Stephen Leon J
Department of Mechanical Engineering
Saveetha School of Engineering
Saveetha Institute of Medical and Technical Sciences, Chennai, Tamilnadu
India

Bharathiraja G
Department of Mechanical Engineering
Saveetha School of Engineering
Saveetha Institute of Medical and Technical Sciences, Chennai, Tamilnadu
India

Jayakumar V
Department of Mechanical Engineering
Amrita School of Engineering
Amrita Vishwa Vidyapeetham, Chennai
India

Experimental Investigations on Mechanical Properties of Friction Stir Welded AA2024-T3 Joints

Friction stir welding is a promising solid state metal joining technique. It can be used to join AA2024-T3 metal plates which cannot be welded using normal fusion welding. Post weld joint efficiency depends completely on the proper selection of process variables as the required heat input for this process is not supplied by an external source but an internal function of the variables. Apart from the process variables tool pin shape also plays a vital role on the delivery of better weld strength. A comparative experimental analysis was done to understand the improvement in the post weld properties on the usage of non-cylindrical tool pin. In order to optimise major process variable for cylindrical as well as non-cylindrical tool pin geometries thermal study had been carried out and optimum heat input conditions were analysed for AA2024-T3 plates. Comparative analyses on friction stir weld joints were made qualitatively and quantitatively to understand the improvement on the introduction of non- cylindrical flat faced pin in the tool.

Keywords: *Friction stir welding, Mechanical properties, Thermal study, AA2024-T3, Optimum conditions.*

1. INTRODUCTION

Application of aluminium alloy AA2024-T3 in the aviation sector is huge. The major problem associated with the usage of AA2024-T3 is, that it cannot be joined using conventional fusion welding technique as it oxidises easily in its molten stage by the unavoidable influence of atmospheric air. So, friction stir welding being a solid state metal joining process is widely used to join AA2024-T3 [1]. Frictional heat developed in the tool/ matrix interface is the only heat source in this metal joining process. When the interface surface temperature reaches closer to the melting point of matrix to be joined, friction along the tool/matrix interface drops down. This decrease in friction, decreases heat generation and maintains the process peak temperature lower than the melting point of the base metal throughout the joining process. Various stages in friction stir welding are shown in Fig. l.

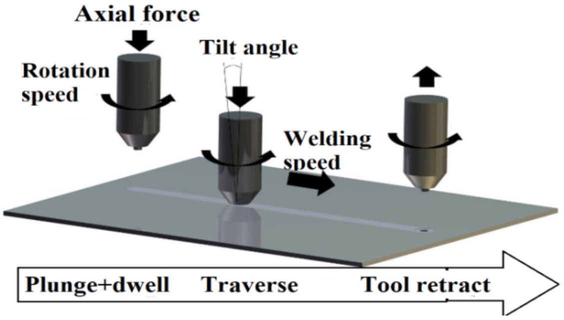

Figure 1. Stages in friction stir welding [2]

In order to optimise the thermal environment during the joining process, temperature rise in the heat affected and the stir zone on the selection of different process parameter ranges has to be analysed. Contact type temperature measurement techniques were used to experimentally measure transient temperature rise in the heat affected zone as this zone does not undergo any plastic deformation [3]. On the other hand, severe plastic deformation in the stir zone complicates the experimental study on temperature rise in the stir zone. So, combined effect of heat generation by the friction and plastic deformation was analysed using CFD model to understand the peak temperature rise in the stir zone [4]. Tang et al. [5] analysed peak temperature rise and temperature distribution along the stir zone using numerical modeling. Rosenthal moving source heat generation can also be used to numerically estimate peak temperature rise during the process [6]. Several analytical equations are derived [7] with respect to the tool geometry in order to estimate the heat generation and the corresponding temperature rise.

In the defect free friction stir welding, the joint efficiency depends on the property degradation in the heat affected zone. A simple way to improve joint efficiency is improving the post weld property of joint in the heat affected zone which can be achieved through proper dissipation of heat flux by enhancing the rate of cooling through its atmospheric contact boundaries [8]. The joint efficiency can also be improved by reducing effective heat supply during the process. But reduction in the heat generation may lead to increase in the yield strength of the material [9] which increases the flow resistance and result in inadequate material flow in the stir zone. Inadequate material flow is the root cause of several weld defects. Material flow at lower temperature in the stir zone can be enhanced by the introduction of flat faced non-cylindrical tool pin geometry [10]. Flat

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Correspondence to: Stephen leon J
Saveetha Institute of Medical and Technical Sciences,
Chennai, Tamilnadu, India.
E-mail: stephenleonj@gmail.com
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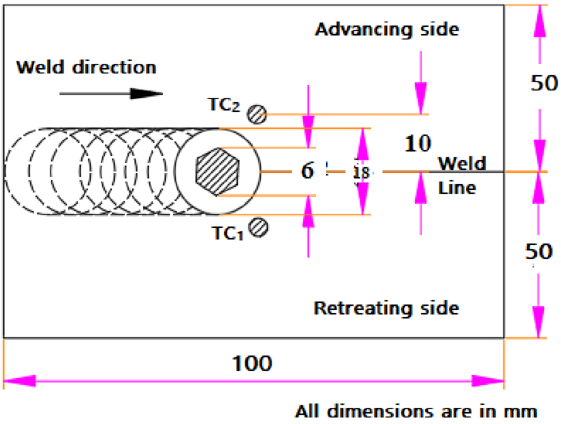
vertical surfaces in the pin and the low volume ratio (Actual volume of the pin / swept volume of the pin during rotation) ensures extra material strain in the stir zone during the joining process.

Major problem in the usage of flat faced pin is unlike cylindrical pin, the stress acting on the pin surface is not uniform as the distance of points in the edge side varies continuously from the axis of rotation [11]. As in the entire joining process, the tool pin is submerged in the parental material to be joined, the tool pin experiences huge principal stress exerted by the material that it handles in the stir zone. The quantity of maximum principal stress depends on yield strength of the material at elevated temperature during the process [12]. Reduction in heat supply improves the joint efficiency in the heat affected zone but it also increase the yield strength of the material in the stir zone which leads to the increase in the principal stress acting on the pin. Increase in the principal stress leads to premature tool failure [13]. This indicates that the thermal conditions during the process need to be optimised with respect to the pin geometry in such a way that it improves the joint strength with minimal effect in the tool life.

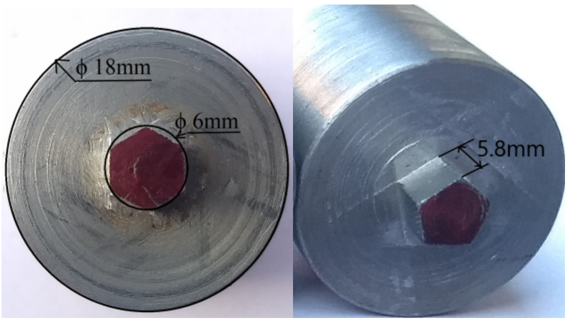
In this paper, the effects of change in tool pin shape on the total heat supply is analysed and the optimum heat input conditions with respect to the selected tool pin shape was defined. Apart from this, a comparative experimental study was carried out to understand the improvement in the joint efficiency on the introduction of flat surfaces in the tool pin geometry. Optimum tool feed rate was also discussed with respect to the tool pin geometry.

2. EXPERIMENTAL ANALYSIS

AA2024-T3 plates of dimension 60mm x 50mm x 6mm were butt joined by friction stir welding technique using Hartford LG 1000 vertical milling machine centre. Mild steel (350 grade) was chosen as the backing plate material. Properties of the base metal are given in Table 1. In order to compare the effects of introduction of flat faces in the tool pin, tools with cylindrical shape pins and tools with hexagonal cross sectional shaped pins (six flat faces) were made using hardened H13 tool steel material. Apart from the pin shape, ranges of other process variables like shoulder diameter, tool rotational speed and welding speed selected for the experimental studies are given in Table 2.



(a)



(b)

Figure 2. Experiment details: (a) Experiment layout, (b) Tool with flat faced pin

K-Type thermocouples (TC1 and TC2) were implanted in the location as shown in Fig. 2 to observe maximum temperature rise during the process in advancing as well as retreating sides. In order to consider the minor difference in temperature rise along the retreating and advancing sides, the average value of peak temperature detected by TC1 and TC2 are considered for analysis (Table 3). Joints obtained from each trail were qualitatively analysed through its macro structure examination and joint efficiencies were quantitatively analysed using tensile and hardness tests.

Table 1. Mechanical and thermal properties of base metal (AA2024-T3)

Property/parameter	Value
Thermal conductivity (W/mK)	151
Specific heat capacity J/g °C)	0.875
Density (g/cm^3)	2.78
Hardness (Vickers)	122
Ultimate strength (MPa)	462
Solidus temperature (°C)	502

Table 2. Input properties/parameters

Property/parameter	Value
Shoulder radius ($R_{Shoulder}$) (mm)	9
Circumscribed pin radius (R_{Pin}) (mm)	3
Height of the pin (H_{Pin}) (mm)	5.8
Work piece thickness (mm)	6
Tool rotation speed (rpm)	800 to 1200
Weld velocity (mm/min)	60 to 80

3. RESULTS AND DISCUSSIONS

3.1 Thermal study

Average peak temperature listed in Table 3represents the peak temperature on the quasi steady state during the welding stage for different trials. As expected, temperature during the process was directly proportional to the tool rotational speed when other process influencing factors were constant. Table 3represents the relationship between the tool rotational speed and the process peak temperature during the joining process for different tool feed rates with the usage of cylindrical and hexagonal pins in friction stir welding tool. It can be observed that the temperature curves flatten when the temperature rise is closer to the saturation temperature of the base metal. For a given feed rate, in every trail the recorded peak temperature is lower with the usage of hexagonal shape tool pin than cylindrical shape pin. The reduction in process temperature indicates the reduction in effective heat supply rate on the replacement of cylindrical pin with flat faced hexagonal tool pin. Reduction in heat supply reduces heat flux conducted through the heat affected zone which in turn reduces the coarsening of microstructure in this zone. Fine grains in this zone improve the post weld mechanical properties of the joint.

Table 3. Peak process temperature during the welding stage (in °C)

Tool Rotation speed (rpm)	60 mm/min		70 mm/min		80 mm/min	
	Cylindrical	Hexagonal	Cylindrical	Hexagonal	Cylindrical	Hexagonal
800	431.5	428.7	408.2	405.8	391.7	389.6
900	447.5	439.4	425.3	422.6	406.7	404.4
1000	465.6	458.1	438.4	429.5	415.8	414.2
1100	471.6	464.8	449.6	439.3	426.9	421.0
1200	473.7	469.5	456.7	446.2	433.0	428.9

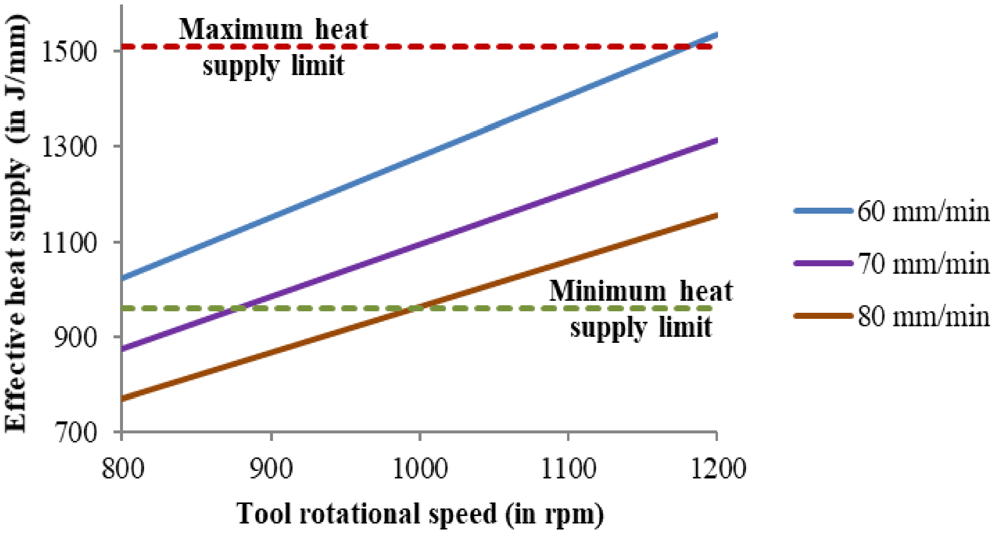


Figure 3. Optimum effective heat supply (cylindrical pin)

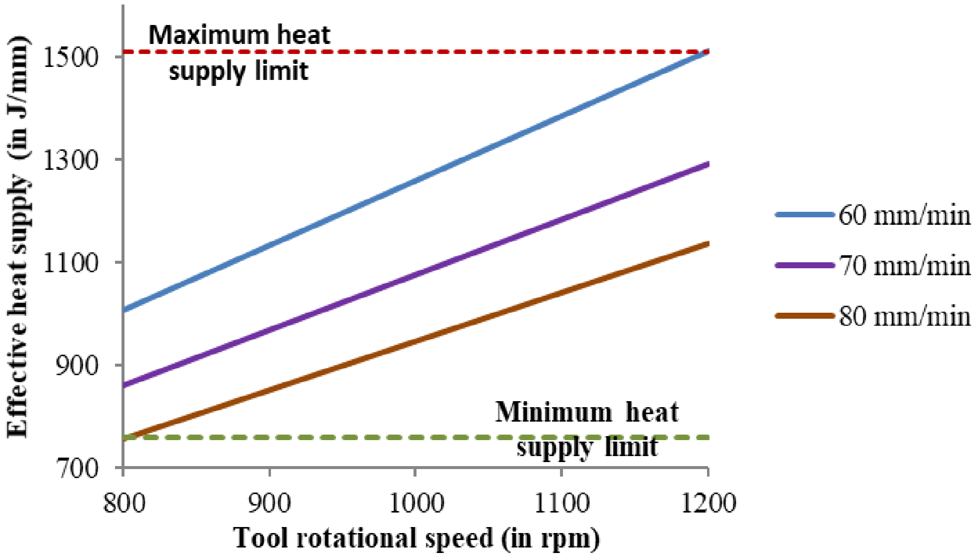


Figure 4. Optimum effective heat supply (Hexagonal pin)

Table 4. Defects in stir zone

Tool rotational speed (rpm)	60 mm/min		70 mm/min		80 mm/min	
	Cylindrical	Hexagonal	Cylindrical	Hexagonal	Cylindrical	Hexagonal
800	*	*	Tunnel	*	Tunnel	Tunnel
900	*	*	*	*	Tunnel	*
1000	*	*	*	*	Tunnel	*
1100	*	*	*	*	*	*
1200	Flash	Flash	*	*	*	*

3.1 Qualitative analysis

Reduction in the process peak temperature by the usage of hexagonal tool pin can be explained through the analytical estimation of effective heat supply during the process. Hexagonal tool pin generates lesser heat compared to the cylindrical tool pin. Heat generation rate can be estimated, for tool with cylindrical tool pin [14],

$$Q_{total} = \frac{2}{3}\pi\tau_{contact}\omega\left(R_{shoulder}^3 + 3R_{pin}^2 H_{pin}\right) \qquad (1)$$

for tool with hexagonal tool pin [15],

$$Q_{non-circular} = \frac{1.54}{3} n 0.13\pi\tau_{contact}\omega\left(R_{shoulder}^3 + 3R_{pin}^2 H_{pin}\right) \qquad (2)$$

Here, n refers to the number of sides in the tool pin, ω is angular velocityand $\tau_{contact}$ is contact stress. Fig. 3 & 4 represents the change in effective heat supply with respect to the tool rotational speed when other variables in equation 1 and 2 are kept constant (Table 2). As effective heat supply notonly depends on the tool rotational speed but also on other factors, it is meaningful to represent optimum heat supply to obtain defect free weld so that the combination of process variables shall be chosen in such a way that it delivers an optimum heat supply in the view of obtaining defect free weld. Minimum and maximum limits of the effective heat supply are given in Fig. 3 & 4 with respect to the tool pin geometry.

Irrespective of the tool pin shape, effective heat supply increases when the tool rotational speed increases. Selection of the low tool rotational speed may help in improving the post weld properties in the heat affected zone. Reducing the tool rotational speed beyond a limit (860 J/mm for cylindrical pin and 760 J/mm for hexagonal pin) causes insufficient heat generation rate during the process which leads to improper material flow around the tool pin under the tool shoulder in the stir zone. Insufficient material flow in the stir zone results with tunnel defects in the joint. On the other hand, increasing tool rotational speed beyond a limit (1510 J/mm) leads to excessive heat supply which causes material to spill out from the edge of the tool shoulder that results in flash defect in the stir zone. To observe the defects in the welded joints macro structure analysis was carried out on the specimens collected from every trail and the observed defects are listed in Table 4. From the results it can be understood that for the same experimental conditions, in few trails, the flat faced pin delivered defect free welded joint and cylindrical pin delivered joints with tunnel defect. This indicates that the volume ratio (actual occupied volume/ swept volume during rotation) of the tool pin has its own role on material flow in the stir zone. It can be observed that volume ratio is less than one for a flat faced pin where as it is equal to one for a cylindrical pin. This lesser volume ratio ensures excess material strain during the process, which in turn improves the material flow even in lower process temperature.

3.2 Qualitative analysis

The quality of the friction stir welded joints can be quantified by the joint strength analysis [16]. This solid state welding normally exhibits superior post weld properties in the stir zone. Coarsening of the grains in the heat affected zone decreases the hardness value as the density of the strengthening agents in the base metal is reduced in this zone. Measuring the post weld hardness value in the HAZ is a simple method to analyse the post weld mechanical property of the obtained joint. The variation in the hardness value with respect to the feed rate suggests that the feed rate should be kept as high as possible to improve the post weld properties in the heat affected zone. This can be explained through the relationship between the process peak temperature and the property degradation in HAZ. Fig. 5 shows the lowest hardness value observed in the heat affected zone on every trail with respect to the peak temperature during the welding stage. The process peak temperature is indirectly proportional to the tool feed rate as the increase in weld velocity reduces effective heat supply. When the process peak temperature is kept lower, the hardness value in HAZ is much closer to the hardness value of the base metal. A maximum hardness value of 111.2HV was observed on the usage of tools with hexagonal pin for a weld speed of 80 mm/min. It can also be observed that almost in all trails, usage of tools with flat faced pin delivered a better weld quality as the heat supply is comparatively lower than the cylindrical pin.

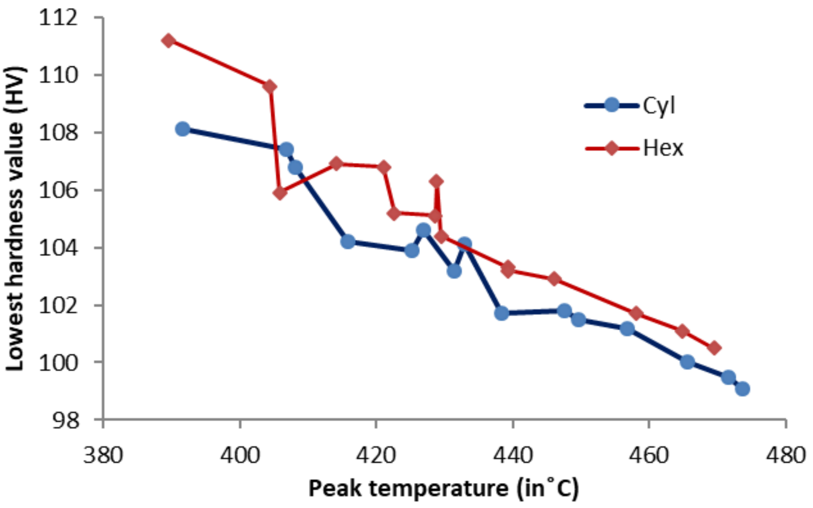


Figure 5. Effect of temperature rise on the harness value in HAZ

Table 5. Lowest hardness value(HV)in heat affected zone (HAZ)

Tool Rotation speed (rpm)	60 mm/min		70 mm/min		80 mm/min	
	Cylindrical	Hexagonal	Cylindrical	Hexagonal	Cylindrical	Hexagonal
800	103.2	105.1	106.8	105.9	108.1	111.2
900	101.8	103.2	103.9	105.2	107.4	109.6
1000	100	101.7	101.7	104.4	104.2	106.9
1100	99.5	101.1	101.5	103.3	104.6	106.8
1200	99.1	100.5	101.2	102.9	104.1	106.3

Table 6. Yield strength of the joint (in MPa)

Tool Rotation speed (rpm)	60 mm/min		70 mm/min		80 mm/min	
	Cylindrical	Hexagonal	Cylindrical	Hexagonal	Cylindrical	Hexagonal
800	308.8	311.3	287.4	317.7	284.7	285.6
900	306.1	310.6	311.4	315.1	295.5	316.8
1000	299.5	304.8	307.7	314.2	299.2	315.9
1100	299.3	303.8	303.5	310.3	312.8	315.1
1200	296.3	301.9	302.1	307.9	312.1	314.9

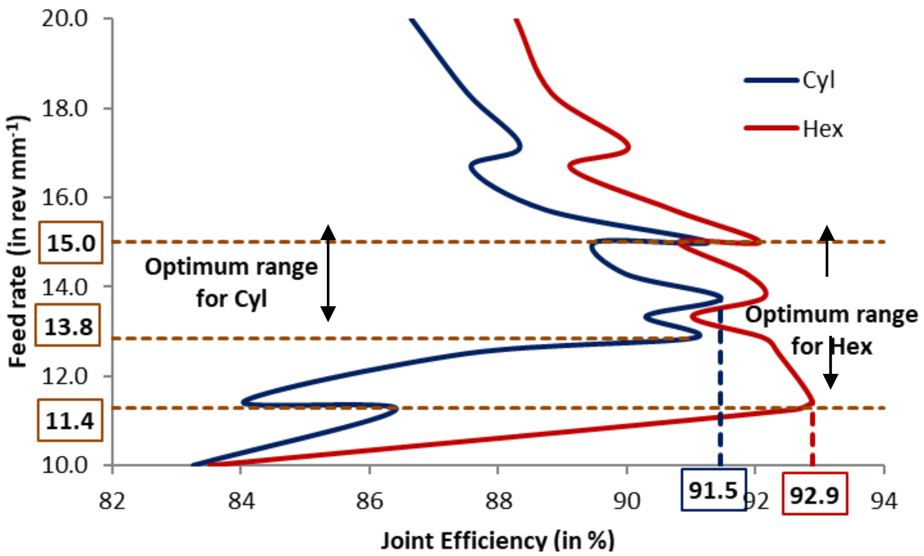


Figure 6. Optimum feed rate

3.3 Tensile test

Identifying the lowest hardness value can explain property eradication in the HAZ. Joint strength can be identified only through tensile test as weld defects in the stir zone are also a key factor that influence the joint strength [17]. Specimens were collected from each trail and tensile test carried out to understand the impact of feed rate on the joint efficiency. Obtained yield strength of each specimen is listed in Table 6. In order to obtain joint efficiency, ultimate strength of the base metal (Table 1) was compared with the ultimate strength of each specimen obtained through tensile test. Comparative analysis between the feed rate and the joint efficiency is shown in Fig.6. On every feed rate, usage of flat faced tool pin delivered better joint efficiency than cylindrical tool pin. When the feed rate was reduced below 13.8 rev mm^{-1}, the joint efficiency was drastically reducing for the joints made by the tool with cylindrical pin although the observed hardness value was high in the HAZ due to the defects in the stir zone (Table 4&5). On the other hand higher strain rate produced by the flat faced pin ensured sufficient material flow till the feed rate was reduced to 11.4 rev mm^{-1}. A maximum of 92.9% of joint efficiency was obtained on the usage of hexagonal shape tool pin. When the feed rate was more than 15 rev mm^{-1}joint efficiency was reducing gradually on the usage of both pins. This is due to the excess heat supply on the low tool feed rate which eradicates the properties in the heat affected zone by reducing the density of the strengthening agents. From this it can be understood that in order to maintain the joint efficiency higher than 90%, the tool rotational speed cannot be increased more than 15 rev mm^{-1}.

4. CONCLUSIONS

Post weld mechanical properties of the friction stir welded joint depend on the effective heat supply as well as on the sufficient material flow in the stir zone. Based on the quantitative and quantitative study on the obtained friction stir welded joints it can be concluded that,

- Weld quality depends on the effective heat supply and the effective heat input depends on many process parameters. Finding optimum heat supply conditions is a simplest way to optimise all process variables. It was observed that choosing process parameters which increases the effective heat input more than 1510 J/mm shall eradicate the post weld properties in the heat affected zone and it leads to excess flash in the stir zone.

• Reducing heat supply reduces property eradication along the heat affected zone but it leads to the formation of tunnel defects in the stir zone due to insufficient material flow. It has been identified that effective heat supply cannot be reduced less than 860 J/mm when using cylindrical tool pin. Inclusion of flat faces in the cylindrical tool pin reduces volume ratio of the pin which enhances the strain rate in the stir zone and ensures defect free weld up to 760 J/mm. This reduction in the allowable optimum heat supply limit reduces property eradication in the heat affected zone during the joining process.

• Optimum tool feed rate range was observed between 13.8 rev mm^{-1}and 15 revmm^{-1}for cylindrical tool pin. Increasing welding speed beyond this optimum range delivers a very low joint efficiency (83%) due to defects in the stir zone even though the observed lowest hardness value in the heat affected zone was closer to the base metal. On the other hand, usage of hexagonal shaped tool pin delivers defect free welds up to 11.4 revmm^{-1}tool feed. Joint efficiency of 92.9% is observed on this feed rate. These results clearly indicate that the use of tool pin with flat faces in friction stir welding tool not only improves the post weld mechanical properties but also facilitates selection of higher tool feed rate so that the machining time can be reduced.

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ЕКСПЕРИМЕНТАЛНО ИСТРАЖИВАЊЕ МЕХАНИЧКИХ СВОЈСТАВА ЗАВАРЕНИХ СПОЈЕВА ЛЕГУРА АА2024-Т3 ДОБИЈЕНИХ ЗАВАРИВАЊЕМ ТРЕЊЕМ СА МЕШАЊЕМ

Ј.С. Леон, Г. Бхаратхираја, В. Јаиакумар

Заваривање трењем са мешањем (ЗТМ) је перспективна техника чврстог спајања метала. Може да се користи за спајање металних лимова легура АА2024-Т3 који се не могу заваривати поступком фузионог заваривања. Ефикасност спојева после заваривања у потпуности зависи од адекватног избора променљивих вредности процеса јер се улазна топлота потребна за овај поступак не доводи из неког спољашњег извора већ од унутрашње функције променљивих. Поред променљивих вредности, важну улогу у добијању боље чврстоће шава игра клин алата. Извршена је упоредна анализа како би се разумело да се својства шава побољшавају коришћењем нецилиндричног клина алата. У циљу оптимизације главних променљивих процеса, геометрија цилиндричног као и нецилиндричног клина алата је испитана термичким поступком а услови оптималног улаза топлоте су анализирани за лимове легуре АА2024-Т3. Упоредне квалитативне и квантитативне анализе спојева заварених ЗТМ поступком извршене су ради бољег разумевања побољшања постигнутог увођењем нецилиндричног равног клина алата.