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Research Paper

Comparison and Analysis of the Effect of Tools with Pins of Different Cross-Sections in the Friction-Stir Welding Method

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Abstract
Friction Stir Welding (FSW) is a solid-state welding method that serves as a suitable alternative to fusion welding for materials such as aluminum, copper, magnesium, and even steel alloys. In this research, samples of Al 5754 H22 and Al 6063 T4 were welded using FSW. The tools employed in this study featured cylindrical and conical pins, both with and without threads. The tool material was H13 hot-worked steel, hardened to 52 ± 2 Rockwell C. The FSW process was performed using a vertical milling machine. The results indicate that the shape of the pin significantly affects the weld structure and its mechanical properties. The pin's geometry greatly influences the flow of plastic materials, as different pin designs employ various material transfer techniques. Consequently, modifying the geometry of the tool pin can enhance the process for joining dissimilar materials. The highest welding quality was achieved with the tool featuring a threaded conical pin, which resulted in a visually appealing weld with no obvious defects. The microstructure of the weld was fine, and the distribution of sediment was uniform with small sizes. The hardness tests revealed that changes in tool geometry did not significantly affect the hardness levels. However, the threaded conical tool provided the highest tensile strength for the weld, with the tensile strength of the weld joint reaching up to 75% of that of the base metal.

Keywords
Friction Stir Welding, Aluminum Alloy, Tool Geometry, Microstructure, Mechanical Properties

1. Introduction
The use of fusion welding to join aluminum alloys causes many problems, such as the loss of the elements in the alloy due to evaporation and their replacement by filler materials, distortion in the welding zone, and the formation of holes in the weld zone. These factors cause some alloys cannot be joined together using the fusion welding method, so comprehensive research on welding methods for such materials is needed [1].

In general, there are many types of welding processes, but the two most common welding processes are fusion welding and solid-state welding. Friction stir welding (FSW) is a subset of solid-state welding. In solid-state welding processes, the connection between parts is made without melting. In general, in FSW, the heat required to create a weld is provided through mechanical energy caused by friction. Then, when the parts reach the state of plasticity due to the heat generated through friction, they are connected by applying two-way pressure. FSW is one of the newest welding methods that is used in various industries, including the aerospace and shipbuilding industries. This welding method has become very popular in the industry today due to its many features and advantages. In the last two decades, a lot of experimental and theoretical research has been done to better realize the welding mechanism, characteristics, and microstructure of FSW [2]. Among the efforts that have been made in this field, the following can be mentioned:

Alizadeh et al. [3] studied the effect of rotational speed and tool feed on the microstructure of aluminum alloy 5456 in the FSW. The results obtained from this article showed that the FSW causes the crushing of intermetallic particles, the homogenization of the microstructure, and the crushing of the grains in the weld zone. Increasing the rotational speed and decreasing the feed speed causes a rise in heat, vertical flow increases, the grain size grows, and leads to a decrease in hardness. Also in research, the effect of FSW welding parameters on the weldability of aluminum alloys with similar and dissimilar metals has been studied. The weldability and strength of joints by the FSW method mainly depend on its parameters. This review highlights previous research work on FSW parameters and their effects on the weldability and quality of aluminum alloys joined to similar and dissimilar metals by this method [4].

Some researchers studied the friction stir welding process on T6-6061 aluminum alloy both experimentally and numerically. Among the most important results obtained, it can be mentioned that the most heat is generated in the shoulder, and generally, the temperature decreases in the direction of thickness. Material flow mainly occurs due to contact and will have a significant speed [5]. For a long time, the generation of heat caused by friction has been used as a method of joining, processing, and creating microstructural changes in materials, and one of its most important advantages is the creation of a very small zone under the influence of heat in the part, and in addition, due to the low energy consumption, it leads to the reduction of environmental pollution. Despite these advantages, the defects that arise in the frictional stirring process may be dangerous, but with the correct control of the process parameters, these defects can be reduced or prevented [6].

In research, Marzban et al. [7] investigated the effect of FSW on grain size, hardness, and wear resistance of Ck 45 steel due to changing the number of passes and tool design. They concluded that increasing the number of passes produces more heat per unit length and also affects grain size and hardness. In addition to this, the parametric analysis of the FSW with threaded and non-threaded pins for welding two sheets of two aluminum alloys Al 7075 and Al 6061 to each other based on theoretical relationships and numerical simulation shows that the heat produced is proportional to the rotational speed of the tool and has an inverse effect with the feed speed of the tool [8].

Based on the results of the simulation, it is determined that with the increase in the ratio of rotational to linear speed of the tool, the material flow in front of the tool increases, and the dimensions of the stirring zone become larger. The maximum temperature and material flow occurred on the advancing side (AS), and the lack of heat caused incomplete material flow around the pin and various defects in the root of the weld [9]. In a study conducted by Soleimani et al. [10], the effect of the tool pin axis position on aluminum alloy in the FSW was investigated. It was found that the tool with the off-axis pin causes a sharp drop in the vertical force required for welding, as well as providing the highest strength for the welded zone. On the other hand, the comparison of the average coefficient of friction in the wear of copper before and after the FSW shows a decrease in wear resistance. Also, the FSW joint is highly dependent on the process parameters, i.e., feed rate, rotational speed, and tool pin characteristics [11-12].

The friction stir weldability of Ti6Al4V T-joints has been investigated. The results indicate that samples always show the strain concentration in the HAZ on the retreating side due to cross-section thinning, leading to the early fracture in the HAZ. Instead, some joints with the highest rotational and welding speed are characterized by a different fracture path starting from the kissing bond defect because of a more pronounced kissing bond defect (i.e., longer and inclined towards the traction direction). Hence, both factors, pronounced kissing bonds and section-thinning on one side, are responsible for low elongation at break. They can be avoided by adopting the correct plunge depth and combination of pin and support radius fillet [13]. One of the main drawbacks of titanium is the welding of this alloy; however, FSW is a good method in joining solid materials, especially titanium and its alloys. In this research, the effective parameter of spindle rotational rate has been varied through the process, and its effect on the mechanical properties was examined. To achieve optimal properties at higher rotation rates, the transverse speed should increase proportionally to the rotation rate [14].

Tang and Shen [15] investigated the effects of preheating treatment on the temperature distribution and material flow of aluminum alloy and steel friction stir welds. The simulation shows that the preheating treatment increased the peak temperature of the steel and also reduced the large temperature difference between the steel and the aluminum alloy in the high-temperature stage. The preheating treatment could reduce the influence of the difference between the two materials on the forming of the welded joint and improve the properties of the welded joint. Also in a study, the effects of pin root diameter, pin tip diameter, and pin taper angle on heat and mass transfer in FSW were quantitatively investigated. It reveals that the torque and transverse force imposed on the pin are increased with the increase of the pin diameter, while the total tool torque varies a little for the tool pin diameter considered in this study. When the pin diameters increase, the viscosity of the materials near the pin decreases, while the temperature as well as the flow velocity are increased [16].

Research hypotheses show that by changing the geometry of the tool in the FSW, the role of the tool geometry in mixing and material transfer can be investigated. It is possible to achieve the appropriate geometry of the tool pin, as well as to achieve better properties and a more appropriate microstructure. In addition, by using the appropriate geometry of the tool pin in the FSW, the welding cycle can be modified to reduce the forces applied to the tool and to prevent excessive wear of the tool.

Due to the importance of the FSW in connecting parts, especially parts with unique applications in the aerospace, marine, and nuclear industries, analysis and investigation of the proper geometry of the tool pin have been carried out on the samples. The purpose of this research is to compare and analyze the impact of tools with pins of different shapes by the FSW method, so the heat is produced by the pin and also by friction between the shoulder of the tool and the part. Therefore, the cross-sectional area of the pin and its dimensions will affect the amount of input heat and the maximum temperature of the process, but the critical factor in addition to determining the ratio of the shoulder to the pin itself is the cross-sectional area and the geometry of the pin. Another function of the tool shoulder is to trap the volume of material being heated. The tool has other tasks, and that is mixing and transferring the material, which is done by the pin of the tool. The degree of homogeneity of the microstructure and welding properties depends on the tool design, which needs to be investigated in this research.

2. Materials and work methods

First, the samples used in friction stir welding operations, such as H22 Al 5754 and Al 6063 T4, are introduced. The pin geometry of the friction stir welding tool will have an effective role in the welding speed, the amount of energy consumed, the type of machine used for the welding operation, and these will have a significant impact on the welded properties. In this regard, the tools used in this research have cylindrical and trapezoidal (incomplete conical) pins designed and made in a simple and threaded way, because tool geometry is one of the most important factors that cause changes in friction stir welding conditions in terms of input parameters used as well as mechanical and metallurgical properties. In this research, the tool material was selected from H13 hot-worked steel, which was hardened to 52 ± 2 Rockwell C. In this regard, the properties of the welding zone can be changed based on the type of metal to be welded, as well as the heat produced during welding as a result of friction. The machine used for welding is a vertical-axis milling machine.

2.1 Choosing the type of samples

The alloys of H22 Al 5754 and Al 6063 T4 that were used as samples for FSW were chemically analyzed by the quantometry method (Table 1). Also, the mechanical properties of the raw samples were tested, the results of which can be seen in Table 2.

Table 1. Chemical analysis of the samples by quantometry method

Specimen	Al	Si	Fe	Mn	Cu	Mg	Cr	Zn	Ti	Ni
H22 Al 5754	96.1	0.068	0.226	0.279	0.052	0.36	0.123	0017	0.018	<0.005
Al 6063 T4	98.8	0.389	0.177	0.014	0.024	0.479	0.005	<0.005	0.005	0.007

Table 2. Mechanical properties of aluminum alloy samples for friction stir welding

Specimen	Tensile Strength, Yield (MPa)	Tensile Strength Ultimate (MPa)	hardness (Vickers)	Elongation at Break (percentage)
Al 5754 H22	185	245	75	15
Al 6063 T4	89,6	172	46	22

The samples with dimensions of 130×50×5 mm were prepared with a wire-cut electro discharge machine to prevent the distortion of the parts and accurately join the two parts to perform the FSW operation, which is shown in Figure 1.

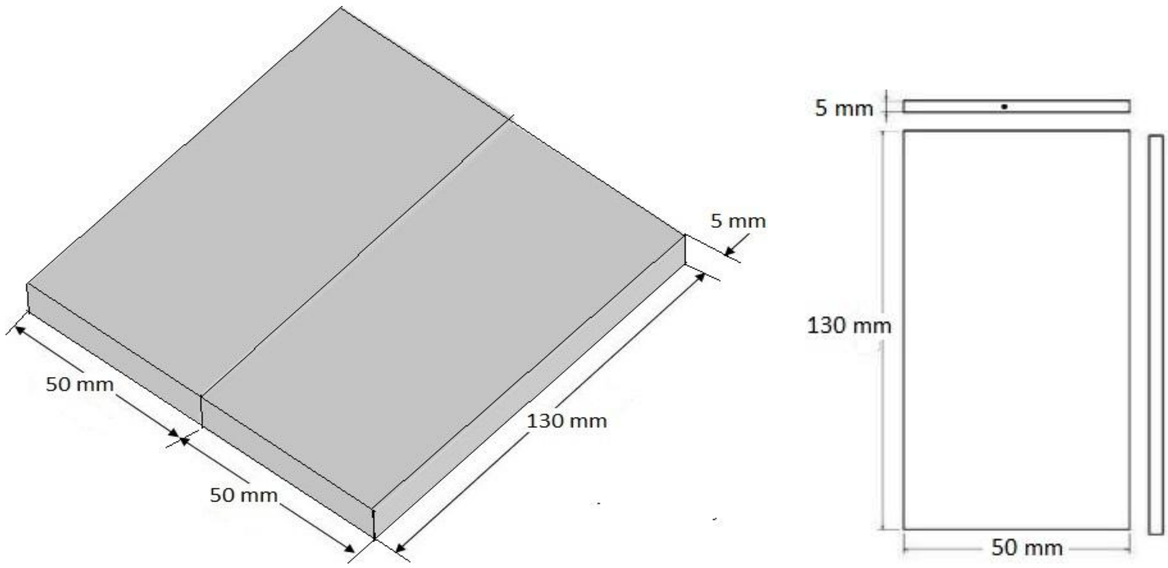

Figure 1. The dimensions of the samples under friction stir welding

2.2 Tool design and construction

The wear of the pin could change the geometric shape of the pin, so it changes the quality of the weld. The material used for the tool should not react with the material of the samples or the environment to change the surface properties of the tool. In this regard, one of the most important factors that cause changes in FSW conditions in terms of device parameters as well as the mechanical and metallurgical properties of welding is tool geometry. In other words, it can be said that the geometry of the welding tool will have an effective role in the amount of energy consumed, the speed of the welding operation, and, finally, it will have a great effect on the welding properties. The material of the tool, in turn, can be changed based on the material of the specimens to be welded and the heat generated during welding due to friction. In this research, the tool used for FSW is made of hot-worked H13 steel, hardened to 52 ± 2 Rockwell C, and was chemically analyzed by the quantum method. These results are consistent with the properties of tool steel DIN 1.3343, which is a part of high-speed steels. Also, the specifications of tools with different pins used in this research are presented in Table 3.

Table 3. Specifications of the tools with different pins used in this research

1	Cylindrical with a diameter of 4 mm and a height of 5 mm
2	A threaded cylinder with a diameter of 4 mm and a height of 5 mm, and a pitch of 0.5 mm
3	Cone-shaped with a large diameter of 5 and, a small diameter of 2.5 mm, and a height of 5 mm
4	A threaded cone with a large diameter of 5 mm and a small diameter of 2.5 with a pitch of 0.5 mm and a height of 5 mm.

In this research, four tools are used, which have cylindrical and Cone-shaped pins. The pin of these tools is simple and threaded; the geometry of the tools used is shown in Figure 2. The external diameter of the shoulder of these tools is 15 mm, the cylindrical pins have a height of 5 mm and a diameter of 4 mm, while the pins that are designed and made cone-shaped have a height of 5 mm, a large diameter of 4 mm, and a small diameter of 2.5 mm. Therefore, the design of tools was considered the main goal of this project. For this purpose, the material of the tools was first selected from H13 hot-work steel, and the design of the tools was done according to the studies. Then, the initial cutting and turning were done on them. A four-axis CNC milling machine is used to shape the tools.

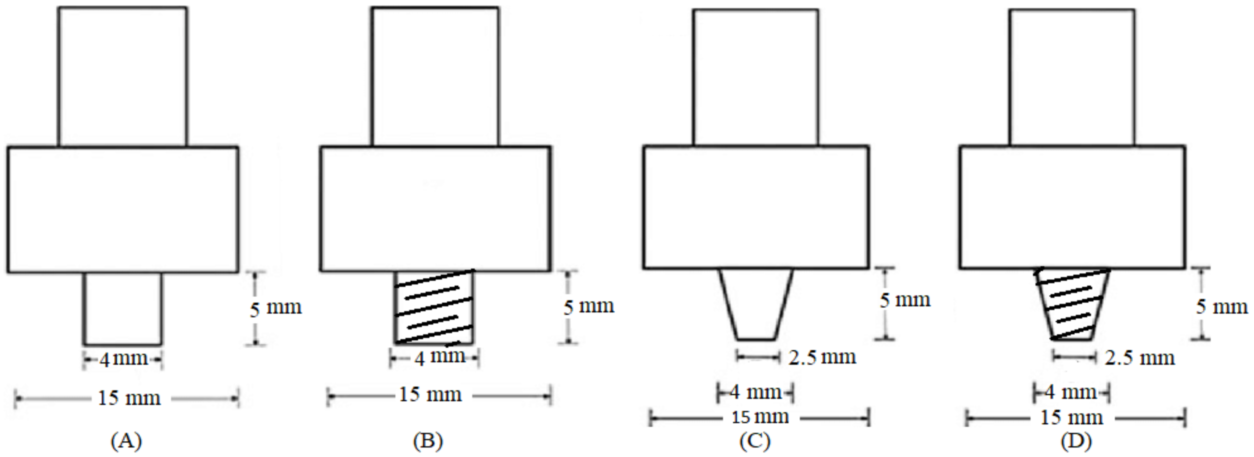

Figure 2. Tools used with threaded and non-threaded cylindrical and conical pins

2.3 The device used for FSW

In this research, a vertical milling machine made by Tabriz Machinery was used to perform FSW on the samples (Figure 3). The main axis of the machine is supported in a vertical position, and with the help of this machine, you can perform tasks such as face grinding, grooving, and curved and angled surfaces. The head of this machine can rotate around the axis, so it is possible to mill inclined surfaces easily. The amount of deviation is adjustable.

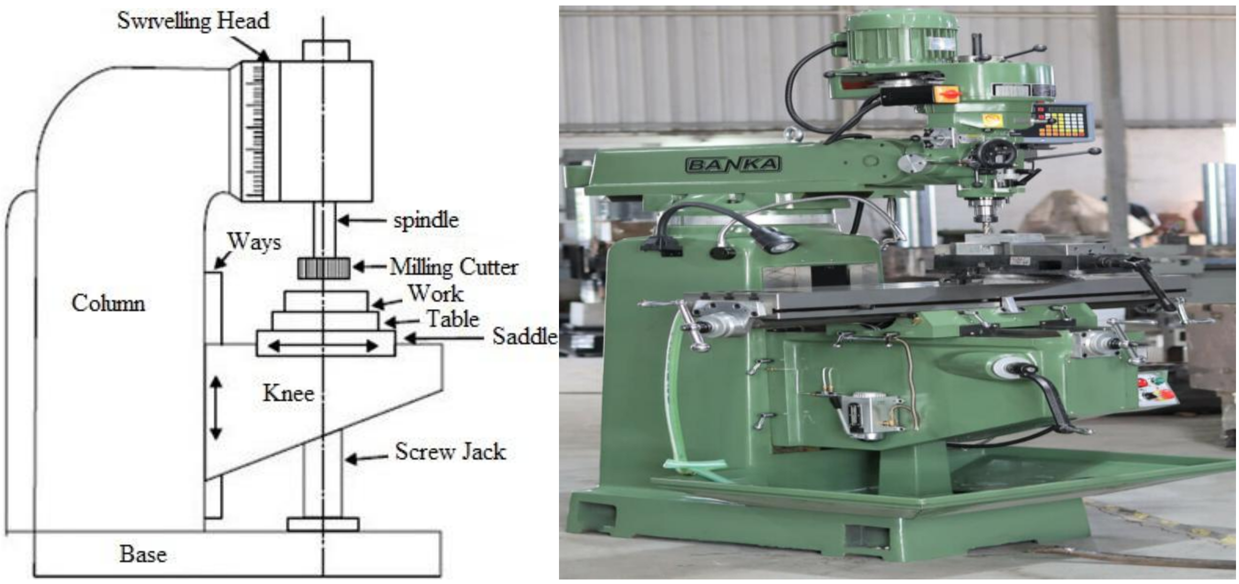

Figure 3. Vertical axis milling machine for performing FSW.

To keep the samples precise, it was necessary to design and make a jig and fixture. For this purpose, the fixture used in this research is made of a steel sheet with dimensions of 300´300´20 mm. Then machining operations were performed on it to create the necessary grooves and holes by a CNC milling machine. After that, the inner surface of the fixture was completely cleaned to minimize the possibility of defects on the surface. The next step is to assemble the relevant cover straps on the fixture (Figure 4).

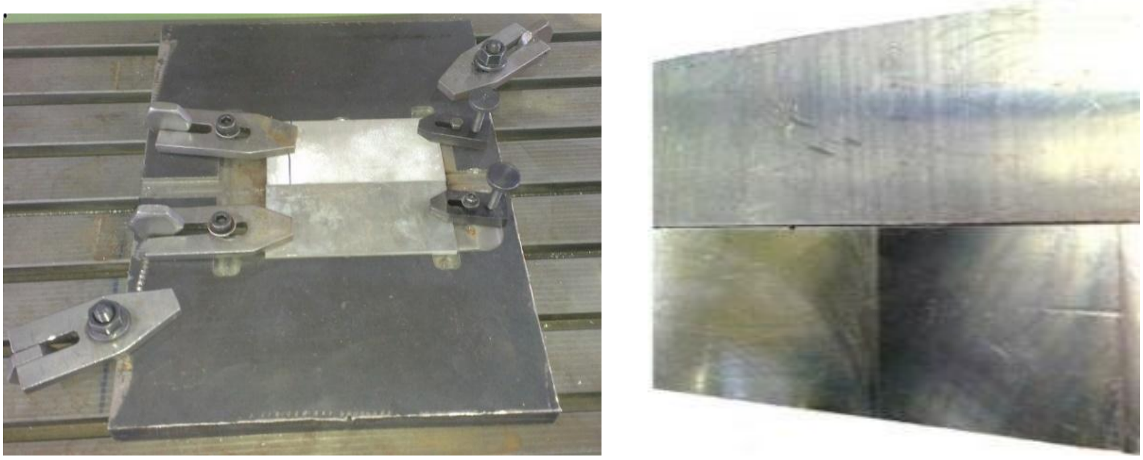

Figure 4. A view of the jig and fixture in FSW operations

2.4 Implementation of welding operations

Initially, the first series of prepared samples is hold on the specially made fixture and is completely restrained using straps. Then, the cylindrical tool with a simple pin (Figure 5-a) is installed in the vertical-axis milling machine. The machine table is vertically approached to the forehead of the tool pin by manual movement, and at this stage, the tool is slowly brought close to the surface of the boundary of the samples so that the tip of the pin contacts the working surface and the boundary between the two tested samples. As soon as contact is made between the face of the pin and the upper surface of the part, and according to the length of the tool, the pin slowly starts to load in the downward direction without applying forward movement until the pin of the tool penetrates to a depth of 5 mm in the part. The implementation of the FSW process can be seen in Figure 6.

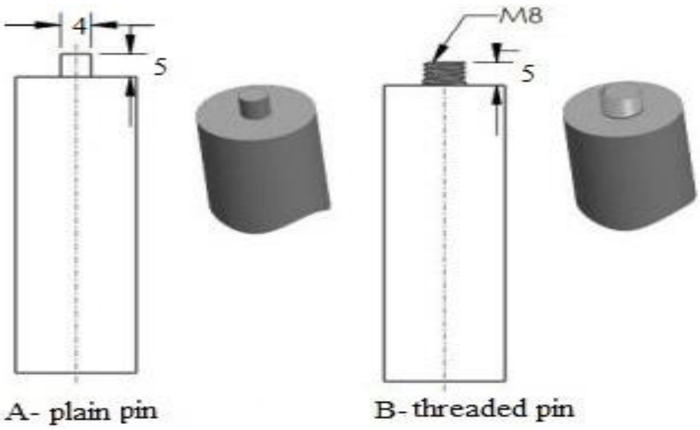

Figure 5. Cylindrical tools with plain and threaded pins

To generate the necessary heat to perform welding correctly, it is necessary to operate the tool in this position for about 5 minutes without applying forward movement on the workpiece. After the complete heating of the samples that are to be joined, the relevant feed lever is engaged, and from this moment on, the feed and rotational movement of the tool starts to travel the path and perform welding operations until the path that needs to be welded is completed. Then the advance movement at the end of the track is stopped, and the tool is slowly raised vertically. In this situation, the operation is stopped. After stopping the operation, both the part and the tool are allowed to cool down, and the welded sample is separated from the fixture, and it is taken to the machine tool workshop to be cut into specified sizes with a wire EDM.

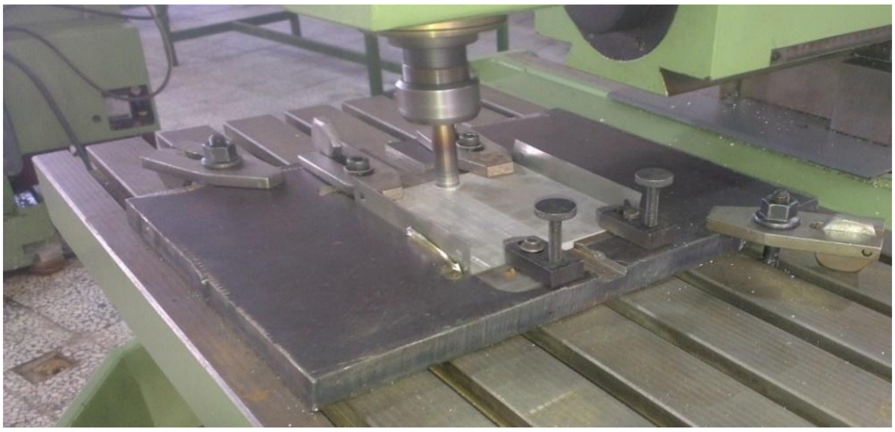

Figure 6. Implementation of the friction stir welding process

To operate with a cylindrical tool with a threaded pin (Figure 5b), the operation is completely similar to the tool with a simple pin with the same conditions and selected parameters. Also, the FSW process was carried out with tools with a conical pin with a threaded and unthreaded profile (Figure 7) with the same conditions.

The welded samples formed with tools with (A) unthreaded cylindrical pins, (B) threaded cylindrical pins, (C) unthreaded conical pins, and (D) threaded conical pins are shown in Figure 8.

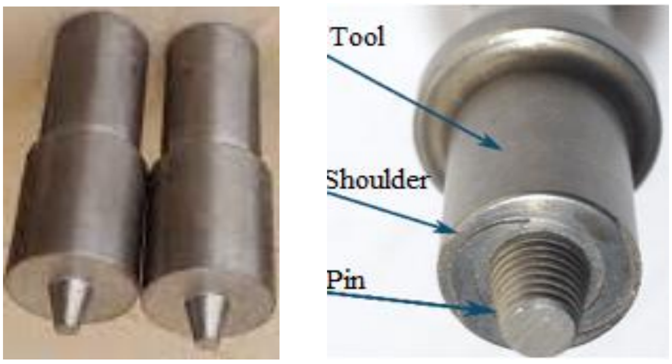

Figure 7. Tools with unthreaded and threaded conical pins

2.5 Tests to examine properties and microstructure

The samples of aluminum H22 Al 5754 and Al 6063 T4 were prepared to perform tests to study the properties and microstructure of the weld. These samples were cut and prepared using a wire-cut machine to minimize heat and residual stresses in the samples. It should be noted that the dimensions of these samples were selected according to the ASTM D638 standard. At this stage, visual inspection, microhardness, tensile strength test, and microstructure examination have been done.

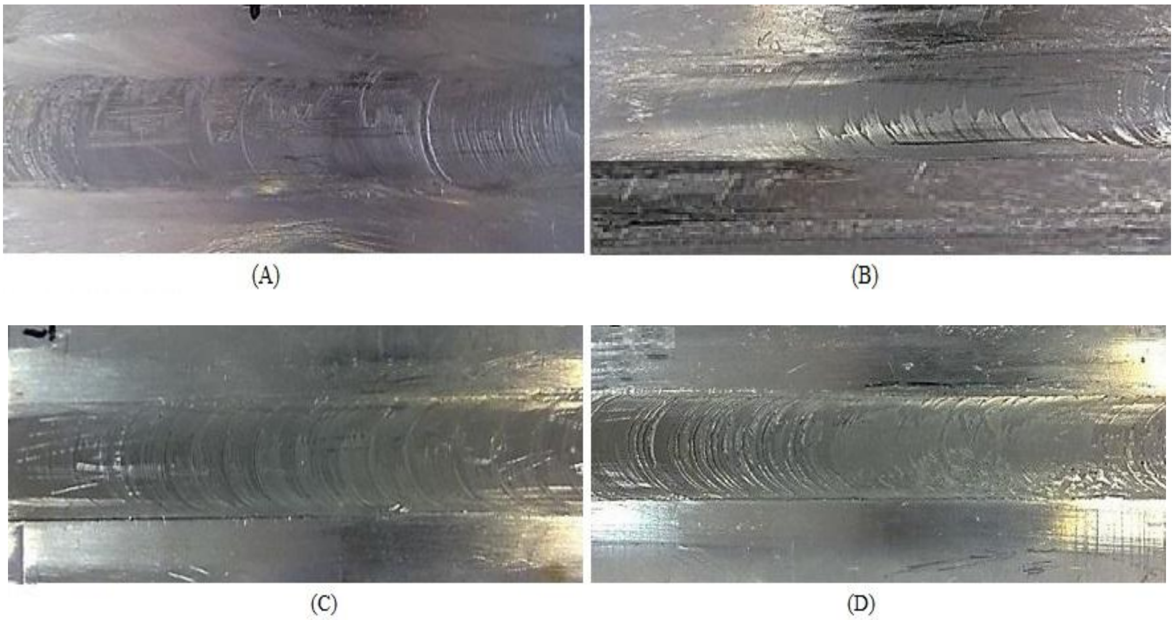

Figure 8. Weld samples made with tools with (a) an unthreaded cylindrical pin, (b) a threaded cylindrical pin, (c) an unthreaded conical pin, and (d) a threaded conical pin

In the first step, all the samples were subjected to visual inspection to check the effect of the geometry of the tool on the appearance of the weld. To measure the hardness of the samples, the Vickers hardness test was used to check the hardness of the weld section. The amount of load of the micro-hardness test machine was set equal to 10 grams, and the duration of applying the load was set to 15 seconds. The test intervals in the measurement area were chosen to be equal to 2 millimeters. Since the force applied in this test is low and this test is very dependent on the surface roughness of the workpiece, the samples were polished. For this purpose, the welded samples were sanded to 3000 grade by sandpaper, and then the surface of the samples was prepared and polished using polishing paste with a polishing machine.

To study the behavior of different zones in the welded samples, tensile strength tests have been done on them, and the results for all samples have been compared. The results of the tensile strength test can provide important information about the elastic modulus, ultimate stress, fracture stress, length elongation of the sample before failure, toughness, and impactability of the material. The sample used in the tensile test, as well as the broken sample in the tensile test, can be seen in Figure 9.
In the present research, the tensile test samples were cut from the stirring zone by a WEDM and prepared for the next stage tests. To achieve the best possible surface, a 0.2 mm chip was removed from the surface of the samples that the shoulder of the tool passed over, and then both sides of the sample were polished well by sandpaper with a grade of 1500. In this way, all the destructive effects due to the lack of smoothness of the surface in the test results are eliminated. In this case, a device with a capacity of 2 tons of force was used, and the test speed was chosen to be 2 mm/min. To study the microstructure of the welded samples, initially, their flat surface was cut and polished and then placed in the etching solution for 40 seconds to observe the microstructure and grain size of the alloy. The weight percentage of the etching solution used is presented in Table 4.

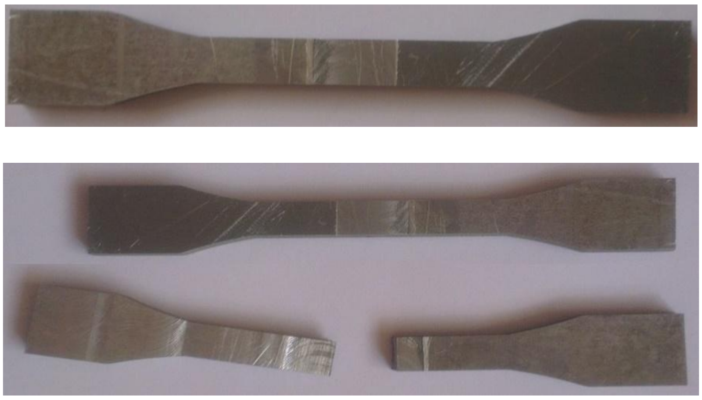

Figure 9. The sample used in the tensile test and the sample after the tensile test

Table 4. Weight percentage of the used etching solution

Materials	HNO3	HF	water	HCL
weight percentage	30	5	5	60

3. Results and Discussion

The cylindrical tool without a thread at the end of the operation has faced the difficulty of the edge coming off and failure. In this regard, it can be concluded that this tool tolerates more resistance than other tools in the FSW, but when this resistance exceeds the pin limit, the pin of the tool will break.
Visual inspection was done to check the structural coarseness of the parts to observe the effect of tool geometry changes on the samples. The results show that the change in tool pin geometry does not have much effect on the appearance of the welded zone. In this regard, it can be stated that the friction stir welding performed by all four tools did not have any negative effect on the surface of the created welds, and this issue can probably be due to the use of equal conditions for the parts during FSW.
The investigation of the microstructure in two zones of the weld line (welded bead) as well as the zone under thermomechanical influence with cylindrical tools with threaded and unthreaded pins, and also with conical tools with threaded and unthreaded pins, has been investigated. To study the microstructure of the samples and the welded zone, first, the required samples were prepared according to the standard dimensions using WEDM. In the following, these samples were ground with sandpapers of grade 3000. Then they were subjected to polishing operations. After ensuring the smoothness of the surface, etching was done on the samples. In this regard, each of the samples was kept in the etching for 50 seconds, and pictures of the samples were prepared after the etching operation.
The cross-section of the weld joint can be divided into four zones, which include the base metal, the welded line or bead, the thermo-mechanically affected zone, and the heat-affected zone (HAZ). Optical microscopy investigations were carried out to study the effect of pin geometry on the microstructure of the welded joint by FSW. The samples were selected from a good surface without visible welding defects. From the figures, familiar and dominant defects of FSW joints, such as holes and cracks, can be found.

3.1 Microstructure in the weld zone with different pins

A flawless joint can be obtained by using threaded cylindrical and conical pin tools in friction stir welding, and there are no holes, cracks, or other defects in the weld. However, Visible defects, such as porosity and other defects, can be found in a joint welded by a cylindrical and conical pin tool without threads, even in this case if the samples are taken from a good-looking weld. The creation of defects and porosity can be seen as a result of the lack of thread on the pin of the tools, which is not able to create the material flow in the plastic state sufficiently during the welding process. Figure 10 shows the microstructures of the weld line zone or the weld bead of the samples welded by four different tools. The figures show that the threaded pins will be useful for generating heat, and also, under the same welding conditions, threaded pins generate more heat than non-threaded pins. As a result, more heat input can improve the material flow in the plastic state.

In addition, the threads on the pin cause an additional downward force, which is useful for accelerating the flow of material in the plastic state, because it causes the flow of material to be transferred from the advancing side (AS) to the retreating side (RS) and then after circulating the pin should return to the advancing side. While the pin without a thread cannot flow the material sufficiently and transfer it. As a result, the insufficient material is returned to the advancing side, and the creation of a phenomenon of porosity will occur in the advancing side. The weld region experiences high temperatures and extensive plastic deformation and is characterized by dynamic recrystallization grains. The rate of deformation of plastic materials and the flow of materials are related to the microstructures and properties of the part. Pin geometry can strongly affect weld microstructures. The grain structure obtained in the welded line zone of the welded samples in FSW operation indicates that the particle size created with a tool with a threaded conical pin causes the particles to be smaller in size than the particles created by the other three pins. In addition, it should be noted that the deposit distribution is influenced by the geometry of the pin.

As can be seen in Figure 11, the deposit size is smaller with the threaded conical pin tool, and the deposit distribution density is higher. While the weld microstructures associated with the three images with the other three pins have a larger grain size, and the deposit and its density distribution are more uneven. Therefore, it can be concluded that the microstructures of the weld using a tool with a threaded conical pin contain smaller grains, and the structure and distribution of the sediment are more uniform, which leads to the improvement of the mechanical properties of the weld. One of the important features of FSW is the different relative flow speeds of plastic materials on the AS and on the RS, which leads to different structures. On the AS, the rate of material flow is higher than on the RS, and as a result, the microstructure changes rapidly, and the lack of necessary transfer of plastic materials in the zone between the weld and the thermal-mechanically affected zone often has a weak characteristic.

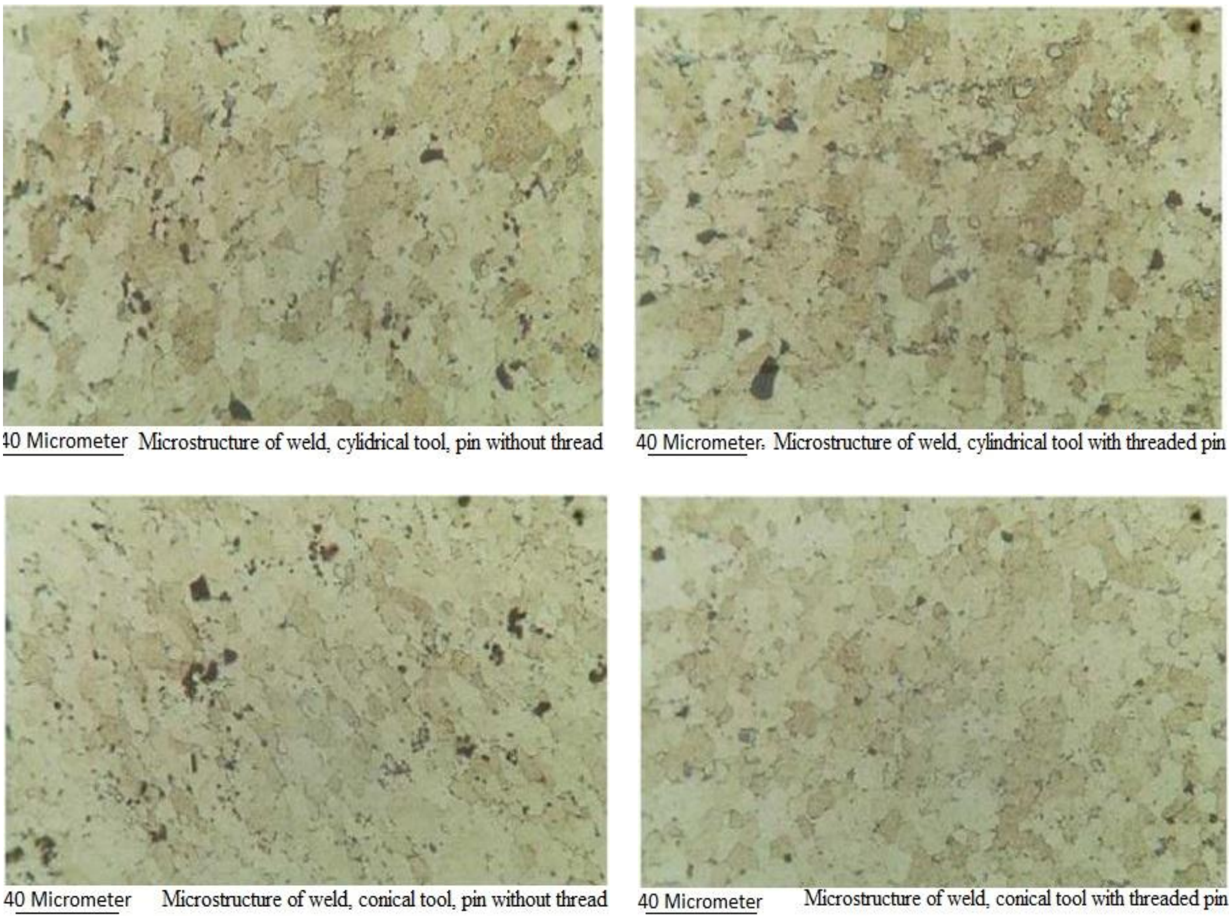

Figure 10. Welded zone microstructures with cylindrical and conical tools with threaded and unthreaded pins

As in Figure 10, the image of the threaded conical pin tool, the penetration level of the pin at the border between the two parts is very suitable, so incomplete penetration is not seen in the samples. The absence of defects and incomplete penetration shows that the height of the pin was appropriate, and it was able to completely paste the edges of the joints. Hence, the welding was done with full penetration. Figure 10 shows the images of the cross-section of the welds in the samples, by conical and cylindrical pin tools without threads. It can be concluded that even though the samples do not have deep cracks and porosity in the visual inspection, the depth of the tunnel holes has been observed. This issue can be due to the presence of impurities in the aluminum alloys or the unsuitability of the agents selected in the welding operation, which cannot be fully identified without further inspections and ultrasonic testing. On the other hand, due to the presence of cracks on the welded surface in all the samples, it can be seen that it is possible to further investigate the cavity changes in the samples by optimizing the welding factors and especially the vertical force.

2.3 Microstructure in the thermo-mechanically affected zone with different pins

Figure 11 shows the microstructures in the weld zone and the thermo-mechanical affected zone on the AS. The upper right side of the image shows the welded line.

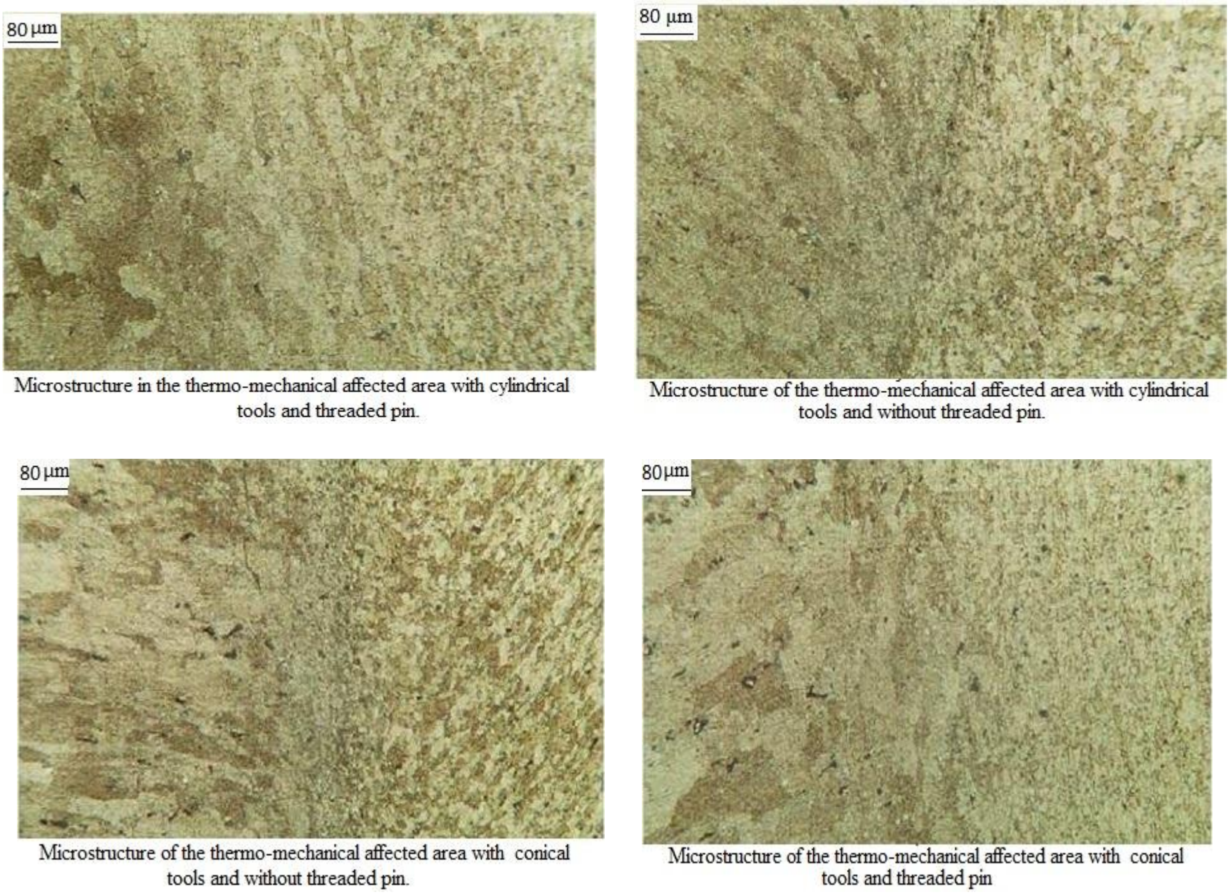

Figure 11. Microstructure of the thermo-mechanical affected zone with cylindrical and conical tools with threaded and unthreaded pins

The lower left side of the image shows the thermo-mechanical affected zone. The grain in the welded line is finer than in the thermo-mechanically affected region. Figure 12 shows that the microstructures change slowly from the welded line region to the thermo-mechanically affected region. The grain in the weld is finer than in the thermo-mechanically affected zone. Figure 11 shows that the microstructures change slowly from the weld region to the thermo-mechanically affected region. The flow of plastic materials in the samples that were welded in FSW with a tool of threaded conical pin can flow sufficiently and also have a lower velocity and a more uniform microstructure. In this case, the grain size changes step by step from the weld to the thermo-mechanically affected zone, which does not have much effect on the welding properties. However, a clear border between the weld zone and the thermal-mechanical affected zone can be seen in the image related to the tool with a cylindrical pin without a thread in Figure 11.

Investigations show that in this case, the grains experienced higher temperatures and more intense plastic deformation in the weld zone, and after dynamic recrystallization, the grains became finer. The tool with an unthreaded cylindrical pin has little effect on the material that exits around the surroundings of the pin, so the degree of velocity between the weld zone and the thermo-mechanically affected zone is very high, and as a result, the material which would flow in the thermo-mechanically affected zone is not enough and incomplete. Temperature changes and plastic deformation in the thermo-mechanical affected zone are not as much as in the weld zone. The tool pin thread will be useful to improve material flow and reduce the degree of velocity between the weld and the thermo-mechanically affected zone. The zone between the weld and the thermally-mechanically affected zone is always the zone with poor properties in the weld joint. From Figure 11, it can be seen that in FSW by threaded pin tools, good weld joints are obtained, the microstructure in the zone between the weld and the thermo-mechanically affected zone can be associated with a smooth transition, and in addition, the zone without specific boundaries.

3.3 Investigating the effect of pin geometry on mechanical properties

The hardness, tension, and bending of the welded samples are investigated by the friction stir welding method with tools with threaded and non-threaded cylindrical and conical pins. The stress-strain diagram of two non-homogeneous pieces of aluminum alloy H22 Al 5754 and Al 6063 T4 for joining in FSW is presented in Figure 12. After preparing the necessary samples for the tensile test, the samples were prepared by WEDM, and then all samples were subjected to tensile and hardness tests. In this research, the distances between the measurements were chosen to be 2 mm. First, for all the samples, the maximum hardness was measured at the center of the weld and at different distances from the center to observe the maximum hardness, then hardness was measured in line with the maximum hardness obtained in the stirring zone on both sides of the weld. The X-axis shows the distance from the weld center, and the Y-axis shows the hardness value in Vickers units. It was found that the change in the geometry of the tool cannot change much in the hardness of the samples. The diagram of weld hardness tests with tools with threaded and non-threaded cylindrical and conical pins is presented in Figure 13.

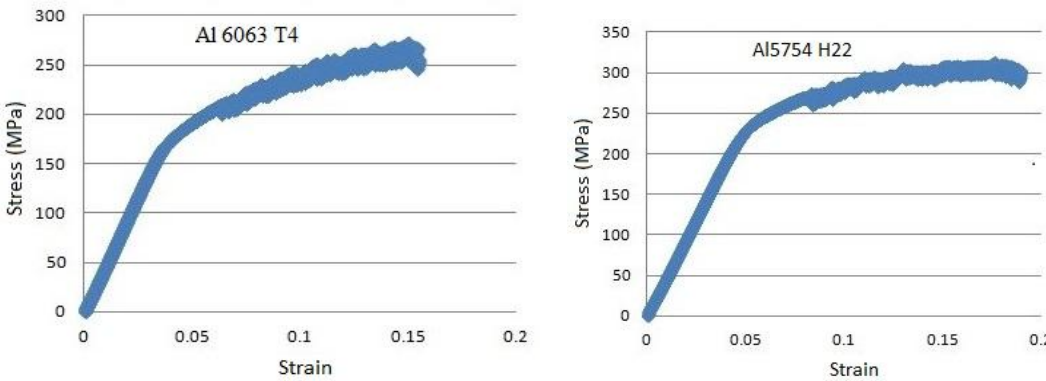

Figure 12. Stress-strain diagram of two dissimilar pieces of H22 Al 5754 and Al 6063 T4

By performing these tests, the maximum tensile strength (UTS) and the maximum elongation have been obtained. According to the graphs obtained, it was found that the tool with a threaded conical pin achieved higher strength than the other tools. Because the better movement of materials and the possibility of better flow of materials will occur by this tool, and this tool creates more heat and also heat preservation for a longer period, and therefore, when the heat is preserved to a certain extent, it leads to a more perfect connection. The hardness chart shows the fact that the geometry of the tool pin did not make a significant difference in the hardness of the weld, and this issue can be considered due to the same and similar conditions for all joints in all samples.

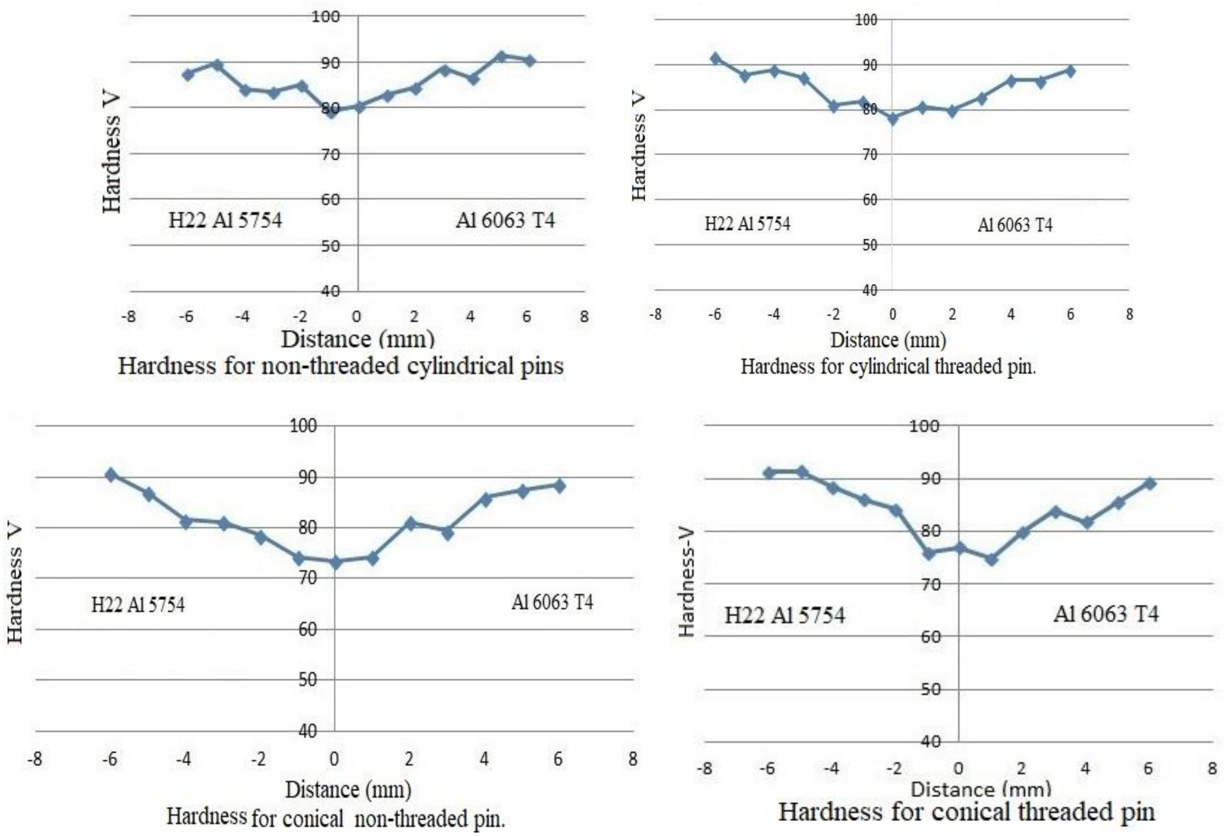

Figure 13. Hardness graph for welds with threaded and non-threaded pins

Another item that was considered regarding the results obtained in the hardness test is that the test is performed on the without flaw section of the part and the effect of defects such as porosity and holes is not taken into account, and for the same reason, a significant difference in the hardness between different parts cannot be seen. Also, in this research, it was found that the hardness in the stirring zone is lower than in other zones. Its initial hardness is due to the work hardening on it by the rolling process. The rolling operation increases the dislocation density in the sheet and increases its hardness. However, the microstructure resulting from the process has the least amount of dislocations, and this means that the effect of work hardening has disappeared after the stirring of the material and the phenomenon of recrystallization. So this phenomenon leads to a decrease in the degree of hardness in the stirring zone.

Figure 14 shows the tensile properties of joints welded by different tools in FSW operations. The diagrams in the figure show that the tensile properties of the joints welded by cylindrical and conical tools with threaded pins are higher than the other two cases, i.e., cylindrical and conical tools with non-threaded pins. When the samples are welded with a conical tool with a threaded pin in the FSW operation, the value of the tensile property can reach 312 MPa, which is equivalent to 75% of the base metal. The tensile properties of samples welded by cylindrical and conical tools with non-threaded pins are lower. The crack occurred in the middle of the weld, which is relative to the deviation of porosity and weld holes, and the crack is located only at the top of the holes.

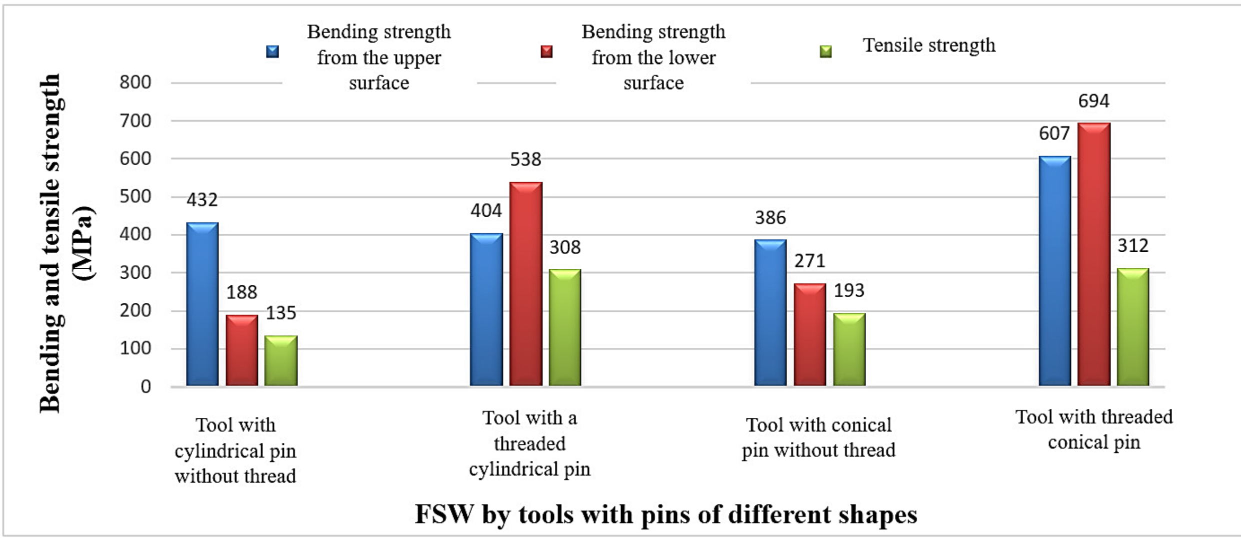

Figure 14. Bending and tensile strength in FSW operations by tools with pins of different shapes

The porosity defect is a very serious defect that strongly affects the tensile properties and leads to a severe decrease in tensile strength. Also, the three-point bending test is used to check the bending strength of the welded joint by using cylindrical and conical tools with different tool pins were performed in FSW.

The bending test consists of two parts, one is bending from the upper surface, which means that the weld on the upper surface is subjected to tensile stress, and the other is bending from the lower surface, which means that the weld on the lower surface is subjected to tensile stress. The results are shown in Figure 14. From this figure, it can be seen that the best bending properties were obtained with the sample welded with a conical tool with a threaded pin in FSW. The bending strength of the weld on the bottom surface is 694 MPa. The bending strength of the weld on the upper level is 607 MPa. These results show that the bending properties of the joint are significantly affected by the weld defect. When the weld formed in the specimens subjected to the bending test with cylindrical and conical pin tools without thread, due to the presence of holes and porosity, the bending strength of the joints was weak.

4. Conclusion

In this research, the connection of two non-homogeneous pieces of aluminum alloy H22 Al 5754 and Al 6063 T4 was done by FSW using tools with cylindrical and conical pins with threaded and non-threaded shapes. The aim is to investigate the microstructure and properties of the obtained weld. The acquired results were reviewed and analyzed. The results of this research are:
The results show that the shape of the pin has a significant effect on the joint structure and mechanical properties. The shape of the pin strongly affects the flow of plastic materials; the geometry of different pins has different methods of transferring materials. Therefore, by changing the geometry of the tool pin, which is the most important influencing parameter in FSW, the process can be improved to connect dissimilar parts.

The best weld quality was obtained using the tool with a threaded conical pin; the appearance of the weld was good, no obvious defects were found, the microstructure of the weld was uniform, the Sediment distribution was uniform, and small sizes were visible.
The hardness test showed that the change in tool geometry does not have a significant effect on the hardness level. The results of the tensile test show that the threaded conical tool gives the highest tensile strength to the weld.
The tensile strength of the weld joint can be equal to 75% of the base metal. In general, a weld joint welded by a tool with a threaded conical pin has the best mechanical properties.
When the weld is done by a conical tool with an unthreaded pin, the zone between the weld (welded line) and the thermomechanically affected zone has poor mechanical properties, because, often, some defects such as porosity and holes occur in this zone. Due to insufficient material flow and a higher speed rate, there is a clear boundary between the weld line and the thermomechanically affected zone. When using threaded pins, the microstructure of the weld zone and the thermomechanically affected zone can gradually change, while the grain size does not change drastically.
When the samples are welded by the non-threaded pin under the same conditions, dislocation defects are formed in the joints. As a result, the microstructure of the weld will be uneven, and the tensile strength will be lower. It was observed that after the tensile test, most of the cracks were formed above the holes and porosity.

5. References

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