results by two multi-axial criteria with experimental data for two batches of specimens.

Load (kN)	Multi-axial criteria		N(estimated)	N(exp.)		N(estimated)	N(exp.)
1.5	SWT	FSS as-welded joints	809537	508135	Cold expanded FSSW joints with level of 3.3%	9886642	5483731
	FS		698075			7240965	
2	SWT		163433	159610		906118	1097503
	FS		158334			1274171	
2.5	SWT		83654	74562		514745	562894
	FS		79126			486752	
3	SWT		26861	32763		50416	63753
	FS		21868			36819	
3.5	SWT		16905	25682		20808	28162
	FS		11730			13869	
4	SWT		11610	10520		12235	13518
	FS		7515			8336	

A new method has been introduced in fatigue life enhancement of FSSW joints.
Fatigue and tensile tests were carried out on as-welded and cold expanded specimens.
FE method and multiaxial criteria have been employed to estimate the fatigue life.
Cold work process improved fatigue life of the joints without changing failure modes.

ACCEPTED MANUSCRIPT