Experimental Investigation of Variation in Mechanical and Microstructural Properties Along the Length of Similar AA6063 FSW.

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Abstract

In this paper, 6063-T4 Al-alloy sheets with dimensions (6x90x200) mm were joined via friction stir welding (FSW). Tow sheets were but welded with square mating edges. The rotating welding tool made of tool steel heat-treated to HRC 60**.** The temperature distribution had been investigated experimentally with constant revolution speed and constant linear speed. A digital reader of twelve channels was used to read and record the temperature with time at each channel as an excel table. Nine K-type thermocouples were positioned along the weld length. The mechanical properties were evaluated (such as tensile strength , microhardness, and microstructure tests) at room temperature in several positions along the length of the joint. The results show that the max. temperature was conducted at the end of the weld to be 375C˚. The relationships between the peak temperature and the time, distance from start, microhardness, tensile strength, and microstructure were discussed. The hardness of the stirred zone was more than the base metal hardness due to refinement of grains by friction stir process. The strength and hardness of the FSW were as min. at the end of the weld due to increasing in heat input to the joint at this region which lead to grain growth at the microstructure of last region.

Keywords: friction stir welding, Temperature distribution, mechanical properties, friction stir process.

المستخلص

في هذا البحث استعملت سبيكة المنيوم من نوع (6063-T4 Al –alloy) على شكل الواح بالأبعاد (6 x 90 x 200) ملم، تمت تهيئتها بشكل تقابلي و بحافات قائمة ثم تم وصلها باستعمال طريقة اللحام بالاحتكاك والتحريك (FSW). أداة اللحام المستعملة تم تصنيعها من فولاذ العدة المقسى الى حد HRC 60. تم عملياً دراسة توزيع درجات الحرارة بثبوت السرعة الدورانية و الخطية لأداة اللحام. تم استعمل قارئ و مسجل درجات الحرارة من النوع الرقمي ذو اثنتي عشر قناة

و الذي يقرأ الحرارة مع الزمن ويتم عرضها على جهاز الحاسوب على شكل جدول ببرنامج معالج الجداول Excel. استعملت في البحث تسعة مزدوجات حرارية من النوع K وزعت بشكل متساوي على طول وصلة اللحام. بعد ذلك تم تقييم المواصفات الميكانيكية على طول وصلة اللحام مثل اختبار الشد و الصلادة المجهرية و كذلك فحوصات البنية المجهرية. النتائج أظهرت ان درجة الحرارة العظمى التي حصلت خلال عملية اللحام كانت 375م° في آخر منطقة من عملية اللحام. بعد ذلك تمت مناقشة العلاقات بين تنوع درجات الحرارة و الوقت و المسافة عن بداية اللحام و الصلادة المجهرية و كذلك البنية المجهرية. ان صلادة منطقة اللحام (stirred zone) كانت أعلى من صلادة المعدن الأساس وهذا نتج عن عملية التنعيم في الحجم الحبيبي الذي حصل نتيجة عملية الاحتكاك و الدعج والتحريك.ان مقاومة الشد العظمى و كذلك الصلادة كانتا كأقل قيمة عند آخر منطقة في اللحام بسبب الزيادة في الحرارة الداخلة الى هذه المنطقة نتيجة الحرارة المتراكمة و التي أدت إلى زيادة في الحجم الحبيبي في هذه المنطقة.

1. Introduction

Friction stir welding (FSW) is an efficient solid joining process that has numerous potential applications in many domains including aerospace, automotive and shipbuilding industries as well as in the military. It combines frictional heating and stirring motion to soften and mix the interface between the two metal sheets, in order to produce fully consolidated welds. One of its main qualities lies in the possibility of joining materials previously difficult to weld, and to offer excellent mechanical properties [1]. The weld is made by inserting a usually threaded pin or nib into the faying surface of the butt welded parts. The nib is typically slightly shorter than the thickness of the workpiece and its diameter is approximately the thickness of the workpiece . The pin is mounted in a shoulder that may be three times the diameter of the nib. The nib and shoulder are pressed against the workpiece, rotated at several hundred revolutions per minute, and advanced along the faying surface. FSW has been primarily used on aluminium alloys (e.g. alloy series 2000, 6000, 7000 and numerous Aluminum – Lithium alloys) and produces nearly defect-free welds for such demanding applications as space hardware at lower cost than conventional fusion welds [2,3]. The low distortion solid –phase welds exhibit metallurgical and mechanical fusion welds achieved by arc processes and additional studies have concluded that the FSW process could significantly improve weld quality and lower production costs associated with welding [4]. The problems related to the presence of brittle inter-dendritic and eutectic phases are eliminated [5-6]. The thermo-mechanical affected zone is produced by friction between the tool shoulder and the plate top surface, as well as plastic deformation of the material in contact with the tool [4]. Systematic welding trials have covered various Aluminum Alloys according to the (2XXX(Al-Cu), 5XXX (Al-Mg), 6XXX(Al-Mg-Si), 7XXX (Al-Zn) and 8XXX (Al-Li) series alloys and each a high level of weld quality and process repeatability has been observed [7].

In the present paper, 6063 Al- alloy sheets (with 6 mm thickness) were joined via friction stir welding (FSW), and the temperature distribution had been investigated experimentally (with constant revolution speed and constant linear speed) along the weld length. The mechanical properties were evaluated by means of tensile and hardness tests at room temperature along the weld length in addition the material microstructure and the different phases were investigated by means of optical observation in different sections along the length of the produced joints.

2. Experimental procedure

2-1. Materials

The material under investigation was a 6063 Al-Mg-Si alloy as rolled sheets of 6 mm thickness with the composition shown in Table (2-1)

Table (2-1).Chemical composition of Al-Mg-Si alloy [8,9].

Element composition %	Si	Fe	Cu	Mn	Mg	Zn	Cr	Al
ASTM Standard	0.2-0.6	0.35	0.1	0.1	0.45-0.9	0.1	0.1	Rem.
As measured	0.21	0.15	0.03	0.01	0.40	0.01	0.01	Rem.

In order to investigate mechanical properties of the workpiece before welding process, a series of tensile tests had been performed to determine the max. tensile strength and elongation. Tensile specimens were machined according to ASTM standard. Tensile results for the material before welding process are listed in Table (2-2), while standard tensile test results for different classes are given in Table (2-3).

Table (2-2).Tensile test results for present work.

6063 Al-alloy	Ultimate tensile strength MPa	Hardness HV Mpa	Elongatio %
	142	63.5	18

Table (2-3). Standard tensile test results for Al-Mg-Si alloy [8].

Temper	Proof strength 0.2% MPa	Tensile strength MPa	Elongation %	Hardness HV
0	50	100	27	85
T4	90	160	21	50
T6	210	240	14	80

From tables above, it is obvious that the selected alloy was solution heat-treated and naturally aged to a substantially stable condition, hence the selected alloy is 6063-T4.

2-2. Configuration of tool and workpiece

A schematic of the welding sequence for a FSW process is shown in Figure (2-1). A specially cylindrical (heat-treated to HRC 60 tool steal) tool with a probe extending from the shoulder. The probe may have a diameter one-third of the cylindrical tool and typically has a length slight less than the thickness of the workpiece [10]. A welding tool comprised of a shank, a shoulder and pin is fixed in a milling machine holder and is rotate along its longitudinal axis. Workpiece material is held firmly in place in a fixture as shown in Figure (2-2). Two 6063-T4 Al-alloy plates, each with a dimension of 200x90x6 mm were butt welded in the adapted vertical milling machine perpendicularly to the rolling direction Figure (2-3). The two plates, with square mating edges, are fixed on a rigid backing-plate, and a clamp or anvil prevents the workpiece from spreading or lifting during welding. The rotating welding tool is slowly plunged into the workpiece until the shoulder of the welding tool touched the upper surface of the plate material.

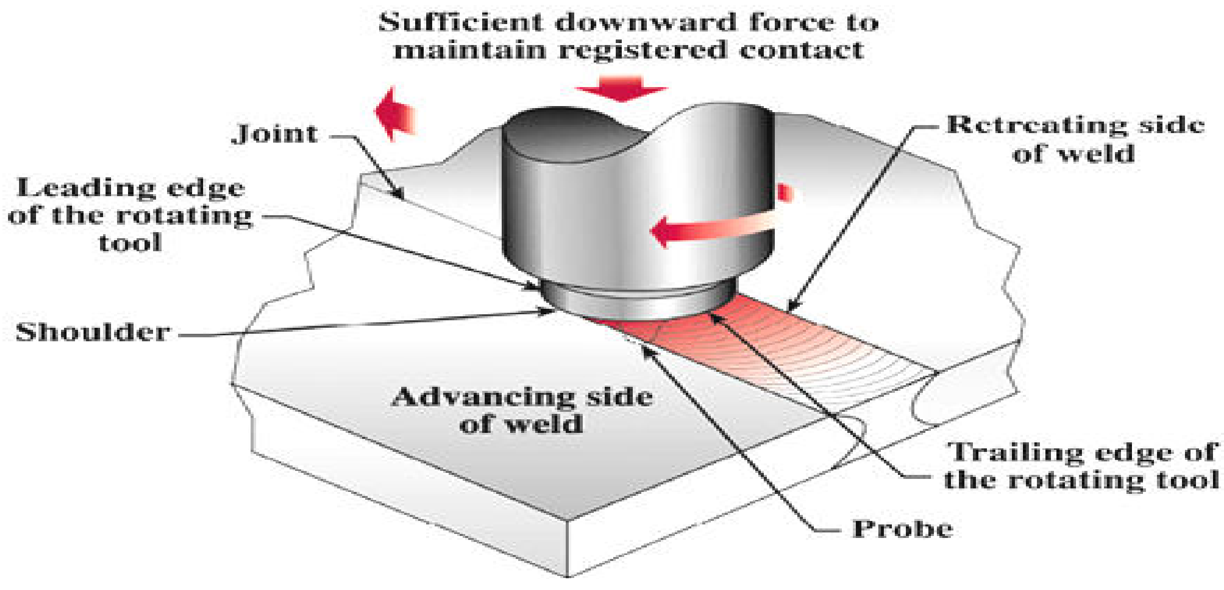

Figure (2.1). Schematic representation of FSW of a butt joint [4].

Figure(2-2).Shows (a) thermocouple reader connect with 9- K type thermocouples,(b) thermocouples distributes along the workpiece surface, and (C) The tool move with rotational speed 1400 rpm and travel speed 110 mm / min.

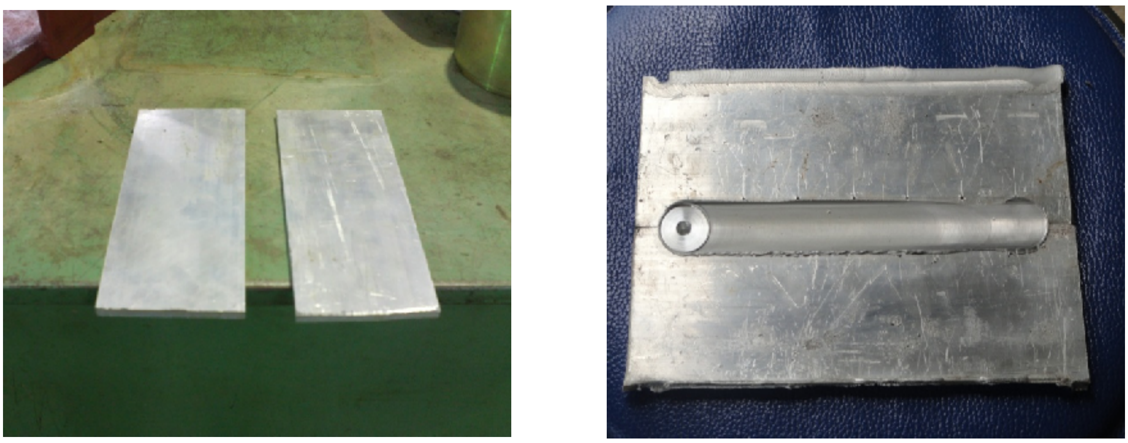

Figure (2-3).Two 6063-T4 Al-alloy plates to be welded before and after FSW.

The tool rotate at the selected revolutional speed for about (30-45) seconds dwell period for preheating [11]. Then the welding tool is forcibly traversed along the joint line until the end of the weld is reached. After that the welding tool has been retracted and the pin of the welding tool leaves a hole in the workpiece at the end of the weld. Table 2-4 shows the processing conditions with constant the revolutionary pitch (welding speed/rotating speed).

Table (2-4). The welding conditions.

Rotating speed RPM	Welding speed mm/min	Revolutionary pitch mm/rev.
1400	110	0.0785

2-3. Measurement of temperature distribution

Nine positions were pointed out on one face of the plates to be welded on the same side and equal distance along the line of the welding as shown in Figure (2-4).

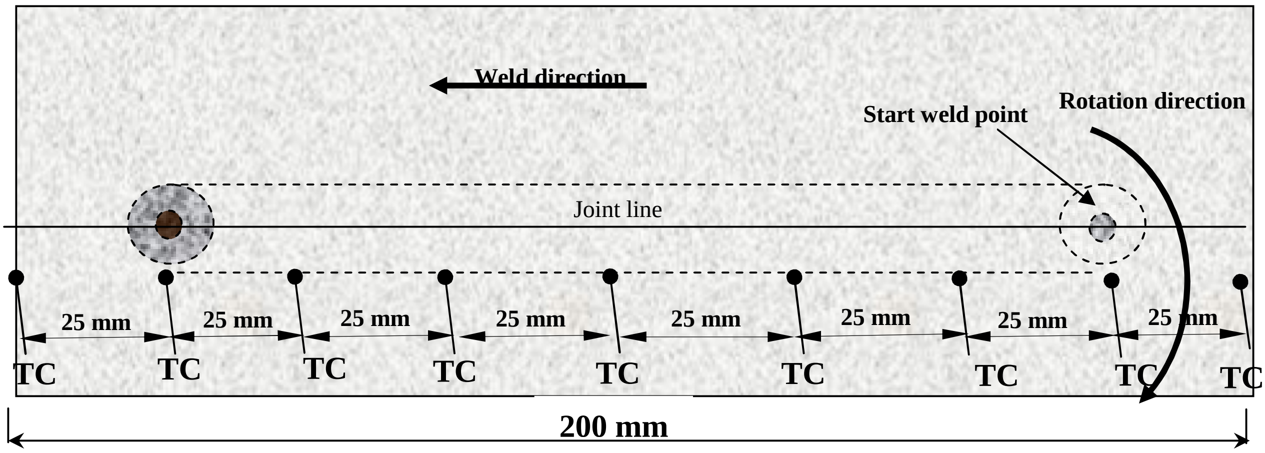

Figure (2-4). Layout of the thermocouples on the workpiece surface.

K-type thermocouples with diameter of 1mm were used. The sensing head of the thermocouples is approximately 1mm long. A drill machine was used to make holes of 1 mm diameter with 1mm depth in the nine positions [12,13]. The rotational speed and the moving speed direction of the tool are shown in Figure (2-4) and the thermocouples are lined on the same side of the setup workpiece with a distance (11 mm) from the joint line, which means that the thermocouples are positioned at the rim of the shoulder when the tool passes by the thermocouples without destroyed them. A digital reader of twelve channels was used to read and save the temperature readings at the same time. Nine-thermocouples were connected to the reader. In the start it read the temperature of the surrounding , then the temperatures will increase during the tool movement and the reader will save these temperatures every one second. The readings were saved in separated Ram which can be inserted in computer to display on the monitor as an axel table.

2-4. Mechanical tests

In order to investigate mechanical and microstructural properties of welded joints and to evaluate the effect of cumulative temperature on the properties, some of destructive tests have been conducted.

2-4-1 Tensile test

Tensile specimens were machined from the welds according to ASTM sub-size specimen geometry shown in Figure (2-5). The tensile tests were performed in order to evaluate the mechanical properties in the different welding positions which were calculated in longitudinal direction. The test was carried out at room temperature using testing machine in a direction transversal to the welding line (transverse specimens). The results of tensile strength and microhardness were averaged of three specimens at each location.

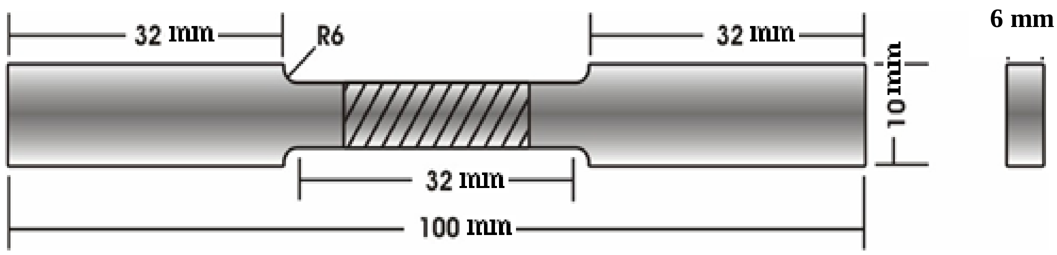

Figure (2-5). ASTM sub-size sample for tensile test.

2-4-2 Microstructure test

Microstructure investigation of welded joints specimens for the microstructure analyses were prepared by standard metallographic techniques and etched with killer's reagent to reveal the grain structure. The microstructure and different phases were observed in the centre of the joint (stirred zone).

2-4-3 Microhardness test

The same specimens of metallurgical tests were prepared for the microhardness measurements were made at mid-section of the joint every (25mm). Microhardness was employed with load (0.5 Kg) by using a (Micro - Veckers Hardness system CV-400 DM) microhardness tester accordance with ASTM.

3. Results and discussions

3-1 Temperature-Time history with moving heat source

Variation of peak temperature is shown in Figure (3-1), which represents a temperature – distribution along the longitudinal direction for nine nodes shown in Figure (2-4). Region 1 shows plunging and dwell period in which the tool rotate at the same position for 35 seconds with rotational speed of 1400 rpm to increase the base metal temperature (pre-heating) as shown in Figure (3-2 a). Region 2 represents the variation of temperature during tool movement. It is obvious that the temperature increase at the beginning due to increase of heat input by dwell, then the temperature decrease and then it increase. The reason of the first increasing in temperature is that the tool is staying near dwell starting position and when the tool moves it will enter the cold area as shown in Figure (3-2 b), therefore, the temperature reduces. After that the effect of heat accumulation will contribute by raising the temperature Figure (3-2 c). Figure (3-1) shows that the temperature at the end of the tool movement is the highest. Figure (3-3) shows the temperature variation which record by using thermocouple reader by means thermocouple distribution along the length of welded joint. It was obvious that the temperature rises slightly until get max. at the location 8 due to cumulative heat with movement of tool during welding along the joint length as shown in Figure (3-2 d).

3-2 Microhardness test results

Hardness profiles for each sample along the weld length are shown in Figure (3-4). From the figure it was obvious that there is an increase in the hardness across the welds compared to the value of the base metal (HV_{500g}=63.5). It is thought that the increase in hardness was due to equiaxed structure or reprecipitation of the solid solution. Furthermore, it can see that hardness value decrease with an increasing in the distance which mean that the temperature become max. at this position (375 C$^{\circ}$). The hardness variation along the weld length with variation in temperature during welding time as shown in Figure (3-4) and Figure (3-5). The decrease in hardness at position 8 (HV_{500g}= 60.6) may belong to the dissolution of precipitates into solution and subsequently the weld cooling rates do not favour nucleation and grains are growing in all the stirred zone as shown in paragraph (3-4).

3-3 Tensile test results

Figure (3-6) shows the ultimate tensile strength at selected positions with constant distance (25 mm) along the weld length. Many of researchers [10,14,15] emphasized that there is a reverse effect between the max. tensile strength and travel speed of the tool, and they show that the max. tensile strength decreases with increasing of rotational speed of the tool, the reason may belong to the heat input to the workpiece so that the strength decrease with increase of heat input (increase rotational speed or decrease of travel speed) and it increase with decrease of input heat (decrease rotational speed or increase of travel speed). In the present case the rotational speed and travel speed were taken as constant values (constant revolutionary pitch) Table (2-4). From the Figure (3-7) it is obvious that the tensile strength decrease with the length of welded joint in the direction of welding. It is believed that the decrease in weld strength with increasing the distance along weld direction was attributed to increase in heat input per unit length of weld due to cumulative heat during welding, therefore, the position (8) had temperature 375C° and the position 2 developed high temperature (315 C°) due to dwell period, for this reason the tensile strengths were min. at these positions, because the high temperature at these positions resulted in more over aging of the weld zone and produce change in microstructure.

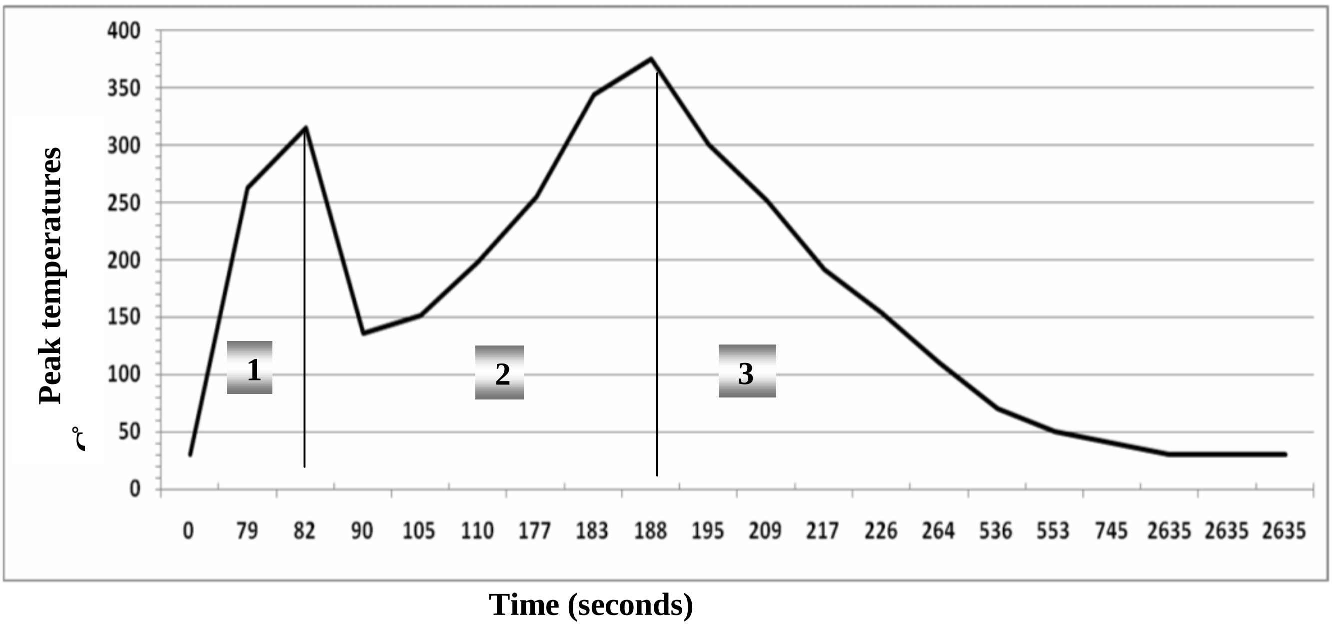

Figure (3-1). Peak temperature variation during welding and cooling.

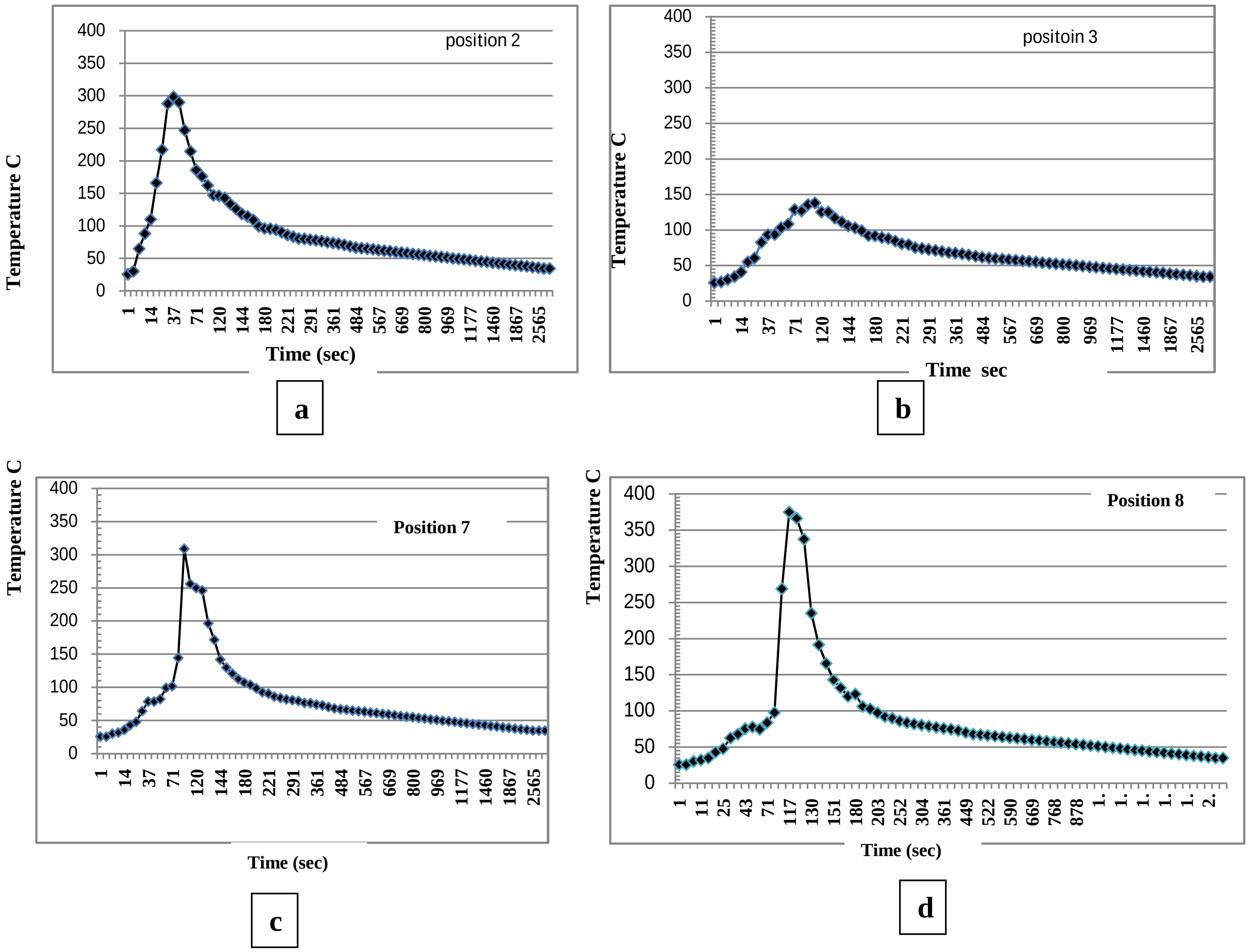

Figure (3-2). Thermal history in thermocouple positions (2, 3, 7 and 8) along the weld length show temperature profile versus welding time.

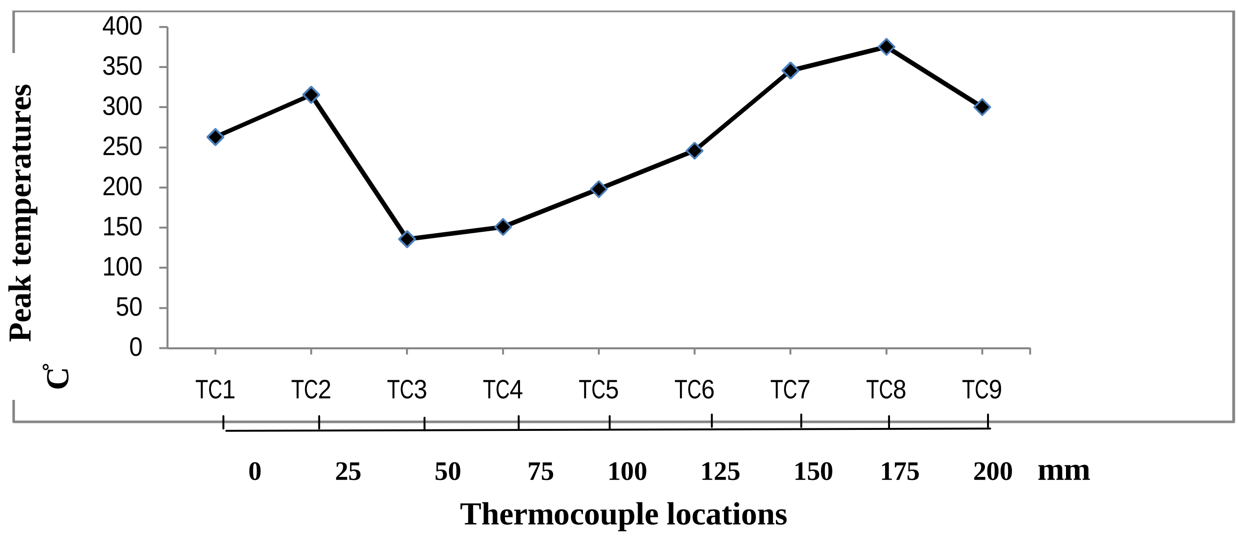

Figure (3-3). Peak temperatures profile in FSW along the weld length.

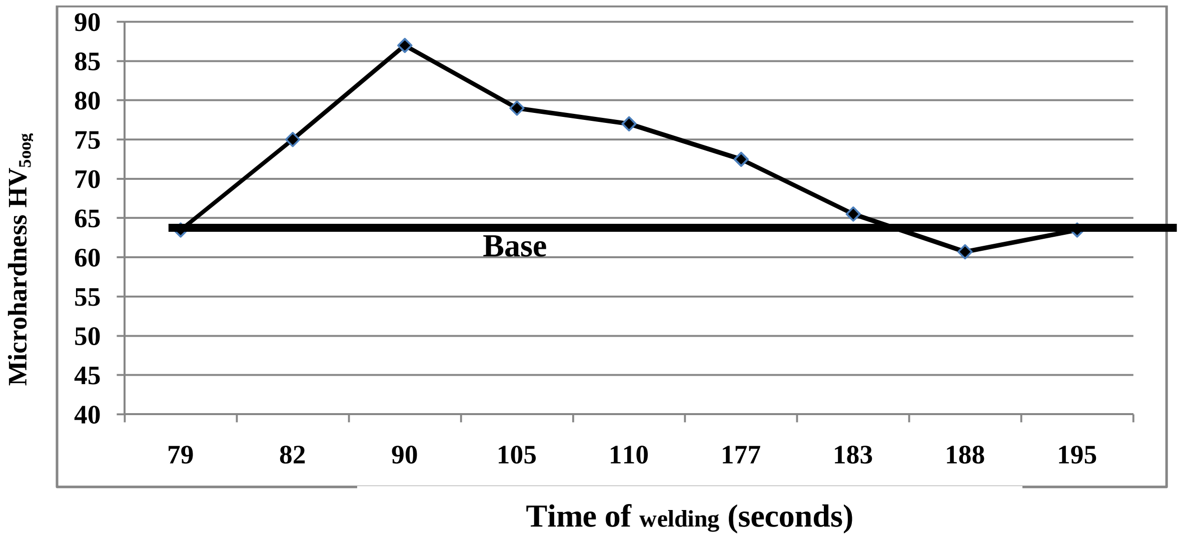

Figure (3-4). Microhardness variation during FSW period.

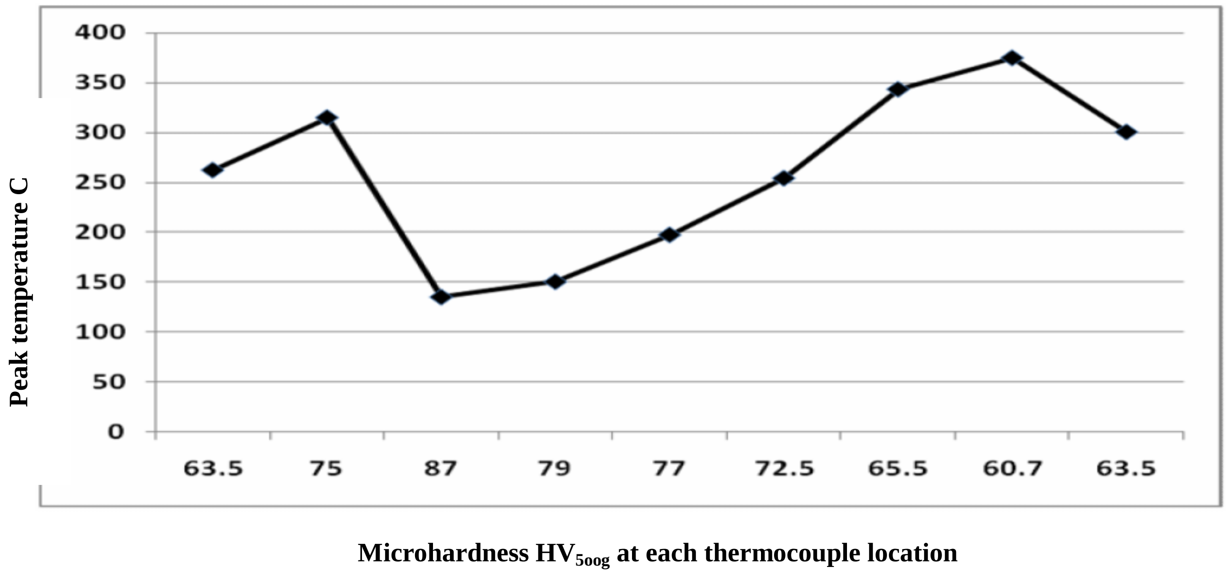

Figure (3-5). Microhardness variation versus temperatures.

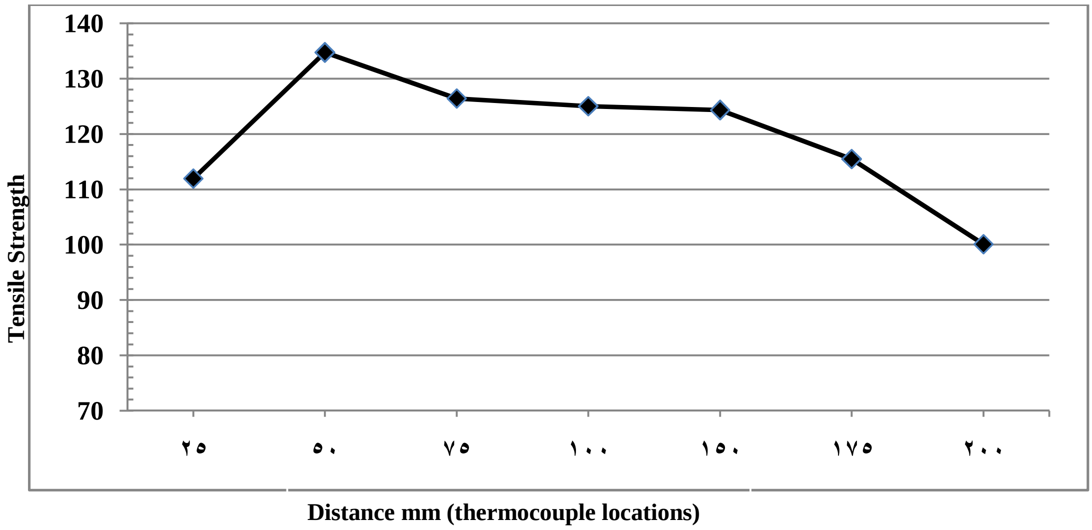

Figure (3-6). Max. tensile strength variation along weld length.

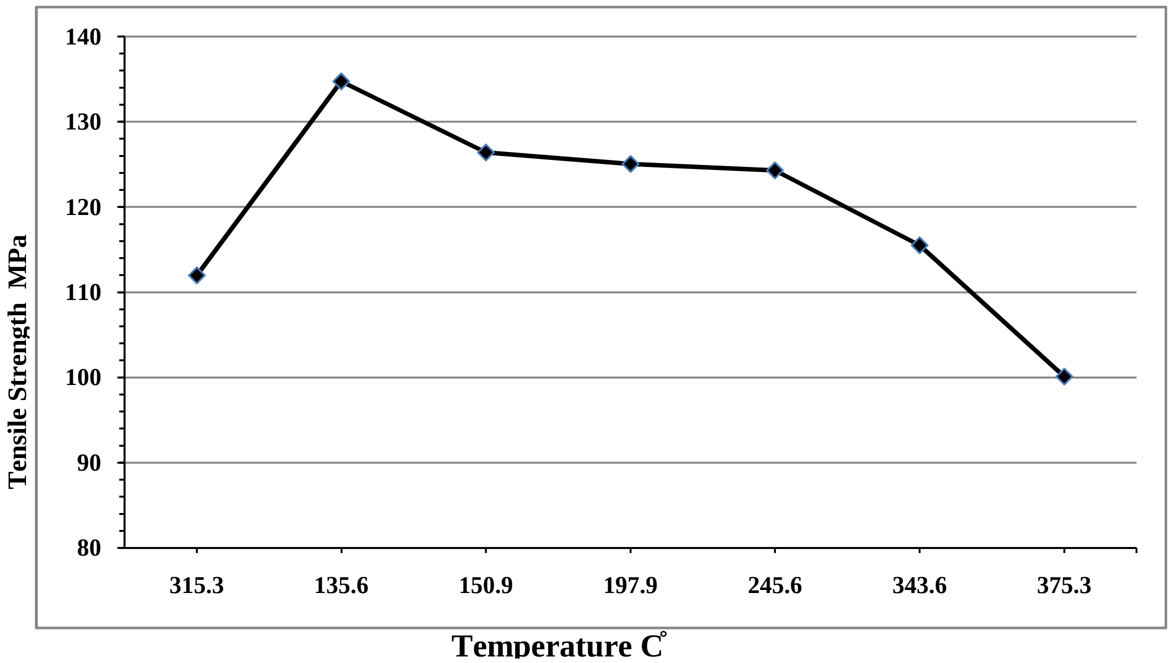

Figure (3-7). Max. tensile strength versus peak temperature at each certain position along weld length.

3-4 Microstructure test results

Figure (3-8) shows the microstructure of the base metal before welding. It is obvious that the base metal exhibited elongated grains due to rolling process.

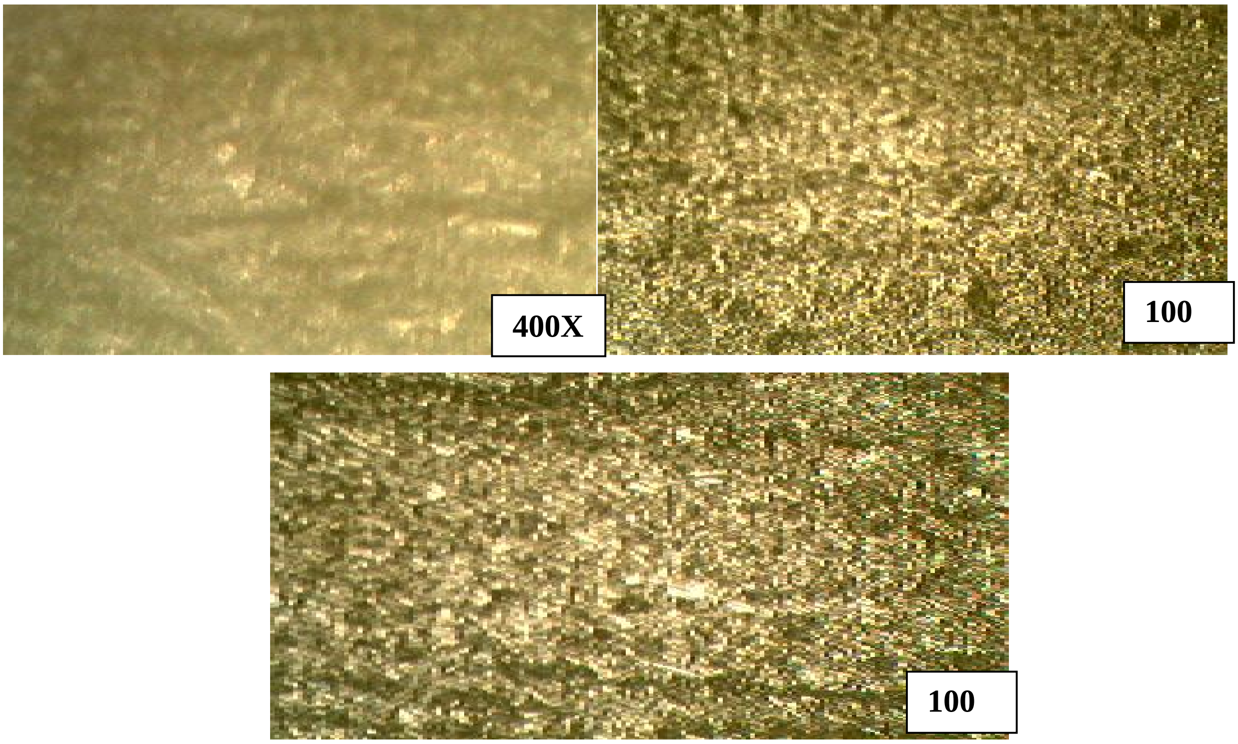

Figure (3-8). Show the elongated grains of the base metal microstructure.

Figure (3-9) shows the microstructure of the weld zone in FS zone along the length of the joint. From the figure it was clear that the grains had produced at the stirred zone to get refined grains at the weld centre due to friction stir process see Figure (3-9 positions 3, 4, 5, and 6). But the cumulative heat during FSW which reaches to about 375C˚ at end of tool movement affect the grains to grow, therefore, the grains are equiaxed and large Figure (3-9 positions 7&8). It is known that the Al-Si-Mg alloy may be recrystallized and grow at temperature range (200-330)C˚ [16]. The experimental rsults show that the achieved temperature during FSW exceeded 370 C˚. Although the growth time was short respective to that allowed for grain-growth in Al-structure see Figure (3-2 d), furthermore, it leads to overage of the grains and growth which affect the properties of the joint along the weld length as discuss in paragraphs (3-1, 3-2, and 3-3). From the results it is necessary to carry out heat treatments for homogenization the properties along the weld length in FSW processes.

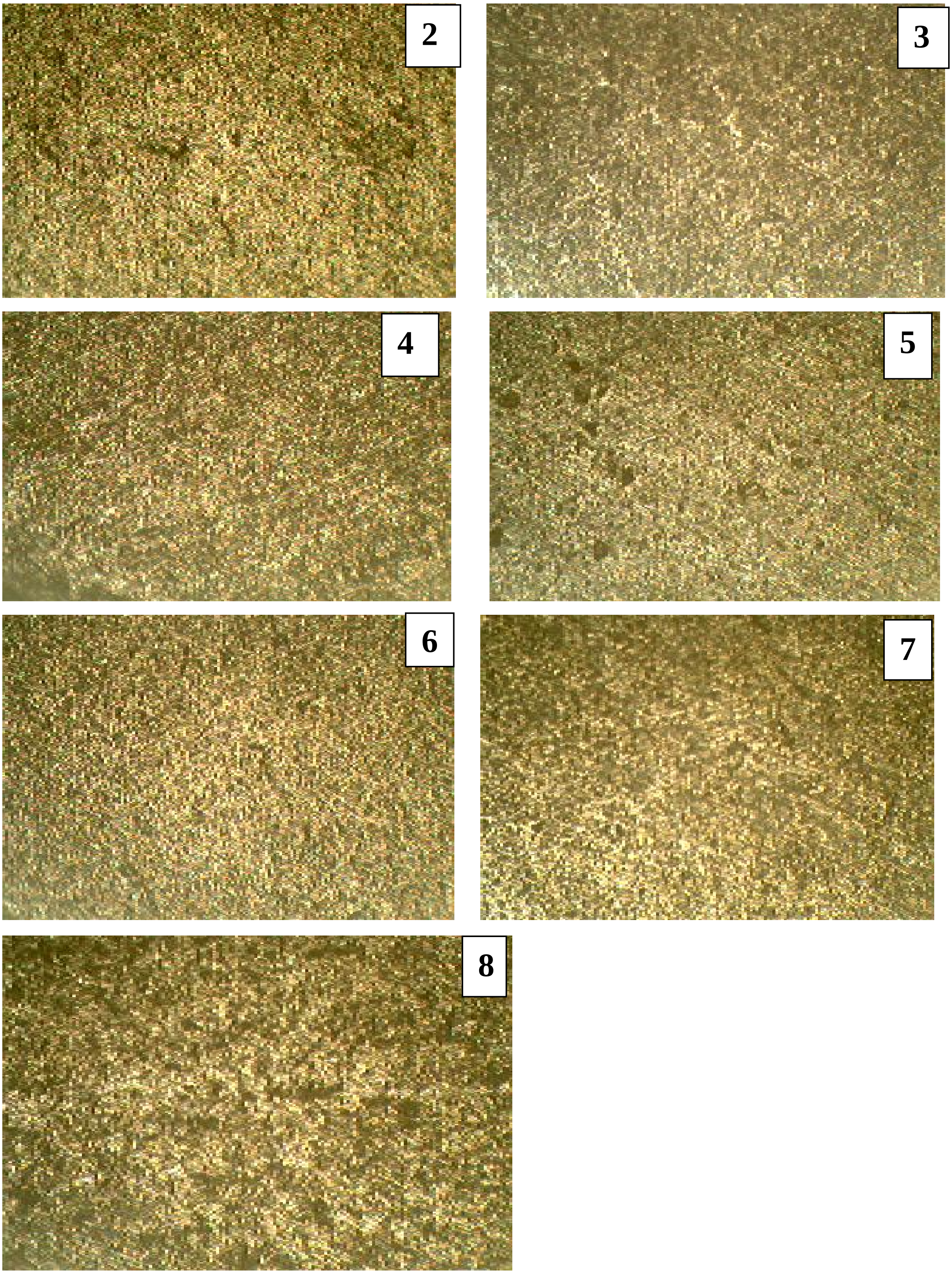

Figure (3-9). Microstructures of stirred zone along the weld length 100X. The sample (2) represents the beginning of plunging and stirring (first dwell) and the sample (8) represent the end of weld (second dwell).

4- Conclusions and further recommendations

4-1 Conclusions:

According to the results of the present work several conclusions can be written:

1- The 6063-T4 Al-alloy can be readily friction stir welded.
2- Maximum temperature in FSW will appear at the end of the tool movement due to cumulative heat.
3- Mechanical properties variate along the length of joint as a result of variation in heat input to the weldment.
4- Refinement of the weld zone grains was very clear which lead to increase of microhardness of the stirred zone above the base metal hardness.
5- Grain growth appear at the end of the weld due to high temperature at this region , which cause decreasing in mechanical properties (hardness and strength).
6- The max. tensile strength of the FSW is about (--)% of the base metal strength and strength values variate along the weld length, where the min. value of tensile strength is pointed at the end of weld (second dwell).

4-2 Recommendations:

1- Make a mathematical model for temperature distribution (theoretical procedure) and compare with the present experimental work.
2- Use robotic welding machine by which can control the change in rotational speed and travel speed in order to control on the heat input to the workpiece as constant amount by decreasing the rotational speed or increasing the travel speed, to withstand the cumulative heat effect.
3- Use the same procedure but for other types of joints (such as fillet or lap) by using the same material.
4- Use low carbon steel instead of Al and compare the results of variation in properties along the weld length.

5. References

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