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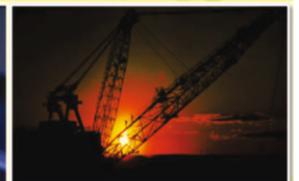
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Assessment of Effective Nugget Size, Nugget Rotation and Failure Mode of Friction Stir Spot Welds of AA2219-O Alloy

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A B S T R A C T

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Weld nugget is core for the integrity of friction stir spot welds. Based on this understanding, the investigation of nugget size, nugget rotation and weld failure mode of friction stir spot welded aluminium alloy of AA2219-O was examined. Tapered pin and featureless pin-less tools were employed in welding the alloy at varying tool rotational speed, dwell time and shoulder plunge depths. Intense nugget rotation and feeble nugget rotation were observed in pinless and conical pin welds respectively. However, bonded size or nugget size was predominantly controlled by tool rotational speed and plunge depth in both categories of weld; the percentage contributions of plunge depth in pinless and conical pin welds are 83.97% and 41.68% respectively. Conical pin weld failed via nugget shear failure across the ring-like weld nugget whereas nugget pull-out and interfacial weld failures were obtained in pinless weld.

1.0 Introduction

Friction stir spot welding (FSSW), a process variant of friction stir welding (FSW) for joining lightweight aluminium alloys is a foremost solid-state joining technology that has gained substantial attentions in the automotive, aerospace, ship building and high speed train manufacturing industries. However, improved mechanical properties of friction stir spot welds (FSSW) are generally attributed to the refinement of nugget zones' grain sizes and substructures (Rajakumar et al. 2012), limited alloy segregation, and reduced heat affected zone (HAZ) and narrow thermo-mechanical affected zone (TMAZ). As a result, weld nugget is an integral appraisal measure for the integrity of friction stir spot welds. Excessive stirring of nugget causes nugget collapse (softening) due to excess heat input while insufficient stirring of weld nugget causes insufficient heat generation and insufficient metal transportation (Rajakumar et al. 2012; Ojo et al. 2016); and eventually, uneven distribution of precipitates occurs and poor metallurgical bonding is created in the inadequately stirred welds. Thus, adequate stirring and intermingling of materials (upper and

lower materials) at appropriate parameter settings are chiefly essential for the formation of sound weld nugget in friction stir spot welds. Equally, the ability of weld nugget to resist abrupt failure or brittle-like behaviour immediately when subjected to loading conditions is a major weld characteristic because brittle failure of weld nugget could be catastrophic to human life. Thus, the propensity of weld nugget to plasticize (undergo ductile behaviour) during axial loading is an essential phenomenon that is yet to be thoroughly investigated in literature.

Weld nugget is the sufficiently bonded metallurgical region that is established between the faying surface (interface between the upper and lower sheets) being welded after plastic deformation and stirring or intermixing of material, aided by the deformation and frictionally induced thermal energy. In literature, the width or size of weld nugget directly controls weld strength of friction stir spot welds while the composition and grain sizes of nugget influences the micro-hardness of spot welds. For instance, Rajakumar et al. (2012) examined the correlation between the properties of weld nugget and tensile strength and it was affirmed that weld nugget properties such as the grain size and hardness of nugget region influenced the strength of welds. Linear relationship

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exists between the nugget properties and with the tensile strength of joints (Rajakumar et al. 2012). Equiaxed fine grained and dynamically re-crystallized microstructures are the typical characteristics of weld nugget. However, welding parameters affects these properties. For instance, Gerlich et al. (2006) affirmed in their work that increasing the dwell time from 1-4 s exhibited a negligible influence on the crystallite dimensions of the weld nugget of 7075-T6 alloy at tool rotational speed of 3000 rpm (Gerlich et al. 2006). This unchanged nugget grain size at 3000 rpm is attributed tool slippage (Gerlich et al. 2008).

The bonded region of the upper plate with the lower plate in friction stir spot weld is expected to undergo some restrains or resistance to loading and longer time to failure by exhibiting some level of plasticization or ductility prior to its eventual failure under axial loading. However, ductility or plasticity of weld nugget under axial monotonic loading is an attribute that has not been comprehensively expounded in literature. In an attempt to examine this criterion, the rotation of weld nuggets (angular displacement) when subjected to loading condition is examined and the fracture patterns undergone by the nuggets are also analyzed. Equally, the effects of tool profiles and welding parameters on nugget morphology and nugget sizes are examined.

2.0 Material and experimental procedures

As-received 1.6 mm thick rolled plates of Alclad AA2219-O alloy were employed for this work. The chemical position of the alloy as specified according to ASTM E1251 standard is shown in Table 1. According to ASTM E8/B557 standard, the mechanical properties of the alloy include: ultimate tensile strength, yield strength and elongation of 146MPa, 63MPa and 22.3% respectively. Tapered pin tool and featureless pinless tool were fabricated on a lathe machine by using a 10mm diameter high speed steel (HSS) tool material. For the experimentation, 1-5s, 1500-3000rpm and 0.4-0.71mm were the dwell time, tool rotational speed and plunge depth respectively. Nugget rotation is the ability of the bonded region of the weld to resist failure by undergoing some level of ductile behaviour before the final separation of the overlapped work-pieces under monotonic axial loading. As a result, in order to examine this behaviour, the friction stir spot welded joints produced on an adapted CNC milling machine were subjected to lap shear failure with the aid of Zwick tensile testing machine. The fracture morphologies of the failed welds were examined under scanning electron microscope (SEM) while the weld microstructures were equally studied under optical microscopy.

3.0 Results and discussion

Monotonic axial loading of tensile shear specimen is required to induce nugget rotation and to cause failure of weld. The ability of

the bonded region to rotate or undergo angular displacement under axial loading indicates that the preliminary axial load is converted to torque or angular displacement energy instead of immediate crack propagation within the bonded region. As a result, this indicates the soundness of weld and the weld's ability to restrict failure under some initial progressive axial loading condition. The assessment of the failed weldments (subjected to axial loading) is carried out in order to identify the degree of angular displacement or nugget rotation of welds. Pinless welds demonstrated slight to intense nugget rotation when compared to conical pin welds. Conical pin welds showed feeble or negligible nugget rotation. However, the detailed results on nugget and its related correlations are expounded in the subsections of Section 3.

3.1 Effect of tool profile on nugget morphology

The choice of tool profile predominantly controls the size of welds' stir zones during friction stir spot welding process; and eventually, the resultant bonded or nugget size of welds is determined by the morphology of the tool. The cross-sectional area of the tool shoulder in pinless weld differs from that of conical pin weld. Thus, more material volume is stirred in pinless welds compared to conical pin welds. Different tool geometries cause different material flow pattern, varying stirred volume of plasticized material and consequently, the resultant weld nugget is affected by the inherent material transport. Material flow occurs around the pin and beneath the shoulder surface in conical pin weld. Thus, this flow region constitutes the stir zone; and effective bonding or nugget occurs within the region of material flow around the tool pin. The welds fabricated with the aid of pinless tool have larger bonded areas or nuggets which can be likened to thin disks or disk-like nuggets formed at the faying surface between the upper and lower sheets as revealed in Figure 1a. Through-thickness flow is the most dominant flow pattern underneath the shoulder surface in pinless welds. As a result, the entire flow area beneath the shoulder is predominantly responsible for the width or size of nugget in pinless welds. However, a circular bonded ring of weld nugget is formed in conical pin welds as shown in the fractured weld surface in Figure 1b. The formed ring-like nugget has a keyhole or notch created by the penetration of the tapered or conical pin at the centre. As a result, the effective bonding of the upper sheet to the lower sheet revolves round the cavity created by the conical pin. Thus, this work corroborates the investigation of Paidar et al. (2015) which affirms that the effect of tool pin geometry (cylindrical and triangular) on the shape of stir zone is more significant than that of other process parameters like tool rotational speed.

Table 1: Chemical Composition of AA2219-O aluminium alloy (wt %)

Alloy	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Zr	Others
2219-O	Bal	0.06	0.14	6.6	0.32	0.02	0.00	0.03	0.04	0.06	0.13	0.03

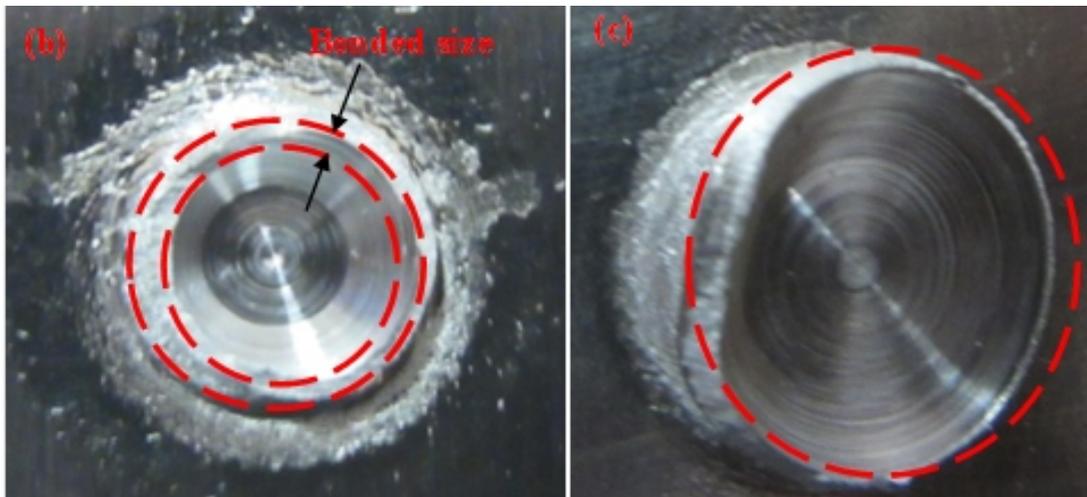


Figure 1: Nugget morphology after failure upon subsection to axial loading: (a) ring-like nugget in conical pin weld (circumferential nugget shear failure); (b) disk-like nugget in pinless weld (nugget pull out)

Likewise, through thickness material flow and penetration of plasticized material into the bulk of the work-piece material occur during pinless friction stir spot welding process to create bonding at the faying surface of the overlapped materials. This is aided by the generated frictional heat and induced deformational energy. As a result, the entire tool shoulder surface enforces enough heat and material sinks into the adjacent region of the lower plate as the tool rotates to form a weld nugget closer to the size of the tool shoulder. Thus, tool shoulder is essentially vital for the formation of weld nugget; it supplies the needed thermal energy (about 70% of requisite heat input) requires for forging the upper plate with the lower plate and it contains extruded material (from the pin) by redirecting it back into the stir zone to create effective bond. As a result, the size of the tool shoulder determines the bonded size of welds in both pinless and conical pin welds. The bonded size in pinless weld is lesser than the actual diameter of the tool shoulder but the overall morphology of the bonded region takes the profile of the shoulder surface. On the other hands, the size of the tool shoulder is limited by the presence of the conical pin in pin assisted welds; as a result, a ring-like bonded morphology is obtained in conical pin welds. However, the observed bonded sizes are significantly lesser than the actual size of the circular profile of the shoulder surface.

The frictional heat generated during FSSW is dependent on the contact area between the tool and the work-piece; subsequently,

the contact area affects the stir zone and the resultant weld nugget. The area or width of the nugget zone increases with heat input and this increase in weld nugget is attributed to the size of tool shoulder and the tool rotational speed (Kanwer et al. 2010). Increase in tool shoulder generates more frictional heat and also, an increase in the tool rotational speed also induces more frictional and deformational heat. However, the heat input contribution of tool pin is as little as 0.1% or 2%. As a result, an insignificant heat contribution is obtained with an increase in pin diameter.

3.2 Effects of welding parameters on nugget size

Apart from material thickness and its composition that are likely going to influence nugget size, the bonded width or nugget size of welds are obviously affected by the choice of welding parameters during friction stir spot welding. Variation in welding parameters affects material flow around the pin, underneath the shoulder surface and eventually causes variable stir zone shape or size. Tool rotational speed is directly responsible for the amount of heat input (frictional energy) generated during friction stir spot welding process. As a result, the thermal energy needed for the formation of the bonding or nugget size in spot welds is dependent on the level of tool rotational speed chosen for the weld. The relationship between bonded size in both pinless and conical pin welded joints are shown in Figure 2a. The bonded size increases and decreases with tool

rotational speed. The least bonded sizes are obtained at 1600rpm in both pinless and conical pin welds compared to tool rotational speed of 1400rpm. This shows a closer agreement with the work of Paidar et al. 2015. Stir zone width is affirmed to increase with tool rotational speed but a saturation level is attained when the tool rotational speed goes beyond a certain level with both cylindrical and triangular pin in the welding of 1.6mm thick AA2024-T3 alloy.

Tool shoulder penetration depth directly controls the compressive axial force applied on plasticized material during friction stir spot welding. An increase in tool shoulder plunge depth produces a rise in the vertical axial force being exerted on the joint or plasticized area of weld. Thus, this facilitates the compression or penetration of material underneath the shoulder surface into the bulk of the work-piece material. As a result, the relationship between bonded size and shoulder plunge depth is shown in Figure 2b. An increase in shoulder plunge depth increases the bonded or nugget size of both categories of joints. The spread area (width) of stir zone is affirmed to increase with an increase in tool shoulder penetration or axial pressure in friction stir spot welds (Paidar et al. 2015).

The influence of dwell time on bonded size does not show the same pattern of trend line in both pinless and conical pin welds. As a result, the effect of dwell time on nugget size is difficult to directly highlight. Further, analytical examination is however required. However, the analysis of variance (ANOVA) is performed to identify the individual contribution of welding parameters on the bonded width or nugget size of pinless and conical pin welds. Going by the rule that any contribution lesser than 10% has a slight influence on a response parameter. It was observed that tool rotational speed and plunge depth are the most dominant parameters influencing the bonded width of both pinless and conical pin welds respectively. Plunge depth has the most significant effect on nugget size in pinless and conical pin welds with percentage contributions of 83.97% and 41.68% respectively as shown in Tables 2 and 3. This wide difference between the contributions of shoulder plunge depth is attributed to the effect of pin profile on the bonded width (pin reduces the overall bonded width of stir zone). On the other hands, the percentage contributions of tool rotational speed are 10.57% and 33.70% in pinless and conical pin welds respectively. The observed contributions of tool rotational speed and shoulder plunge depth are in good agreement with the work of Paidar et al. 2015 which affirms that higher tool shoulder depth (or axial force) and tool rotational speed (heat input) facilitates the formation of enlarged width and size of stir zone in friction stir spot welds. As a result, the

synergetic or combination effect of tool rotational speed and plunge depth significantly determines the bonded size or nugget size of friction stir spot welds. Meanwhile, dwell time has an insignificant or negligible influence on the bonded size in both categories of welds.

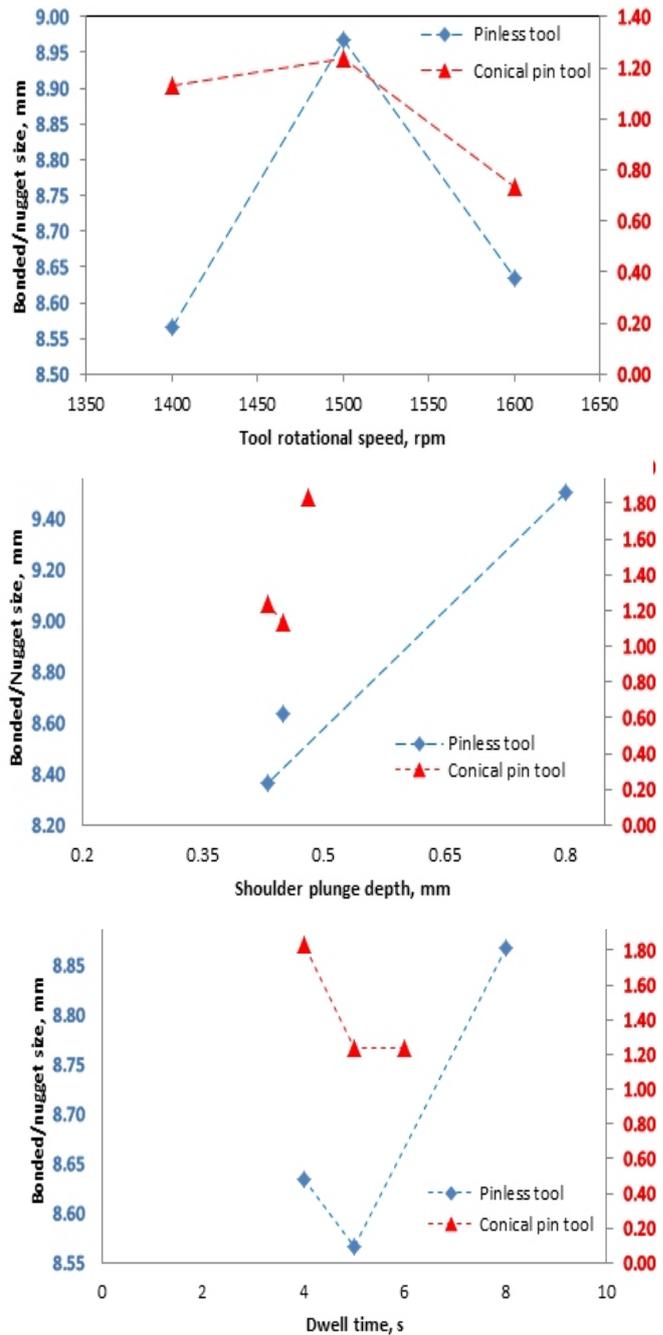


Figure 2: Relationship between bonded size and (a) tool rotational speed; (b) shoulder plunge depth; (c) dwell time

Table 2: Analysis of Variance (Bonded size) - pinless welds

Source	DF	Seq SS	Adj SS	Adj MS	F-value	P-value	Contribution
Rotational speed	2	0.18149	0.18149	0.090744	19.13	0.050	10.57%
Plunge depth	2	1.44136	1.44136	0.720678	151.90	0.007	83.97%
Dwell time	2	0.08416	0.08416	0.042078	8.87	0.101	4.90%
Error	2	0.00949	0.00949	0.004744			
Total	8	1.71649					

S- 0.0688799; Rq- 99.45%; R-sq (adj)- 97.79%

Table 3: Analysis of Variance (Bonded size) - conical pinwelds

Source	DF	Seq SS	Adj SS	Adj MS	F-value	P-value	Contribution
Rotational speed	2	0.055467	0.055467	0.027733	1.38	0.421	33.70%
Plunge depth	2	0.068600	0.068600	0.034300	1.70	0.370	41.68%
Dwell time	2	0.000267	0.000267	0.000133	0.01	0.993	0.16%
Error	2	0.040267	0.040267	0.020133			
Total				8	0.164600		

S- 0.141892; Rq- 75.54% ; R-sq(adj)- 2.15%

3.3 Nugget rotation

During axial loading of the tensile shear specimen, a slight rotation or re-orientation of weld nugget occurs in order to ensure that the line of force (due to the loading) aligns with the centroid (centre of gravity) of the weld nugget. However, in order to ensure some degree of nugget rotation, the weld nugget needs to restrict abrupt failure or brittle-like behaviour; the weld nugget needs to show a significant ductile behaviour. As a result, this attribute of tensile shear specimen (nugget rotation attribute) is a measure of nugget/weld soundness. Nugget rotation is a means through which the bonded region of friction stir spot weld absorbs some load/energy to induce rotational equivalence of the applied axial force (torque) on the overlapped region of the work-piece prior to crack propagation and failure. As a result, some significant time is needed to produce weld rotation in friction stir spot welds before the emergence of any palpable failure. Therefore, for a nugget to undergo angular displacement or rotation during loading condition, the bond between the upper and lower plates needs to be sound and the inherent nugget properties of the spot weld need to support plasticity or exhibit some ductile behaviour. The notable nugget properties of friction stir spot welds include the bonded or nugget size and metallurgical properties like grain size and hardness. However, nugget hardness does not change significantly with welding parameters during FSSW (Sajed et al. 2016). As a result, it was not used as an index in qualifying angular displacement or rotation of nugget during axial loading. The bonded size is employed to access and to compute the angular displacement or nugget rotation of welds.

The applied axial force on the tensile shear specimen performs two significant functions, namely nugget rotation and crack

propagation or growth. The preliminary force on the specimen is converted to energy or torque for the rotation of the weld nugget to attain a critical angle while the progressive increase in the axial loading causes stress concentration at the weakest point around the weld nugget and the eventual crack propagation. Thus, the weld that undergoes obvious nugget rotation before the final separation of the upper and lower material exhibits higher lap shear failure load and energy, and prolonged separation time as compared to the weld with slight rotation.

3.4 Weld failures under monotonic axial loading condition

The typical illustrations of failure path in conical pin weld and pinless weld are shown in Figures 3a and 3b respectively. Crack propagation in a circular path around the established keyhole of conical pin weld is the observed failure mode of probe or conical pin assisted welds as shown in Figure 4a. This is described as nugget shear failure mode or shear failure of effective weld nugget. Based on the morphology of fracture surfaces and observed cross-sections of friction stir spot welds, the applied force or stress on the weldment causes crack growth emanating from the hook feature, and the crack propagates around the effective ring-like nugget of the weld to cause final failure. Also, this form of failure with inherent weld defect (hook) could not support significant nugget rotation because the force required for angular displacement of nugget initiated crack growth during axial loading. As a result, predominantly feeble or negligible nugget rotation accompanies shear failure mode of conical pin welds.

However, in the case of pinless weld, the maximum stress acts on the effective nugget's centroid due to no significant metallurgical

defect within the nugget. The axial force acting on the weld causes angular displacement or rotation of nugget and the weld edge or nugget edge undergoes some straining. As a result, the strained nugget edge develops into a crack and propagates into the nugget width/length (along the faying plane toward the weld centre) or into the nugget thickness. The crack propagation into the nugget width is referred to as interfacial shear failure; a combined opening and shearing through the nugget width or bonded region occurs in this form of failure mode. On the other hands, the crack propagation through the nugget thickness or heat affected zone along the nugget circumferential boundary is referred to as nugget pullout. Necking-shear failure commences at the nugget edge in the stretched region of the weldment (HAZ) and propagates via a circumferential path without a significant interfacial shearing along the bonded width as observed in Figure 4b. Conclusively, both interfacial shear failure and nugget shear failure produces nugget rotation or angular displacement in pinless welds.

3.4.1 Stress analysis on fractured weld specimen under axial loading

Considering the fracture patterns in pinless and conical pin welds, the stress analysis on the weld nugget is examined. Nugget shear fracture in conical pin weld and interfacial shear fracture occur in friction stir spot welds fabricated with conical pin tool and pinless tool respectively. Based on the configurations in figure 5, two stresses act on the nugget to initiate fracture; they are tensile (perpendicular or normal) stress and shearing or tangential stress. The force parallel to the resisting area of the weld nugget causes shearing stress on the weld area. In figure 5, the definitions of the given parameters are highlighted as follow: F is the axial force

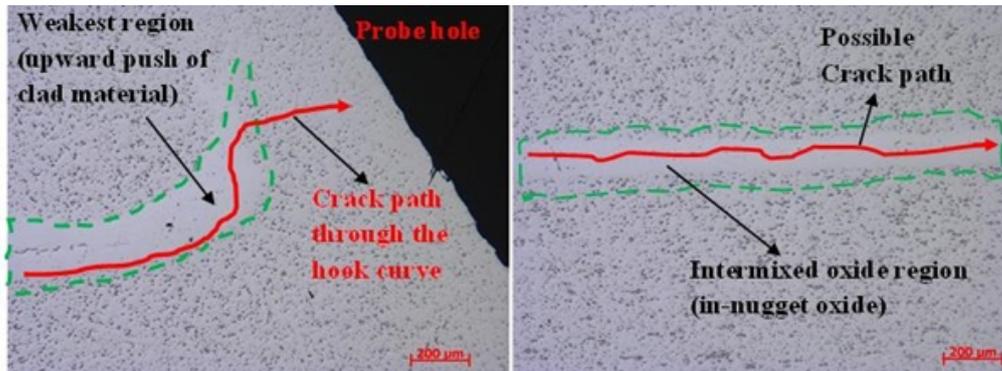


Figure 3: Illustration of failure path on welds (a) conical pin weld showing shear failure into probe hole (b) pinless weld failure

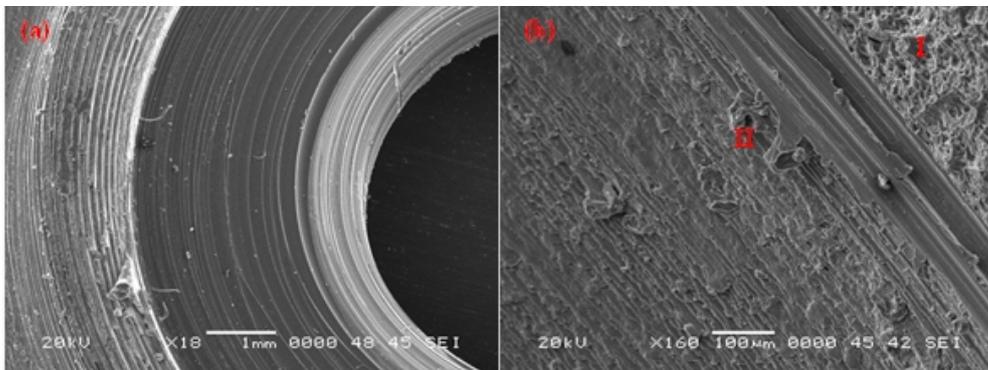


Figure 4: Failure surfaces along the weld nugget (a) conical pin weld (b) pinless weld (I- final ductile dimple failure and II-plasticized crack growth/propagation zone)

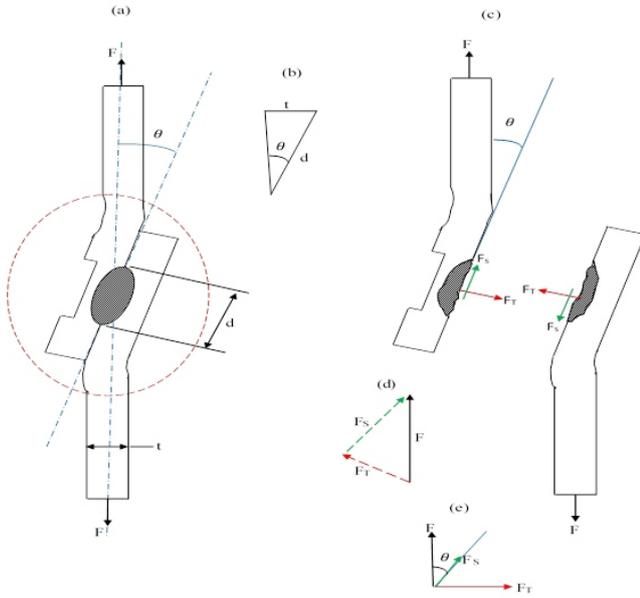


Figure 5: Axial loaded pinless weld (a) nugget rotation of weld; (b) angular displacement of nugget; (c) fractured specimen with stress pattern; (d) free body diagram of sheared specimen; (e) force resolution

By Pythagoras theorem (according to figure 5), the nugget rotation of weld or angular displacement of nugget prior to complete separation of the upper sheet from lower sheet is expressed as shown in equation 1. Equation 1 is rewritten as equation 2 via change of subject of the formula.

$$\sin \theta = \frac{t}{d} \quad (1)$$

$$\theta = \sin^{-1} \left(\frac{t}{d} \right) \quad (2)$$

The resolution of forces (tensile and shear forces) with respect to the angular displacement of nugget can be performed according to figure 5d or e. Therefore, the resolved tensile and shear forces are given in equations 3 and 4 respectively.

$$F_T = F \sin \theta \quad (3)$$

$$F_s = F \cos \theta \quad (4)$$

As a result, the stresses (tensile and shear stresses) acting on the nugget according to figure 5c is computed using the angular shear and tensile forces in equations 3 and 4 respectively. By going with the normal convention, stress is a vector quantity and it is the ratio of the directional applied force on the weld to the nugget area. Also, the nugget or bonded area of the weld is expressed in equation 5. Then, the tensile stress is expressed in equation 6.

$$A = \frac{\pi d^2}{4} \quad (5)$$

$$\sigma = \frac{4F_T}{\pi d^2} \quad (6)$$

By substituting the value of F_T (in equation 3) into equation 6, the tensile stress acting on the weld nugget is rewritten as equation 7. Similarly, equation 7 is reduced by replacing $\sin \theta$ with t/d to form equation 8 as the derived expression for tensile stress.

$$\sigma = \frac{4F \sin \theta}{\pi d^2} \quad (7)$$

$$\sigma = \frac{4Ft}{\pi d^3} \quad (8)$$

In the same manner, the shear stress generated during axial loading of the weld is expressed as equation 9. By replacing F_S in equation 9 with $F \cos \theta$, then, the expression for shear stress becomes equation 10. F_S is the resultant force acting on the nugget area (A) being sheared.

$$\tau = \frac{F_s}{A} \quad (9)$$

$$\tau = \frac{F \cos \theta}{A} \quad (10)$$

According to the trigonometric rules, cosine θ can be expressed in terms of $\sin \theta$ as illustrated in equation 11. As a result, the $\sin \theta$ in the expression is reduced to equation 12.

$$\cos \theta = (1 - (\sin \theta)^2)^{1/2} \quad (11)$$

$$\cos \theta = \left(1 - \left(\frac{t}{d}\right)^2\right)^{1/2} \quad (12)$$

Thus, the shear stress acting on the weld nugget is obtained by substituting equation 12 into equation 10 to obtain equation 13.

$$\tau = \frac{F}{A} \left[1 - \left(\frac{t}{d}\right)^2\right]^{1/2} \quad (13)$$

The value of A (nugget area) as illustrated in equation 15 is substituted into equation 13 to obtain the derived expression for the shear stress acting on the weld nugget shown in equation 14.

$$\tau = \frac{4F}{\pi d^2} \left[1 - \left(\frac{t}{d}\right)^2\right]^{1/2} \quad (14)$$

Nevertheless, the equivalent stress acting on the weld nugget is computed based on Von Mises equation illustrated in equation 15. By substituting the values of equations 8 and 14 into equation 15, the derived equivalent stress acting on the weld nugget is shown in equation 16. The reduced equation 16 becomes 17 and the final derived expression for the equivalent stress acting on weld nugget (interfacial fracture mode) is given in equation 18.

$$\sigma_e = \sqrt{\sigma^2 + 3\tau^2} \quad (15)$$

$$\sigma_e = \sqrt{\left(\frac{4Ft}{\pi d^3}\right)^2 + 3\left(\frac{4F}{\pi d^2} \left(1 - \left(\frac{t}{d}\right)^2\right)^{1/2}\right)^2} \quad (16)$$

$$\sigma_e = \sqrt{\left(\frac{4Ft}{\pi d^3}\right)^2 + 3\left(\frac{4F}{\pi d^2}\right)^2 \left(1 - \left(\frac{t}{d}\right)^2\right)} \quad (17)$$

$$\sigma_e = \frac{4F}{\pi d t} \left[3 - \frac{2t^2}{d^2} \right]^{1/2} \tag{18}$$

However, the stress analysis in conical pin welds follows the same procedure as that of pinless weld but the bonded size or bonded area of conical pin weld differs from that of pinless welds. As a result, the area exposed to stress distribution or concentration is not similar in both welds. The schematic illustration of conical pin welded joint subjected to axial loading is shown in figure 6. Due to the pin hole of the conical pin welded joint, a ring-like bonded area or nugget is created in the welded joint. As a result, this ring-like bonded area is the effective bonded area required for the stress analysis of conical pin welded joint.

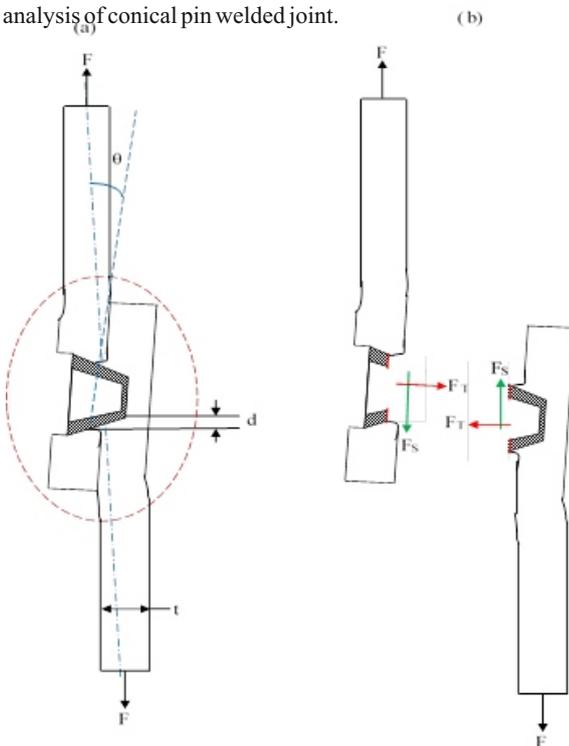


Figure 6: Axial loaded conical pin weld (a) feeble nugget rotation of weld; (b) fractured specimen with stress pattern

Therefore, the effective area of conical pin welded joint is given in equation 7.39.

$$A = \frac{\pi(D^2 - d^2)}{4} \tag{19}$$

Where D and d are the outer and inner diameters of the bonded ring-like nugget of conical pin welded joint. Then, the tensile stress acting on the conical pin welded joint can be expressed as shown in equation 20 while the shear fracture acting on the weld is given in equation 21.

$$\sigma = \frac{4F_T}{\pi(D^2 - d^2)} \tag{20}$$

$$\tau = \frac{4F_S}{\pi(D^2 - d^2)} \tag{21}$$

Where F_T and F_S are tensile force and shear force acting on the weld during axial loading condition. These forces can be expressed in terms of rotational angle or nugget rotation as shown in equations 22 and 23 respectively. However, F is the axial force applied on the work-piece during axial loading process.

$$F_T = F \sin \theta \tag{22}$$

$$F_S = F \cos \theta \tag{23}$$

If the nugget rotation in conical pin welded joint is negligible or approximately zero. It signifies that shear force (F_S) is the most dominant force during axial loading of the joint and tensile force (F_T) will be negligible. As a result, the axial force that is applied on the work-piece or weldment is responsible for shearing of the weld nugget. Thus, the shear-force acting on the work-piece is given in equation 24 and the shear stress is rewritten as equation 25.

$$F_S = F \tag{24}$$

$$\tau = \frac{4F}{\pi(D^2 - d^2)} \tag{25}$$

Thus, the dominant stress acting on the conical pin welded joint (nugget) is the shear stress, whereas both tensile stress and shear stress act on pinless welded joint. Likewise, nugget rotation in pinless weld is majorly associated to the tensile stress induced on the weld nugget. In other words, the shear stress is not responsible for nugget rotation.

4.0 Conclusion

Welding parameters affect the resultant bonded size or weld nuggets in both pinless and conical pin welded joints. Tool rotational speed and plunge depth are the most dominant parameters influencing the bonded width or nugget size of both pinless and conical pin welds respectively. Plunge depth has the most significant effect on nugget size in pinless and conical pin welds with percentage contributions of 83.97% and 41.68% respectively.

The axial loading of tensile shear specimen performs two significant tasks which are nugget rotation and crack propagation. The progressive initial axial loading is converted to torque for the rotation of the overlapped region of weld while a progressive increase in loading beyond the energy required for nugget rotation

causes the emergence of crack growth. The degree of nugget rotation or angular displacement of welds is greatly dependent on the nugget size or width of welds. Nugget rotation occurs in welds with large bonded size compared to those with small bonded region. However, intense nugget rotation is observed in pinless welds while feeble nugget rotation occurs in conical pin welds.

Nugget shear failure across the ring-like weld nugget is the fracture mode observed in conical pin welds whereas nugget pull-out failure and interfacial weld failures are the notable fracture modes of pinless welds. Equally, intense nugget failures are notable in welds with nugget failure modes.

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