RESEARCH PAPER

The impact of Tool ratios on nugget welding temperature during Friction stir spot welding using different parameters.

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Abstract: - Friction stir spot welding (FSSW) is one of the significant and inexpensive process for joining between material plates. This is because this process depends on friction between the welding tool and the workpieces without using a heat source. Many parameters were used in FSSW such as rotation welding tool, tool force, friction coefficient, tool geometry .In this research, the effect of tool ratios on FSSW process with some important parameters were numerically investigated using FEM software to illustrate the behavior of each parameter on nugget welding temperature of FSSW process using AA2024-T3 sheets. The results display that tool ratios were effected on FSSW process via using some parameters: tool rotation speed, welding force, friction coefficient, and pin depth.

Keywords: - Tool ratios, numerical model of FSSW, pin depth, rotation tool speed.
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1. INTRODUCTION

Nowadays, The FSSW process make interesting for engineers and technicians due to make a high mechanical properties for products, and low cost process. So this process participates in the final step of manufacturing process to make joint mechanical parts, in addition, many effective parameters on this welding process were employed such as welding tool geometry, tool rotation, materials types, tool size, sheet thickness, etc.…[1-3]. In 2008, a thermal model of FSSW process of AA6061-T6 was numerically investigated using FEM to show the effective parameters in FSSW process: rotation tool, and tool welding depth. They also found that they proofed all parameters affected on the FSSW process [4].

The impact of pin geometry on tensile stress for FSSW process was experimentally studied of AA5754-O using two different pin geometries. They revealed that the tringle welding pin had double tensile stress of cylindrical welding pin [5]. In 2010, the effect of tool geometry was numerical investigated using four types of welding pin: cylinder pin, cone pin, inverse cone pin, and tringle pin, with connection of two different shoulder shapes. They concluded that the tringle pin had higher stress than other pin [6]. The effect of tool shape on mechanical properties and microstructure for FSSW process was experimentally investigated of AA6061-T6 using four different tool shapes. They discovered that the threaded cylindrical tool had got highest tensile strength, in addition, the threaded triangular pin had a highest elongation than all tools [7].

In 2022, the thickness effect was experimentally investigated as parameter to show the effect of AA6082 thickness in FSSW process. They used different rotation speed and different thickness of AA6082 sheets. They concluded that the joint between two different thickness sheets had higher hardness at tool speed 600 rpm [8]. After that, in the same year, a numerical simulation of FSSW for dissimilar sheets was numerically modeled using finite element method. They used two types of sheets: Aluminium-6061, and Magnesium AZ-31B to show the effect of stress and temperatures at dwell time stage. They proofed that the temperature increases due to increase rotation speed at dwell time stage [9]. A numerical model of FSSW process using finite element method for AA6061sheets. They shows three steps of friction spot welding process numerically. They founded that the numerical results for temperature close to experimental results [10].

The optimum parameters of FSSW process was numerically investigated of AA6061T6 using FEM software and comparing with experimental FSSW welding. They discovered that the welding tool rotation had highest effective parameter on strength and hardness of welding parts during FSSW, in addition they found the experimental welding results were close to numerical results [11].In 2024,The two parameters were numerical and experimental investigated of AA6061 such as welding pin speed and plunge depth, to show temperature and stress distribution. They found that the highest shear load had got between two AA6061 sheets with optimum parameters [12].

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In 2025, the welding tool rotation effect was experimentally investigated as parameter to show the effect of pin rotation on welding of two AA6082 sheets during FSSW process. They utilized different tool rotation speed with fixed dwell time during welding process. They discovered that the highest hardness and strength of welding joint between two sheets at 500rpm at 5s, also they found that the increasing temperature during welding process was happened at 30s for different tool rotation speed [13]. In same year 2025, the effect of welding plunge depths were numerical investigated for AA7075-T6 sheets to show the effect plunge depth on thermal and strain during welding process, and also they validated the numerical welding temperature-welding time curve with experimental curve. They found that the numerical curve close to experimental curve for temperature-time for welding two AA7075-T6 sheets, and also found that the thermal and strain increases duo to increase plunge depth [14].

The aim of this research is to build a numerical model of five tool ratios of FSSW process for AA2024-T3 sheets using FEM software. In addition, effective parameters will be employed for comparison such as welding force, rotation tool speed, friction coefficient, and pin depth to display the effective tool ratio on nugget region temperature duo to comparing with other tool ratios.

2. Metal used in FSSW:

Aluminum alloy AA2024-T3 sheets with sheet thickness 3mm were used to illustrate the FSSW process between Aluminum sheets and welding tool, in addition, it will be discovered sheets behavior during welding process. The dimensions of welding tool was shown in figure (1).

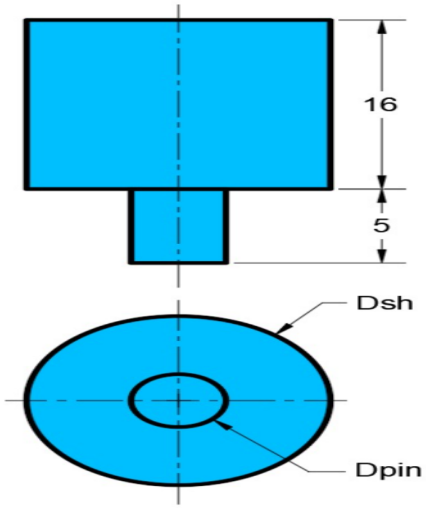

Fig. 1, Welding tool dimensions.

The chemical composition of AA2024-T3 sheet was collected as shown in table (1)[15,16]. The simulation FEM software depends on mechanical and thermal properties for AA2024-T3 sheet as shown in table (2) [15][16].

Table 1. chemical composition of AA2024-T3[15][16]

Elements	Mg	Fe	Mn	Si	Cr	Zn	Ti	Cu	Al
Element percentage	1.5	0.197	0.645	0.103	0.027	0.181	0.042	4.84	Rem.

Table 2. Mechanical and thermal properties of AA2024-T3 [15] [16]T3 [15] [16]

Metal	Density (Kg/m^3)	Modulus of elasticity (GPa)	Poisson's ratio	Thermal conductivity (W/m.K)	Specific heat capacity [J/Kg.K]
AA2024-T3	2780	72.4	0.33	164	881

3-Numerical Model:

A numerical model of FSSW was considered two mathematical solution such as thermal generation and mechanical deformation. The best numerical solution depends on finite element method to represent two solutions of metal behavior during welding process. The thermal generation represents friction generation between welding tool and aluminum alloy sheets, while, the mechanical deformation represents the force generation between tool and aluminum sheets. The numerical model have been further clarified as following below.

generation come from welding shoulder and welding pin. Equation (1) show the general heat generation for heat

transfer of FSSW processuation (2) shows the heat generation duo to relationship between welding friction, pin rotation speed, and welding tool force during welding process: s=2πΨRΩS ……2

3-1Thermal generation model:

The thermal generation duo to friction between rotation welding pin and metal sheets was represented by thermal generation model, so this model create the main thermal process of friction using FEM. Schmidt et al. heat generation formula represents general thermal analytical formula for FSSW process, and this analytical formula signifies two effective heat generations: thermal generation of shoulder for sliding friction and sticking friction [17]. In addition, this thermal model proposed ninety percent of heat

Equation (3) demonstrates the thermal generation duo to plastic strain of welding sheet during welding process:

Qp=ςτέ ……3

Table 3. displays the parameters of equations (1),(2), and (3).

Symbol	Meaning	Symbol	Meaning
Z	AA2024-T3 density	Ψ	frictional coefficient
D	Specific heat	R	Pin radius
G	Heat generated	Ω	Pin rotation speed
t	Time	S	Welding force
J	heat conductivity	τ	Shear stress
T	Temperature	έ	Strain rate
ς	heat dissipated ratio		

3-2 Tool ratio:

Tool ratio define as a shoulder-pin size ratio as shown in figure (2), so the FSSW process depends on this tool ratio which it makes friction welding area between tool and workpiece, and this ratio plays an important parameter on FSSW process that make heat generation of shoulder and pin and AA2024-T3 sheets. Table (4) displays the effective tool ratio:

Table 4. Tool ratio

No.	Title	Symbol	Tool ratio	Equivalent
1	Tool ratio-1	TR-1	28/15	1.867
2	Tool ratio-2	TR-2	28/10	2.8
3	Tool ratio-3	TR-3	28/8	3.5
3	Tool ratio-4	TR-4	28/5	5.6
4	Tool ratio-5	TR-5	28/3	9.34

All welding ratio in table (4) were used in FSSW model.

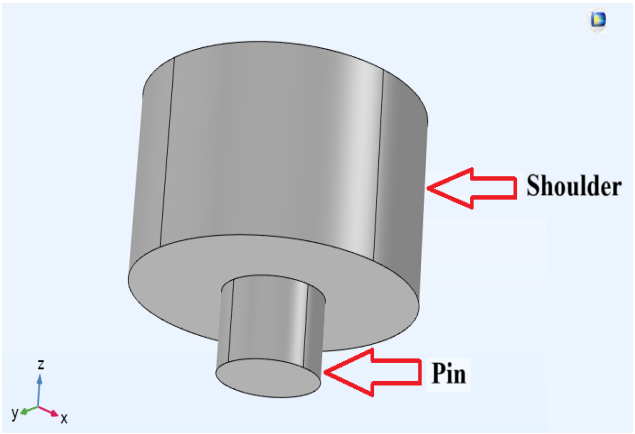

Fig.2. Friction stir spot welding tool.

4-Results and discussions:

First of all, starting to valid numerical results with experimental results by make comparison between experimental and numerical solution to show the reality of numerical results, so figure (3) show the validation of numerical results by creating comparison between two curves for nugget zone temperature with welding time, the experimental results were requested from [18], in addition, ref. [18] used speed rotation 525rpm, dwell time 2sec, tool ratio 3.6, feed rate 0.47mm/min, sheet thickness 2mm, axial force 2980N [18]. Also, all welding parameters were used in numerical solution to show the perfect validation, finally, it shown that numerical curve close to experimental curve.

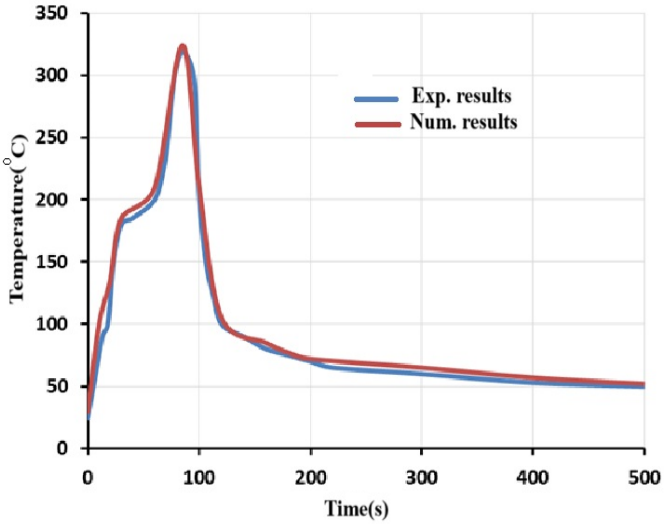

Fig. 3. Comparison between numerical solution curve with experimental curve [18].

The simulation results of FSSW were obtained from COMSOL software. So Figure (4) shows the temperatures distributions of AA2024-T3 sheets. It can be seen that the highest temperature focus on welding tool. Parameters were used in simulation (friction coefficient 0.4, rotation speed 850rpm, axial force 20kN.

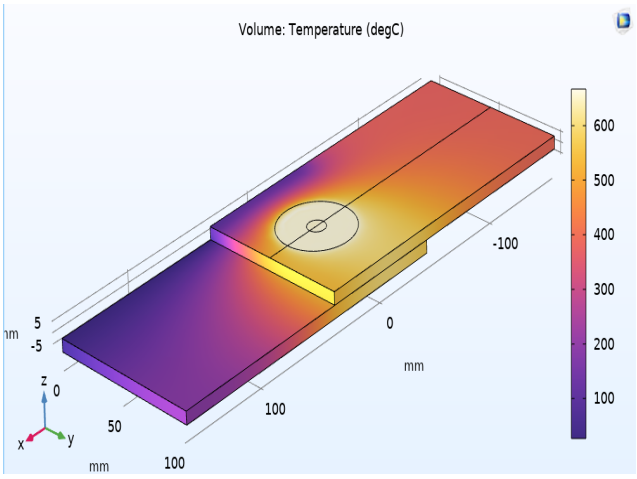

Fig. 4 Temperature distribution of FSSW.

The tool ratios play an important role on FSSW especially between sheets welding process, so that makes different welding situation depending on friction issue between welding tool and sheets, Fig.(5) shows the effect of tool ratios on temperatures distributions of nugget welding zone. The horizontal axis is tool ratio while the vertical axis is nugget welding temperature (℃). It can be seen that the nugget welding temperature decreases duo to increase tool ratio this is because the increase tool ratio makes lowest friction area between welding tool and AA2024-T3 sheets during welding process. Finally, the maximum nugget zone temperature is 630ºC at tool ratio 1.867, while the lowest nugget zone temperature is 185ºC at tool ratio 9.34.

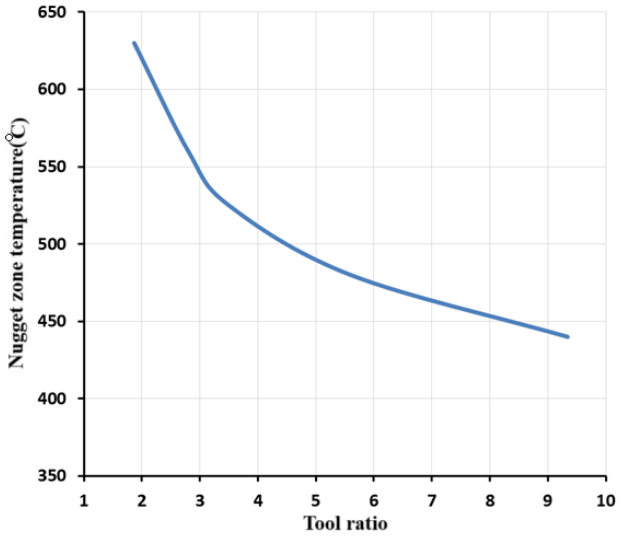

Fig. 5 Tool ratio effect on nugget welding temperature during FSSW.

The axial welding force is a significant parameter on FSSW process, so this parameter effect on welding temperature making changing in welding situation. Figure (6) illustrates the influence of axial welding force on the welding temperatures distribution for difference tool ratios. The horizontal axis is axial welding force while the vertical axis is nugget zone temperature (℃). It can be noted that the welding temperature increases duo to increase axial welding force for all welding ratios this is because the increase axial force will making high force or pressure in welding area that create high friction between welding pin and workpieces . In addition, the tool ratio-1 curve had highest curve than all ratio curves this is because the tool ratio-1 had lowest equivalent ratio with highest pin diameter. Finally, the welding temperature increases duo to increase the friction between welding tool and workpieces. Lastly, the maximum nugget zone temperature is 630ºC at tool ratio-1 and 20kN, while the lowest nugget zone temperature is 185ºC at tool ratio-5 and 5kN
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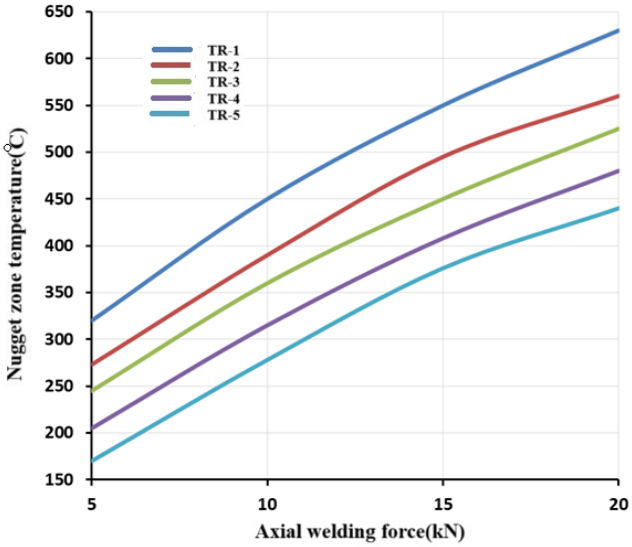

Fig.6 Effect of axial welding force on nugget welding temperature for difference ratios at constant parameters: n=850rpm, μ=0.4, Dt=2s.

Another important parameter is rotation tool speed which makes different condition for thermal situation of FSSW process. Figure (7) shows the impact of rotation tool speed on the nugget region temperatures for difference tool ratios. The horizontal axis is rotation speed while the vertical axis is nugget region temperature (℃). It can be seen that the nugget region temperature increases duo to increase rotation speed for all welding tool ratios this is because the increase rotation speed will create high friction between welding pin and sheets. In addition, the tool ratio-1 curve had highest curve than all ratio curves this is because the tool ratio-1 had lowest equivalent ratio.

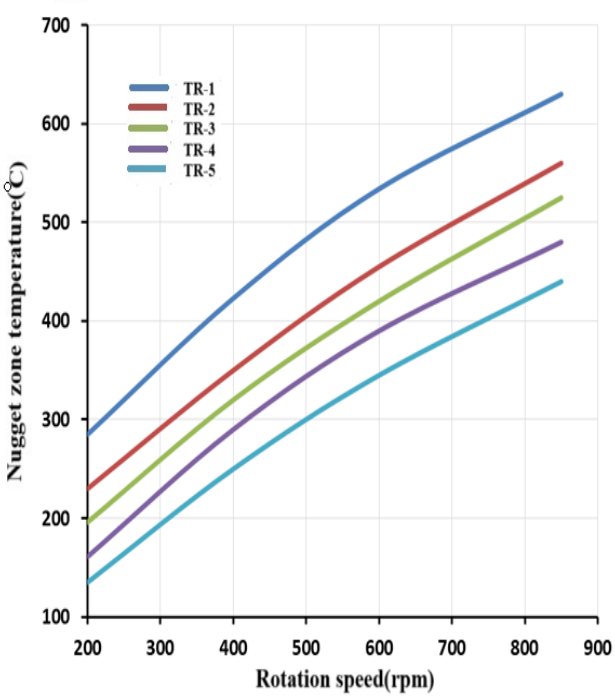

Fig. 7. Effect of rotation tool speed on the on nugget welding temperature for difference ratios. at constant parameters: F=20kN, μ=0.4, Dt=2s.

Pin welding depth is an important parameter that welding process depending on this parameter, Figure (8) displays the effect of pin penetration on the nugget region temperatures for difference tool ratios. The horizontal axis is pin depth while the vertical axis is nugget region temperature (℃). It can be realised that the nugget region temperature increases duo to increase pin penetration for all welding tool ratios this is because the increase pin depth will make high friction between welding pin and sheets for all sides and create high temperature between friction parts. In addition, the tool ratio-1 curve had highest curve than all ratio curves this is because the tool ratio-1 had lowest equivalent ratio.

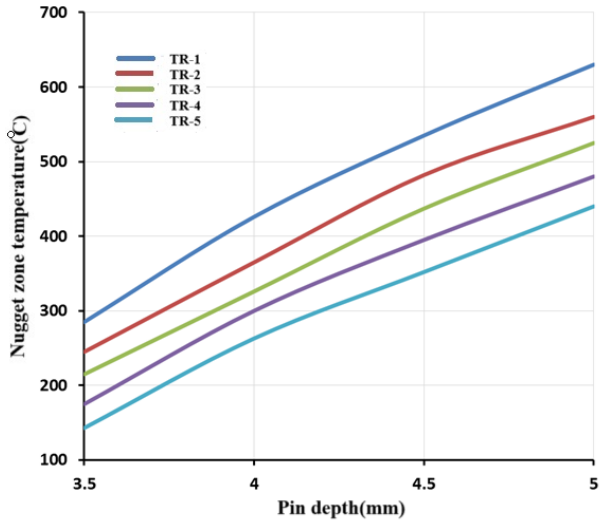

Fig. 8. Effect of pin depth on the on nugget welding temperature for difference ratios at constant parameters: n=850rpm, μ=0.4, Dt=2s.

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5- Conclusions:

The effect of five tool ratios on nugget welding temperature for FSSW were numerically investigated using FEM software, and also four parameters were used in FSSW simulation to show the impact of these parameters with different tool ratio on nugget welding temperature. The main conclusions are below:

1-A numerical results were validated and had good agreement with experimental results [18].

2- The tool ratios had affected on nugget welding temperature, so that the nugget welding temperature decreases duo to increase tool ratio for welding two AA2024-T3 sheets.

3- A nugget welding temperature was affected by axial welding force, so that the nugget zone temperature increases duo to increase axial welding force for welding two AA2024-T3 sheets.

4-The rotation tool speed is a significant parameter in FSSW, so that the nugget zone temperature increases duo to increase rotation tool speed for welding two AA2024-T3 sheets.

5- A tool depth is an important parameters on FSSW, so that the nugget zone temperature increases duo to increase tool depth for welding two AA2024-T3 sheets.

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