EFFECT OF SELECTED TOOL SHAPE ON FRICTION STIR WELDING METAL FLOW OF ALUMINUM TO COPPER

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الملخص:
يتضمن شذا البحث دراسة عملية لمعرفة سلوك جريان المعادن الغير متماثلة في عملية اللحام الأحتكاكي الدوراني وذلك للحام معدني النحاس والألمنيوم. وكذلك لدراسة تأثير رأس الأداة المربع والأسطواني على شيئة الجريان لمعدني الأساس. وقد أعطى رأس الأداة المربع خواص وصلة لحام افضل من الشكل الأسطواني وقد كان معظم التدوير الخلطي واقعاً على جانب معدن الألمنيوم مع حبيبات ناعمة من النحاس متوزعة في في جانب الألمنيوم. وكانت شنالك منطقتان بارزتان لهيئة الخلط الناتج، وقد مثلت المنطقة الأولى تأثير كتف الأداة ومثلت المنطقة الثانية تأثير رأس الأداة. وكان تأثير الخلط على جانب النحاس اقل مقارنة بجانب الألمنيوم مع تكون أشكال طبقية مايكروية للنحاس والألمنيوم على جانب النحاس من الوصلة. وأن شذه الهيئة الطبقية تمثل مصدر الحبيبات الناعمة المتوزعة في المنطقتين البارزتين العلوية والسفلية لجانب الألمنيوم.

Abstract:
This work includes an experimental procedure to studying the behavior of flow of dissimilar metal in the friction stir welding process to joining Aluminum to Copper. And investigating the effect of square and cylindrical probe tool shape on the joint metal flow behavior. The findings demonstrate that the square probe shows better joint properties than the cylindrical probe, and that the most stirring effect happens on the aluminum side with fine copper rich particles embedded in aluminum matrix. There are two recognized regions, the first region represent the effect shoulder and the second represents the probe stirs effect. The stir effect in the Cooper side is less than the stir effect in the Aluminum side with a laminate form of rich Copper to Aluminum. These laminates are the source of the fine particles founded in aluminum side upper and lower regions.

Key words: FSW (Friction stir welding), dissimilar welding, solid state welding process, tool design.

Introduction:

Friction Stir Welding (FSW) is a solid state welding process patented by The Welding Institute in 1991.A rotating pin tool is passed along a butt weld seam literally stirring the faying surface of the weld together. Typically, the diameter of the pin tool is equal to the thickness of the parts to be welded and its length is slightly shorter than the thickness of the part [1].
Combinations of dissimilar soft metals or alloys give the advantage of the properties of both the materials, where the main known traditional two soft metals are aluminum and copper and their alloys [2]. In electrical, aerospace, shipbuilding and automotive industry joining of these two metals have high importance. It is known that the joining of Aluminum to Copper using metallurgical

methods is very difficult due to the high variation of physical and chemical properties of the two metals, especially the high thermal conductivity of copper and aluminum [3], which make it is very difficult to join either copper or aluminum or both by conventional welding methods. Brazing and soldering processes can join aluminum to copper with moderate join quality in applications of HVAC (*heating, ventilation and air conditioning*), but this process limited in most cases with pipe connections. Friction stir welding and explosive welding are force-joining methods used to join similar an dissimilar metals or alloys by applying external, sudden force to mix the adjoins alloys with each other to introduce good joining bond. Other methods like brazing or diffusion bonding may be used to join dissimilar alloys with each other. It is important to know that (FSW) is not limited to joining processes, but it is also used for improving the mechanical properties of alloys such as surface hardening, toughening, or particles addition to processed surfaces to improve its properties [4].

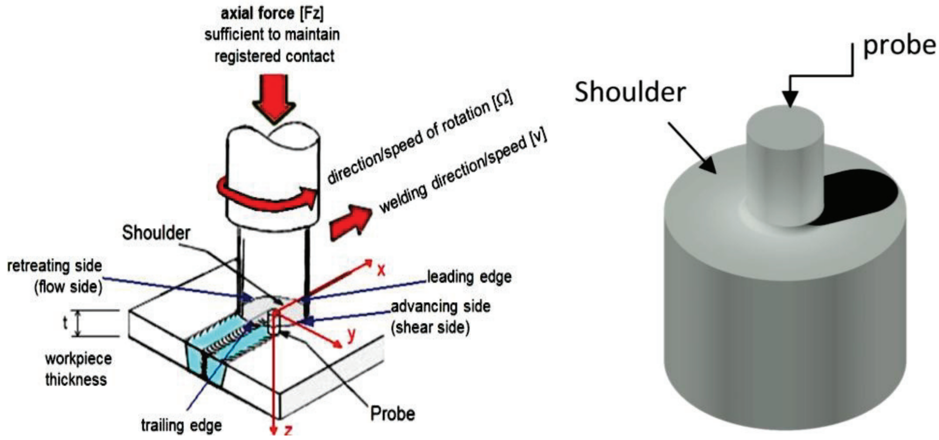


Figure (1): friction stir welding (FSW) process

The joining process in friction stir welding (FSW) includes a solid-state joining process patented by the Welding Institute in 1991 involving plastic deformation of the materials to be join. The base metals is not melted which uses a third body tool and a rotating force to mix and join a two facing surfaces. Yet, the joining mechanism is very complex as it depends on many variables such as materials, feed speed, rotating tool speed, axial force, centering of the tool, temperature, and tool geometry[1].

The production systems of (Al/Cu) enable the achievement of new engineering solutions to combine copper´s improved mechanical, thermal, and electrical properties with aluminum's low weight and cost. Nevertheless, although some experiments in FSW of aluminum to copper have already been reported, sound joining of these metals has not been achieved [5]. Several issues still require extensive research. For instance, the intermetallic phases of formation mechanisms and their relation to welds morphology and final strength are analyzed, but the mechanism needs more investigation to achieve perfect sound joint [1]. Welding conditions have various influences on the metallurgical phenomena which takes place during friction stir welding. As example the boundary conditions in FSW are complex to define. Material at the interface may either stick to the tool when it has the same local velocity as the tool or may slip at lower velocity contacted material[6]. At stick condition the generated heat came from bulk while at slip condition the heat generated at contact surface to high values locally. These two conditions produce two different flow shape, metallurgical structure and different joint mechanical properties [7].

Typically, the length of the probe is slightly shorter than the thickness of the parts, but the tool's geometry and shape are the key to produce good mixing of the workpiece material. This paper shows the effect of changing the traditional threading tool probe to a simple shapes and it interacting with the workpiece. The steel tool is comprised of a shank, shoulder and probe, as

shown in Figure (1). The welding tool rotates along its longitudinal axis in a conventional milling machine and the workpiece material is firmly held in place by a fixture [8].
The shoulder is pressed against the surface of the metal, generating frictional heat while containing the softened weld metal. The probe causes some additional heating and extensive plastic flow of the workpiece material on either side of the butt joint. In most cases the probe is threaded and this thread assists in ensuring that the plastically deformed work piece material is fully delivered around the probe, resulting in a void-free weld. To achieve full closure of the root, it is necessary for the probe to pass very close to the back plate, since only a limited amount of plastic deformation occurs below the probe, and then pass very close to the probe surface. The microstructure and XRD analysis of FSW joints of copper and T2/aluminum observed clearly an onion ring structure in the stir zone indicating good material flow [9,10]. Also joining aluminum to copper studied experimentally using a FSW process by adding some material powders during the process to analyze the influence of the microstructure and mechanical properties of the joints [11].

Experimental procedure

The friction stir welding process is accomplished using conventional milling machine as shown in figure (2) which represent the rotating head of the machine during FSW process at a rotation speed of (1000, 1200) RPM and feed of 30mm/min. The materials chosen are two plates of commercially pure copper (C12100) according to ASTM-B224(0.01%P, 0.016%Ag) and aluminum (1100) with a chemical composition shown in table (1)

Table (1): Chemical composition of two metals used to joint together.

Elements %wt.	P	Ag	Fe	Si	Zn	Mn	Cu	Al
copper (C12100)	0.01	0.016					Rem.	
Al (1100)			0.0.67	0.88	0.09	0.034	0.12	Rem.

Two alloys fabricated with dimensions of (150x45x 3) mm. Mild steel tool [12] was used with a shoulder diameter of 20 mm and two configurations of probe design, cylindrical, with 2 mm diameter and square with 2x2 mm cross section, both had a depth of 2.2 mm as shown in figure (3).

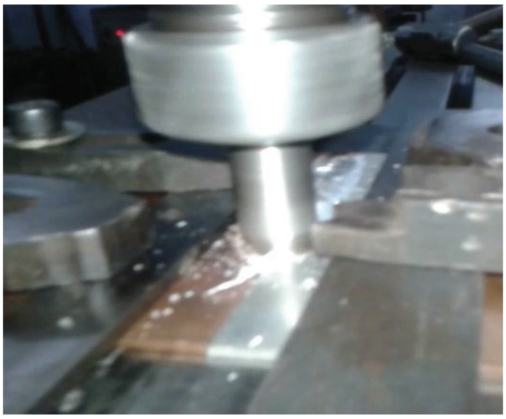


Figure (2): Butt joint configuration for two copper and Aluminum plates.

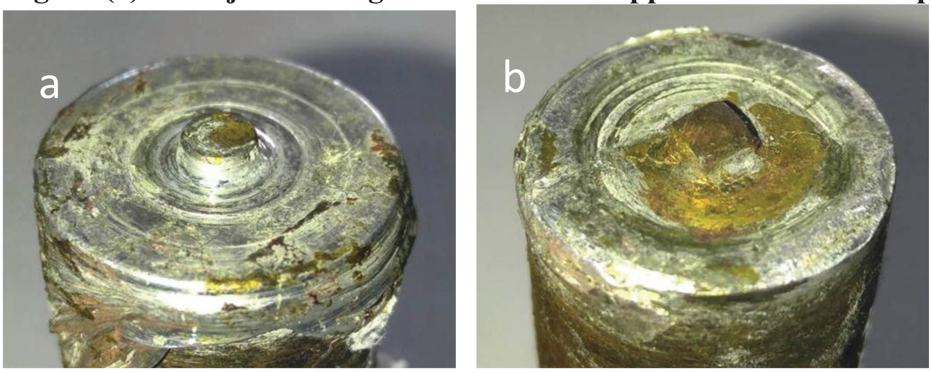


Figure (3): The probe profiles used. a) Cylindrical probe. b)

After completing one pass joint done for the square probe tool type and two passes for the cylindrical probe tool type. The joint samples, sectioned normally across the welding line with samples of (95x20x3mm) preparing for the tensile test. Tensile test done and the failure or maximum value recorded as shown in table (2)

Also the remaining of specimens sectioned across the welding joint to examine the micro-structural properties as shown in figure (4).

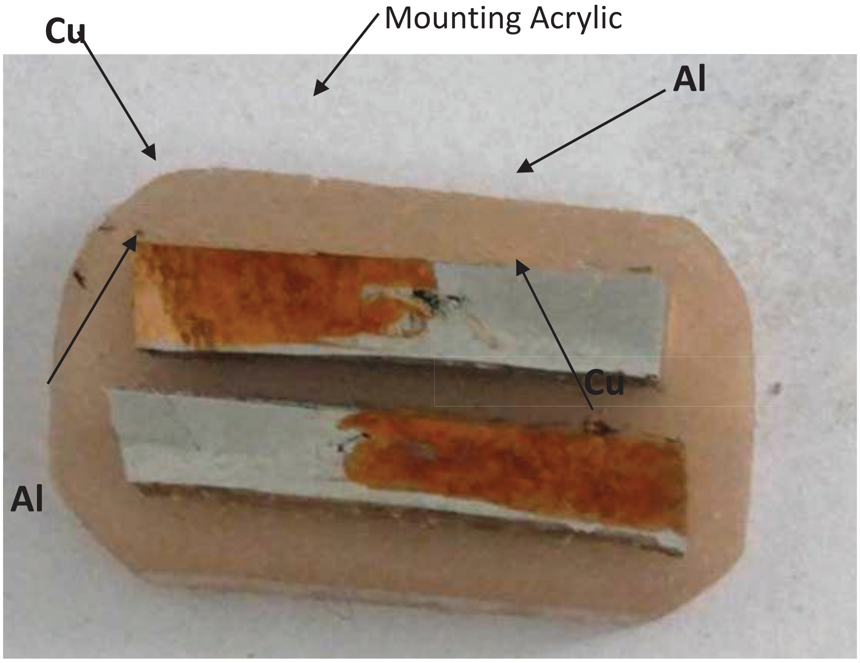


Figure (4): Micro-structural specimen for square and cylindrical probe.

Table (2): Ultimate tensile values for the Friction stir welded

Sample Number	MPa
Sample 1 (rounded probe shape) 1000rpm	26.02 ±5%
Sample 2 (square probe shape) 1200 rpm	36.74±5%
Sample 3 (rounded probe shape) 1200 rpm	31.14±5%

T ıg papers at a grit of (320 to 2000 PPI-Particle per Inch). After that, they were polished using diamond paste of grain size of 0.3□m to obtain highly polished surface, and finally they etched by (5% hydrofluoric acid - 5% iron chloride - 90% distilled water concentration), then directly washed by distilled water to remove the remaining acids and dried by hot air drier. Micro-structural examination was done using electron scanning microscope assisted with EDS (Energy dispersive spectroscopy detector) and BSE (Back scatter electron detector).

Results and Discussion:

The most important investigation of this work is study the flow mechanism of dissimilar base metals as copper and aluminum during the FSW process due to different mechanical and thermal properties of the used materials. The average yield tensile stress for aluminum specimens used was 105±5MPa, and for copper is78±4MPa. After testing the three samples, the data recorded at failure are shown in table (2) where an accuracy of ±5% related to tensile machine. All values were below the yield tensile strength of the base metals with a considerable value which indicated low joint properties. Scanning electron imagesof the specimens were done by SEM model VEGA3-LM supported with Oxford-MAX3 EDS detector. Figure (5) shows a backscattered electron image of welding joint for sample (1). Bright and dark color represents copper and aluminum respectively, where the mixed region shown as a conein the upper region of the image. For indicating the concentration of the copper in aluminum, Figure (6) represents the energy dispersive spectrophotometer (EDS) analysis, which shows that copper is transferred less than aluminum.

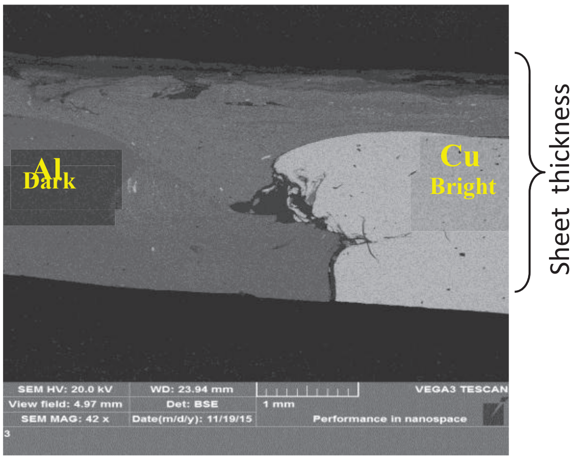


Figure (5): SEM (BSE) for welding joint for sample (1)

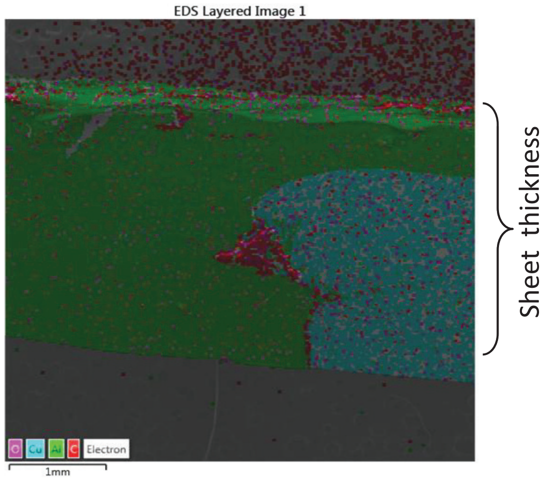


Figure (6): SEM-EDS map image analysis for welding joint for sample (1)

Also figure (6) shows the good mixing of copper in aluminum side and the copper side is poor or no aluminum with copper just it founded in the upper portion (right hand side of the figure (6)).

In the normal conditions with similar metals joining there are tno concentration of mixing for two sides of joint due to the same material, but in case of dissimilar metals such in this work the mixing behavior is different due to the thermal and mechanical properties of the two joined metals. In this work the copper owned high melting temperature (1084^{o}C) compared to aluminum (660^{o}C) and instantaneous increasing in temperature due friction and plastic deformation during process lead to decrease the plastic resistance of aluminum more than copper. So the aluminum tends to move with tool more than copper as shown in figure (5).

Area and point EDS tests achieved as shown in figure (7) and table (2) to determine the concentration numerically of each metal. The concentration of copper in the mixing region represent 10% in most cases. Spectrum point 32 shows 100% copper because this region represents a copper chip in aluminum matrix. While point 36 and 43 represent a gap in welding joint filled later with acrylic by mounting process.

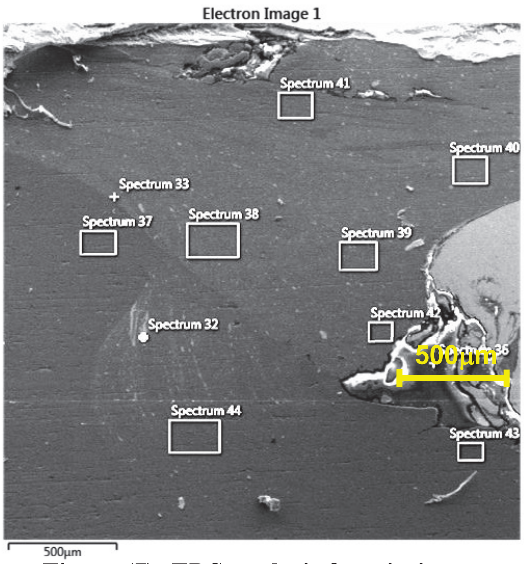


Figure (7): EDS analysis for stirring

Table (2): Chemical analysis for selected regions in different positions at friction stir

Spectrum No.	% wt. of Al	% wt. of Cu
32	0	100
33	92.1	7.9
36	Oxygen + carbon	
37	100	0
38	90	10
39	90.6	9.4
40	90.5	9.5
41	92.6	7.4
42	89.3	10.7
43	Oxygen + carbon	
44	94 + 3.5(O)	2.5
Error (б)%	0.6-1.4	0.4-0.8

Metal distribution can be divided into two regions. The upper region represents the shoulder stirring effect while the lower region (2) represents the probe stirring effect. In this work, the shoulder stirring effect is powerful and more homogenous than probe due to large contacted area compared to small probe as the tool configuration shown in figure (3). Also, it can be seen from figure (5) and figure (8) that the copper concentration in upper region more than lower region, which can be related to higher relative tangential speed of (tool - base metals).

Figure (9) represents the rectangular probe welding joint cross section, and it can be seen there are also two discrete regions (upper and lower) with the more stirring cross area and coarser copper particles in aluminum matrix.

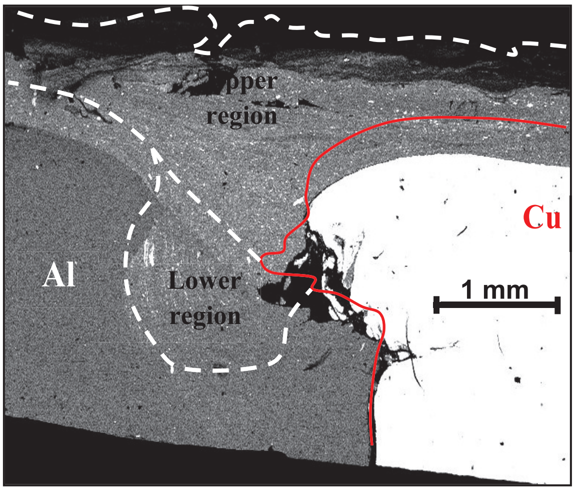
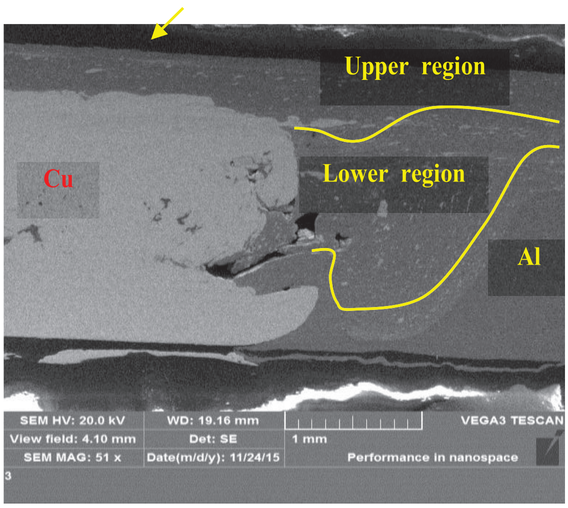


Figure (8): The FSW regions using cylindrical probe.



Figure(9): Square probe FSW effect

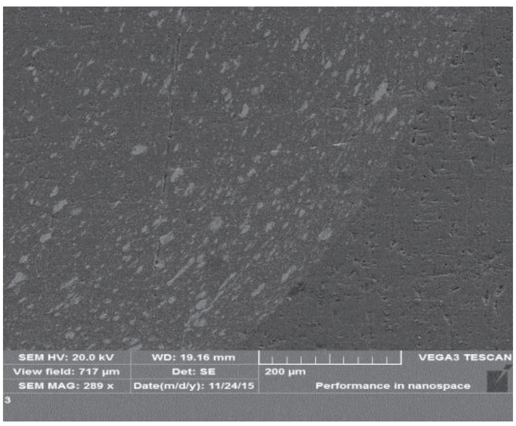


Figure (10): Interface region (Stirred-base Al).

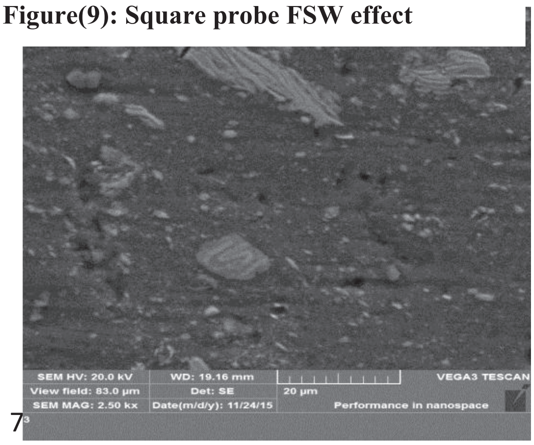


Figure (11): Distribution of stirred copper particles in aluminum matrix in region (1)

It can be seen from figure (10) there is a discrete line between stirred and aluminum base metal. This line represents a surface in a 3-dimensional perspective. By magnifying a copper particles in figure (10), it can be seen that these particles are micro-laminated (copper to aluminum) as shown in figure(12)with layer thickness less than 700 nm and very fine copper particles with grain sizes from 1 mm to 20 nm but with no Solubility between two dissimilar metals.

The generation of laminated (copper-aluminum) or named as formation of complex mixing structures with a tumultuous fluid-like morphology [7]. particles can be explained in Figure (12) which shows a boundary region denoted in the figure (9) by an arrow in upper left side. The lamination process begins at the copper surface and during the stir time a small chip separated as shown in figure (11) and floated in aluminum matrix.

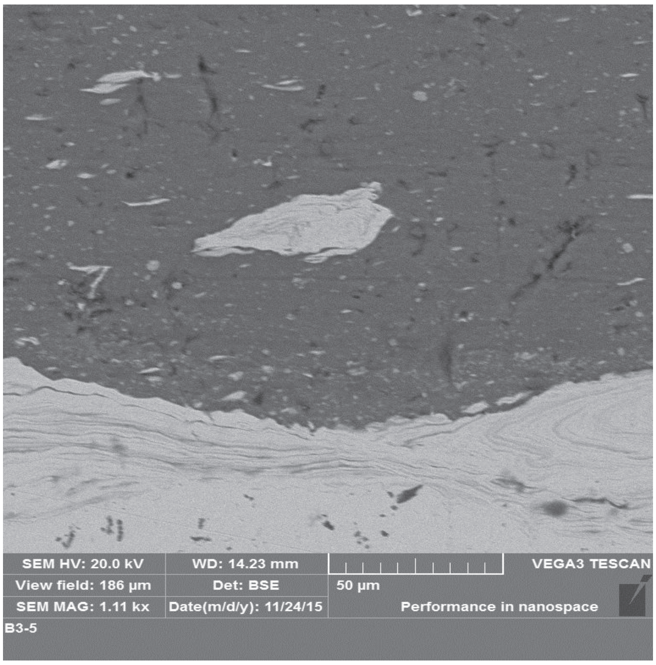


Figure (12): generation of laminated (copper-aluminum) particles

Conclusion:

From the results mentioned above, it can be concluded that:

1- The square probe gives strengthen joint than a cylindrical probe tool.

2- There are two recognized regions, the first one is the region generated due to stir effect on the shoulder area of the tool and the second region is generated from the stir effect of the probe.

3- The lower melting point metal stirred more than higher melting point metal due to annealing effect.

4- No solubility between the two metals.

6- The laminated regions form is concentrated in the strongest metal side and the particulate form is foundon the weaker metal side.

Recommendations:

1- Shift the tool path toward the copper side.

2- Simulate the process numerically to compare the results with experimental processes.

3- Change the probe shape to a threaded design and observe the metal flow behavior.

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