Friction Stir Welding of 6061 Aluminum Alloy with Diferent Pin Tools and Rotation Speed

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Abstract:

Joining aluminum alloy by fusion welding usually creates many problems because the heat melting point leads to aluminum oxides which prevent the joining process. This is because metals oxide acts as on heat insulter in addition to the problems of microstructure such as solidification cracks, void, porosity, slag inclusion and poor mechanical properties. Thus, friction stir welding is considered the best method to weld aluminum alloys because of joined low temperature, no of solidification and no filler metal or flux used. These results in good properties in joint and recrystallizing in the stir zone. In this work the mechanical properties (tensile strength, microhardness and impact strength) of 6061 aluminum alloys with different pin tool (cylindrical threaded pin SCT, tapered cylindrical threaded pin TCT and triangular threaded pin TT) and different rotation speeds (450, 560 and 900)RPM at constant welding speed (35mm/min) has been studied .The results show that the microstructure is very fine and homogenous with all tools, super tensile strength using TCT tool at rotation speed (560RPM) equals to (370MPa),in additions hardness has increased but still lower than of base metals .The impact strength has also increased with all the tools compared to that of base metals.

Keywords: 6061aluminum alloys, Friction stir welding (FSW), Rotation speed and Pin tools.

الخلاصة:

ربط سبائك الالمنيوم بواسطة اللحام الأنصهاري يولد مشاكل كثيرة بسبب نقطة الانصهار الحرارية العالية التي تقود الى اوكسيد الالمنيوم الذي يمنع عمليات الربط لان الاوكسيد الناتج يمثل عازل بالإضافة الى مشاكل البنيه المجهرية، تشققات الانجماد ، المسامية، الفراغات، الخبث والشوائب، وخواص ميكانيكيه ضعيفة ولهذا فلحام الخلط الاحتكاكي يعتبر طريقه مثلى للحام سبائك الألمنيوم٦٠٦١ بسبب الربط بدرجات حرارية منخفضه وعدم وجود ماده مالئه او حشو وبالتالي الحصول على خواص جيده للربط ومن ثم اعادة التبلور في منطقة الربط.

في البحث الحالي تم دراسة الخواص الميكانيكية مثل مقاومة الشد ومقاومة الصدمة بالإضافة الى البنيه المجهرية لسبيكة الالمنيوم٦٠٦١ مع مختلف الادوات المسننة والتي شملت اداة أسطوانية، اداة أسطوانية مسننه ، اداة مثلثة الشكل وعند مختلف سرع الدوران٩٠٠،٥٦٠،٤٥٠دورة–دقيقه بسرعة لحام ثابته مقدارها٣٥ملميتر–دقيقه. .النتائج اوضحت من خلال البنيه المجهرية حصول تجانس ونعومه في الحبيبات في منطقة الخلط في جميع الادوات المستخدمة مع مقاومة شد قصوى للأداة الأسطوانية المسننة عند سرعة الدوران٥٦٠دوره–دقبقه تساوي ٣٧٠ميكباسكال وزياده في الصلادة ولكن افل من المعدن الاساس .اما مقاومة الصدمة فلوحظ زياده كبيره في جميع الادوات مقارنة بالمعدن الاساس.

الكلمات المفتاحية: سبيكة الالمنيوم٦٠٦١، لحام الخلط الاحتكاكي، سرعة الدوران، الاداة المسننة

1. Introduction :

The friction stir welding (FSW) technique is considered environmentally friendly, needs less energy and can be welded dissimilar metals without problem and with different thicknesses and profile, FSW was initially used to weld Al-alloys and then developed to be to weld Mg, Cu, Ti, matrix composites, lead, some steels, stainless steels, and different material combinations. [P.Prakash et al.2013] Friction stir welding started by the welding Institute (TWI) of Cambridge in December1991 [Kazem ,2014; Vinayak and Bhatwadekar, 2015]. The principle of FSW is rotating shouldered tool plunges into the joining point of plates and the heat is originally developed from the friction between the welding tool and the welded material as shown in figure (1),which causes the welded material to be soften at a temperature less than its melting point [Shrikant and Shete, 2014].

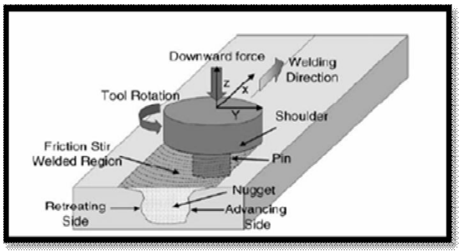


Figure 1: Schematic drawing of FSW process [Sattari *et. al*., 2012].

In FSW, the heat required for joining is generated by the friction between the work pieces and tools, it depends on the tool geometry and welding parameters [Mohanty *et. al*., 2010]. The rotating tool moves along the weld line and develops frictional heating of the material, causing it to plasticize and produces a high integrity weld. However, there are numerous defects need to be addressed in welding process, such as holes, tunnels, cavity and 'surface lack of fill' defects at the joint area of the aluminum alloy. These defects can lead to the degradation of the tensile properties and ductility strength of the welded material [Mohanty,2010]. The tool is divided in to two main functions: heating piece of work and movement of material to produce the joint. The degree of heating deals with the tool and pieces that work and plastic deformation of pieces itself. The more heating softens the area around the pin and movement of rotational tool lead to movement from the front to the back the pin [Surendrababu *et. al*., 2013]. Temperature increases and high strain rate deformation lead to the formation of micro structurally different zones [Carloneand and Palazzo, 2013] Parent metal (BM): where material is not deformed, also may be subjected to cycles heating but no change in mechanical properties or in structure change, Heat affected zone (HAZ): in this zone mechanical properties and microstructure change because of cycles heating, Thermo mechanical affected zone (TMAZ): in this zone material not only is subjected to heating cycles but also deformed plastically, structure is tight deformed and Stir zone (SZ): where recrystallization is completely occurred. In this zone because deformation at high temperature soft grain volume can be shown which strength and hardness increase of zone welded metal. Different friction stir welding area are shown in figure (2)[Sattari *et. al*., 2012; Trimble *et. al*., 2015].

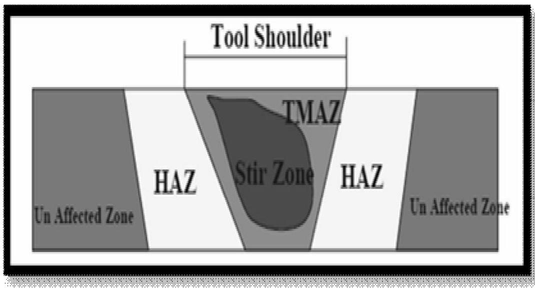


Figure 2. Schematic of different friction stir welding area [Sattari *et. al*., 2012].

2. Experimental Method:

Aluminum alloy 6061 was used in this study. The mechanical properties and composition of this alloy shown in table (1)and(2). Two aluminum plates, having the dimensions 8 mm in thickness, 150 mm length and 100 mm in width, were placed on a flat metal plate. Before starting welding process, two pieces of aluminum plates was cleaned using ethanol to remove the oxides on the surface of the plates.

Table 1: Mechanical properties of the 6061.

Yield strength(MPa)	225
Ultimate tensile strength (MPa)	284
Elongation (%)	22.3
Hardness(HV)	235

Table 2: Chemical composition (weight %)

Elements (%)	Measurement (%)
Cu	0.4
Mg	1.2
Fe	0.7
Si	0.8
Zn	0.25
Al	Bal.

In this work there are three different tool pin geometries profiles (1) Cylindrical threaded pin SCT, (2) Taper cylindrical threaded pin TCT and (3) triangular threaded pin TT. The X13 tool process parameters used are given in table 3. The shoulder of the tool was the same diameter of 20 mm. The length of the pin was 7.6 mm as the required welding depth of the plates. The rotation speed (450, 560 and 900) RPM and at welding speed 35 mm/min, with a 2 tilt angle. The process parameters of FSW and tool dimensions are shown in table 4.

Table 3: Chemical composition (weight%) of FSW tool .

C	Cr	Mn	Si	Fe
2-2.3	11.5-13	0.3-0.35	0.34-0.4	Rem

Table-4: FSW process parameters and tool dimensions.

Process Parameters	Values
Rotation speed (RPM)	450,560,900
Welding speed(mm/min)	35
Pin length (mm)	7.6
Shoulder diameter(mm)	20
Pin diameter(mm)	8
Tool pin geometry	SCT, TCT, TT
Tool materials	X13 tool steel

After welding, the specimens were cut in the direction perpendicular to the line of the work of welding features for preparing tests (tensile, impact, micro hardness). Tensile test was measured according to the ASTM B 557M, and charpy impact test according to ASTM E23 and Vickers hardness.

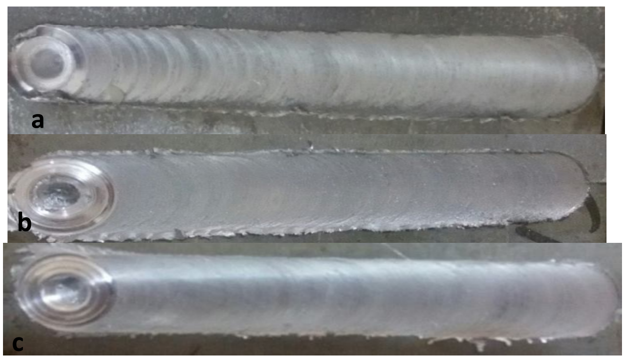
3. Results and Discussion.

3.1 Effect of pin profile and rotation speed on the appearance of the weld :

The photos of weld surface appearance is made with different friction stir tools (SCT, TCT and TT) and different rotation speed (450, 560 and 900) RPM at constant welding speed (35mm/min). It can be seen from the pictures that good surface appearance will be obtained using all these tools at high rotation speed because the increase the heat input leads to flow and stir materials. The appearance of the weld was clean and no clear defects can be found. Figure (3): shows the photos of weld surface appearance made with the cylindrical threaded pin (SCT) profile at different rotational speed (450, 560 and 900) RPM at constant welding speed (35mm/min). It can be seen from the pictures that surface appearance of the weld is tunnel defect at 450RPM because of low temperature and low material flow .

Figure(3): Appearance of welding using cylindrical threaded pin(SCT) at different rotation speed (a) at 450 RPM,(b) at 560 RPM and (c) at 900RPM.

Figure (4): shows the photos of weld surface appearance made with the taper cylindrical threaded pin (TCT) at different rotational speed (450, 560 and 900) RPM. It can be seen from the pictures that good surface appearance has been obtained at high rotational speed.



Figure(4) : Appearance of welding using tapered cylindrical threaded pin (TCT) at different rotation speed (a)450RPM,(b)560RPM and (c) 900RPM.

Figure (5): shows the photos of weld surface appearance made with the triangular threaded tool pin profile (TT) at different rotational speed (450,560 and 900) RPM. It can be seen from the picture that in all the three cases weld appearance is good at high rotation speed 560RPM and 900 RPM but less in 450RPM.

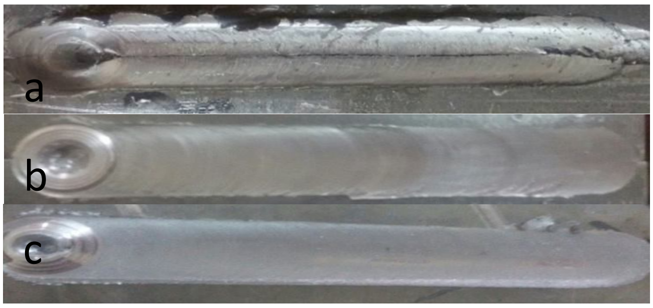


Figure (5) : Appearance of welding using triangular threaded pin (TT) at different rotation speed (a) at 450RPM (b)560 RPM and (c) 900RPM .

Note, the good welding at high rotation speed because all tools concavity play vital role in restricting material inside shoulder and the screw thread will be beneficial to the heat generation, under the same weld parameter, the pin with screw thread will generate more heat than the pin without screw thread. More heat input can improve the flow of the plastic material. On the other hand, the screw thread on the pin exerts an extra downward force that will be beneficial to accelerate the flow of the plastic material[Hua *et. al*., 2005].

3.2 Microstructure

The specimens were tested at variable rotation speed (450,560 and 900) RPM and different tools "pins" The microstructure of nugget zone where microstructure consisted of equaled grains with the volume of less than large grains of BM. wedding by SCT tools shows that the microstructure is smaller as shown in figure 6 (a,b,c and d) .More heat input can improve the flow of the plastic material. In (TCT) tools has experienced high temperatures and extensive plastic deformation, and is characterized by dynamically recrystallized grains. Pin forms influence the nugget structure greatly. The structure of Fine grain concomitantly in the nugget area is welded by (SCT) tools and the size of the grain is smaller. The distribution of precipitate is in flounced by pin. The volume of the precipitate is finer and the density distribution is higher. The nugget microstructures welded by (TT) tools and the volume of the grain is bigger compared to (TCT) and (SCT).

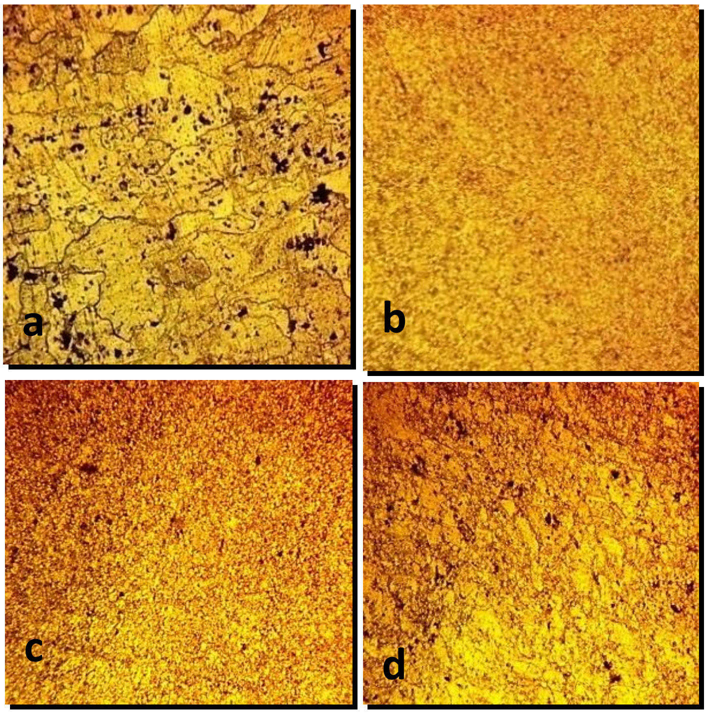


Figure (6): The microstructure of (a) base metal , (b) 560RPM at TCT tools, (c)560RPM at SCT tools and (d) 560RPM at TT tools.

Grain size increases with the increase of rotation speed in all the tools. One of the important stages of the FSW is the difference of plastic zone on the advanced and the retreated side, whose structures are different in nature [Carloneand, 2013].The microstructures in weld nugget decreases size of grain when the rotation speed increases in all the tools. That microstructure change smoothly from nugget to TMAZ. Welded by SCT tools ,the material flow possible easily, the grade of speed is smaller and the structure is even. The volume grains changes from one area to another from nugget to TMAZ, this will not influence the property very much. welded by (TT) tools. That is in the process of welding, the area of nugget zone is represented temperature and plastic deformation very high , however after recrystallized, soft grain came into existence, so speed at nugget is very high alsoTMAZ,but the temperature and deformation in TMAZ are not in the same as they are in nugget zone area [Hua *et. al.,* 2005; Ilangovan *et. al*., 2015].

3.3 Microhardness

The table (5) shows microhardness profile transverse cross NZ, TMEZ, HAZ and BM on the transverse cross section of joints welded at different rotation speeds. Increasing rotation speed influences on hardness of NZ and TMEZ but slightly effective for HAZ Micro- hardness in NZ, and TMAZ increases with the increasing rotation speed but stays lower of BM at a 450 RPM rotation speed and welding speed 35 mm/min in TCT tools are higher value than it is in SCT and TT tools. This tendency suggests that significant increase of hardness with increasing rotation speed is not a function of grain size but a function of size and distribution of second phase particles and precipitates. Grain size is less effective on hardness in NZ compared to other factors. At rotation speed of 560 RPM hardness value starts again to increase a value than that of base metal was obtained at NZ region.

Table(5): The microhardness (HV) measurements at SCT.

SCT				
Rotation speed (RPM)	BM	HAZ	TMEZ	NZ
450	234	185	123	143
560	198	190	120	166
900	200.5	170	111	135

Hardness in these regions towards TMAZ is still lower than that of BM. Unlike coarsening, dissolution leads to a subsequent recovery of hardness in all the tools in table (6) hardness starts to decrease and a minimum value is achieved, at about 900 RPM in all the tool, the same effect where some precipitates might have coarsened and lost their coherency due to thermal history. This significant increase of hardness could be attributed mainly to the second phase particles size ,distributions and dislocation density, where increasing the rotation speed mean increasing strain [Rajesh and Subramanian, 2015].

Table (6): The microhardness (HV) measurements at TCT.

TCT				
Rotation speed (RPM)	BM	HAZ	TMEZ	NZ
450	222	170	152	173
560	206	163	140	193
900	197	170	142	159

All the tool have the same effect with rotation speed but the (TCT) gives higher speed from other tools because (TCT) produce more homogenous and high temperature during flow metals in the friction stir welding leads to high plastic deformation and also some defect produced results which have low heat input and poor material mixing results. In general the effect of tool geometry less than effect of the rotation speed and welding speed on hardness. Table (7) .

Table (7): The microhardness (HV) measurements at TT.

TT				
Rotation speed (RPM)	BM	HAZ	TMEZ	NZ
450	204	165	120	129
560	248	160	125	149
900	227	155	120	155

3.4 Tensile strength

The stress-strain curves shown in figure (7), (8) and (9) the engineering stress-strain relationship of welded products for cylindrical threaded pin (SCT), tapered cylindrical threaded pin(TCT) and triangular threaded pin (TT) at(450,560,900) RPM rotation speed. It is Show that the ultimate tensile strength (UTS) equals (280Mpa) at tapered threaded pin (TCT) as compared to (SCT) and (TT) tools and it equals (250 MPa) and (210Mpa) at rotation speed (450 RPM) and welding speed (35 mm/min).

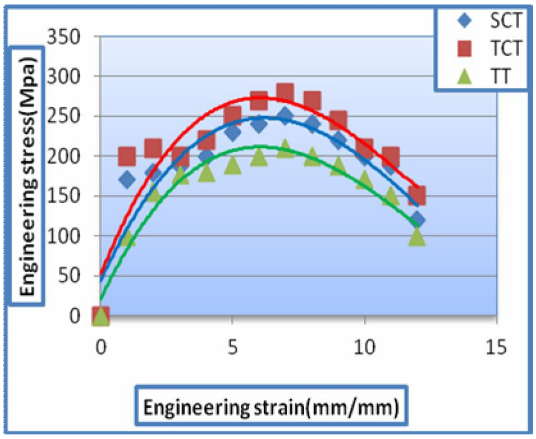


Figure 7 : The relationship between engineering stress-strain curve at rotation speed (450RPM) and welding speed (35 mm/min) .

It is Shown that maximum tensile strength and elongation in (TCT) equals (370Mpa) and (310Mpa) at (SCT) and (230Mpa) at (TT) at rotation speed equals (560RPM). The tensile strength, yield strength and elongation. All the tools increased at increase rotation speed and they decrease welding speed and give super tensile strength at (560RPM). The anthers factors effects the properties may be due to the fact that the shoulder surface provides most of the thermal flux through friction and the probe geometry affects the local material flux during the FSW process.

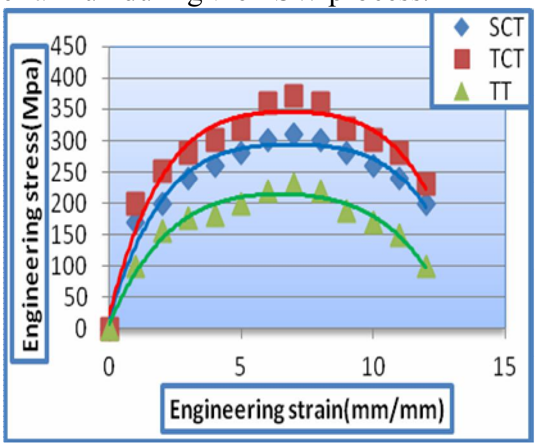


Figure 8: The relationship between engineering stress-strain at rotation speed 560 RPM and welding speed 35mm/min.

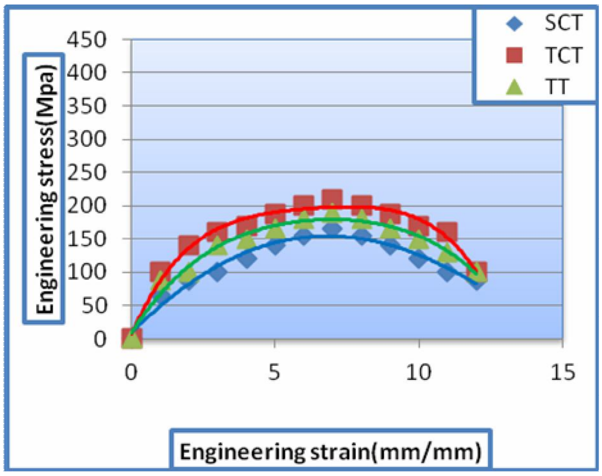


Figure 9 : The relationship between engineering stress-strain at rotation speed (900RPM) and welding speed 35 mm/min .

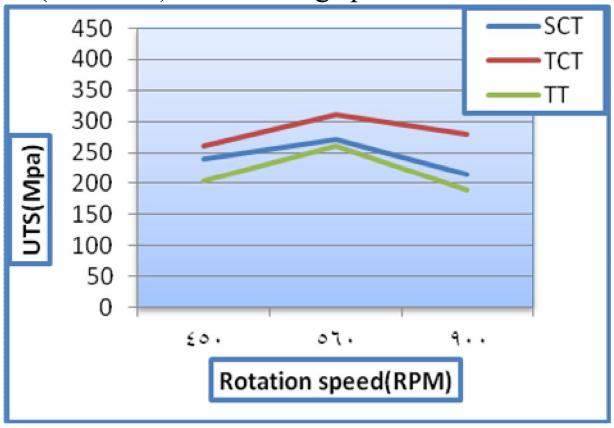


Figure 10 : Effect of tool pin profile and rotation speed and ultimate tensile strength at welding speed 35mm/min .

The properties of fracture and tensile of materials that friction stir welded depend on hardness and welding defects in joints area of which in turn function of the welding parameters. If there are no defects in joints, the properties of tensile are only affected by the micro hardness distributions .Increasing tensile strength of joints welded at rotation speeds from (450 to 900) RPM could be attributed to a clear increase of hardness in the HAZ. The free defects in the joints is that the fracture get on retreating side more than advancing side. Higher temperatures due in break in retreating side and therefore fracture happens in this side. This result sufficiently indicates that the tensile strength on the advancing side is higher than that in the other side. The advancing side shows slightly hardness very high than the other side [Rajesh and Subramanian, 2015]. For the purpose examine defects variables and welding operation on tensile properties of the joints, tool (TCT) produced better welds was used. Figure (10) shows the effect of tool rotational speed and figure (11) show the effect of welding speed on tensile strength of the joints a maximum tensile strength of (370MPa) was obtained at rotation speed (560 RPM) by using tool (TCT). Increase the tensile strength by increase rotation speed and decrease the welding speed but continuous increase of the rotation speed lead to decrease the UTS and elongation as shown in figure (12) because the increase in the temperature leads to dislocation and growth of the precipitates [Jalal and Kazim, 2013].

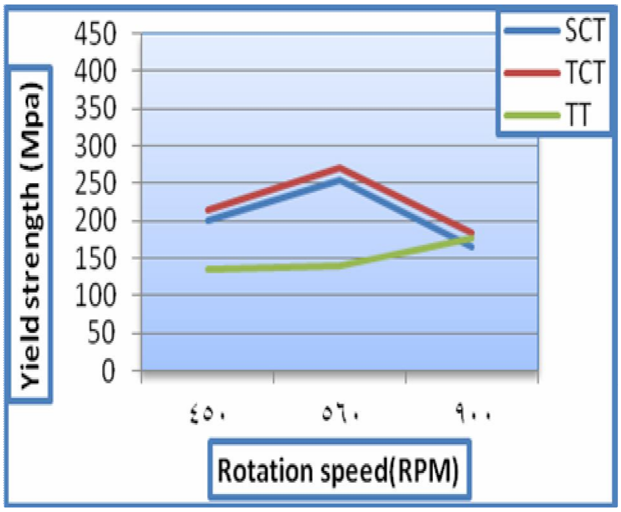


Figure 11: Effect of tool pin profile and rotation speed on the yield strength at constant welding speed 35 mm/min.

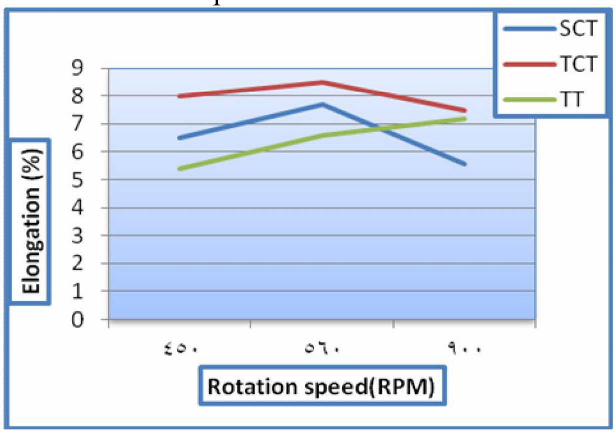


Figure 12: Effect of tool pin profile and rotation speed on the elongation at constant welding speed (35 mm/min).

3.5 Impact test

The two pieces of 6061 Welding by FSW with different tools (Cylindrical threaded pin SCT, Tapered cylindrical threaded pin TCT, Triangular threaded pin TT) with a change in rotational speed,. results the impact of welding higher than the impact energy of base metal because the grains in the center welding area (nugget zone) are fine, and equiaxed and smaller than base metals, this is the reason for the occurrence of recrystallization process and temperature generated during friction between tools (pin) and metals [Radisavljevic, 2013] .

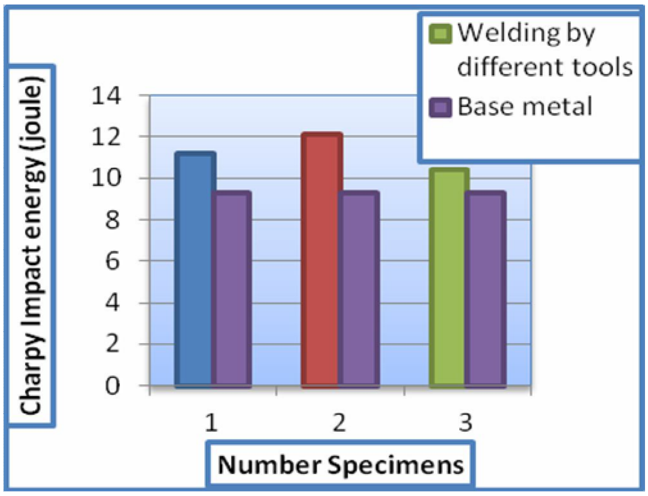


Figure 13: Effect between impact energy and shape of tools at rotation speed (450RPM) and welding speed (35mm/min) .

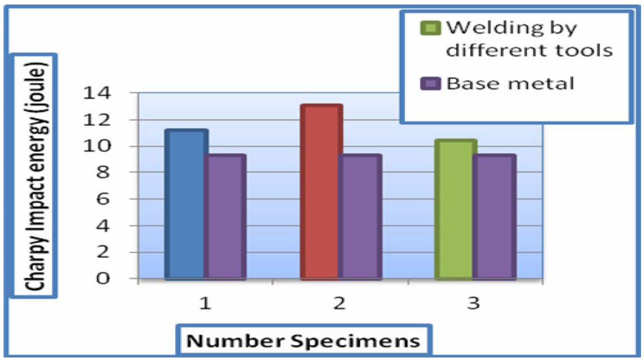


Figure14: Effect between impact energy and shape of tools at rotation speed (560RPM) and welding speed (35mm/min) .

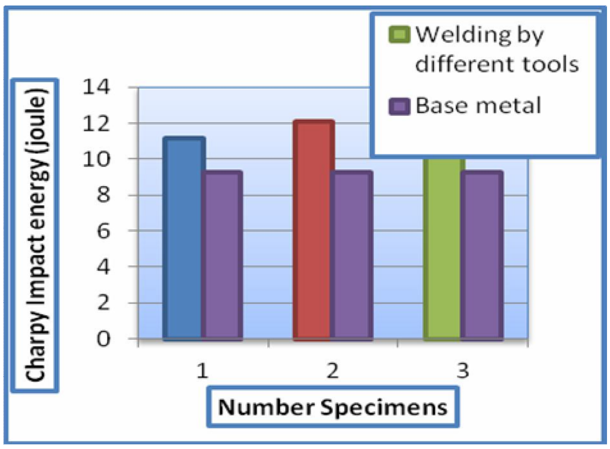


Figure15: Effect between impact energy and shape of tools at rotation speed (900RPM) and welding speed (35mm/min) .

That maximum impact energy in (TCT) tools at (450 RPM) rotation speed and (35 mm/min) welding speed equals to (12.1J) as compared to (SCT) equals to (11.2) and (TT)equals to (10.4J) indicates to improve the impact that heat input in this time help to increase strength and therefore improve the impact toughness and also effect on tool shape. The effect tool geometry is smaller than the that of the impact energy. The approximate results in the most speed and increase the rotation speed into (900 RPM) the impact energy of the welding decreases in general at similar welding speed and there is no improved in the impact energy by the increase of the welding speed because effect of rotation speed is oppressor where the biggest part in the temperature friction results in rotation speed in the tool welding as seen in figure (13,14 and15)[Jalal and Hazim, 2013].

4. Conclusions

This investigation is an attempt that has been made to study the effect tool form profile (Cylindrical threaded pin SCT, tapered threaded pin TCT and triangular threaded pin TT) on formation of friction stir welding zone welded 6061. From this investigation, the following important conclusions are derived:

1. There are relationships between the form of the tool and variables operation for FSW of 6061 aluminum alloy. Tool form is very specialist for deciding the weld quality.
2. Hardness is of high value in NZ and TMEZ at TCT tools compared with SCT and TT and Hardness increased with the increased rotation speed and decreases welding speed in all the tools because the SZ and TMEZ is fine and equal to the grain size.
3. Maximum tensile strength by using tapered cylindrical threaded pin (TCT) is equal to (370 MPa) at rotation speed (560RPM).
4. Tensile, yield strength and elongation increase with the increased rotation speed but still lower from base metal.
5. Most of the results show that the impact strength increases at all the too welding as compared to the base metals and equals (9.3J). The impact strength in (TCT) tools equals (12.1J) at (450RPM).

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