

Increasing FSW join strength by optimizing feed rate, rotating speed and pin angle

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Abstract. Principally the join in Friction Stir Welding (FSW) is formed due to mechanical bonding. At least there are two factors determines the quality of this join, first is the temperature in the area around the interface and secondly the intense of mixing forces in nugget zone to create the mechanical bonding. The adequate temperature creates good flowability of the nugget zone and an intensive mixing force produces homogeneous strong bonding. Based on those two factors in this research the effects of feed rate, rotating speed and pin angle of the FSW process to the tensile strength of resulted join are studied. The true experimental method was used. Feed rate was varied at 24, 42, 55 and 74 mm/minutes and from the experimental results, it can be concluded that the higher feed rate decreases the tensile strength of weld join and it is believed due to the lower heat embedded in the material. Inversely, the higher rotating speed increases the join's tensile strength as a result of higher heat embedded in base metal and higher mixing force in the nugget zone. The rotating speed were 1842, 2257 and 2904 RPMs. The pin angle determines the direction of mixing force. With variation of pin angle: 0°, 4°, 8° and 12° the higher pin angle generally increases the tensile strength because of more intensive mixing force. For 12° pin angle the lower tensile strength is found since the force tends to push out the nugget area from the joint gap.

1. Introduction

Recently, in the name of efficiency, metals with high strength to weight ratio are more preferable [1,2]. One of the prospective candidate is aluminum, which has strength to weight ratio higher than steel the most commonly used metals today. The drawback of the aluminum is its low weldability in term of fusion welding [3]. On the other hand, the welding institute (TWI) developed solid state welding, such as friction welding and FSW [4,5]. Basically, FSW mechanically joins two piece of metals in the same manner of unifying two lumps of clay. Hopefully this solid state welding fills the gap of aluminum low weldability.

Figure 1 shows how FSW is applied. The heat obtained from friction between tool and workpiece increases temperature, especially in the area close to the interface. Around 90% of heat is obtained from friction between shoulder and workpiece, while 5% is attained from the probe (pin) and the rest is collected by plastic strain developed in the base metal [6].



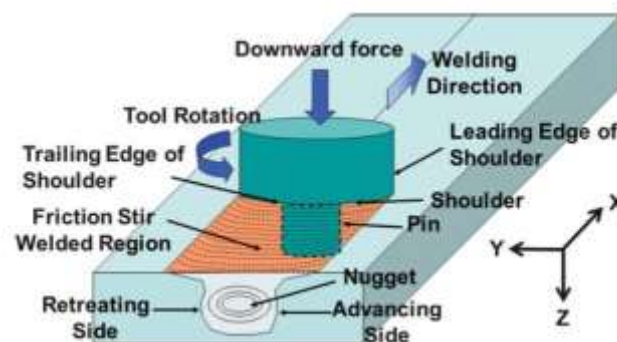


Figure 1. Schematic of FSW process [7].

In FSW process are developed five region types as shown in figure 2, those are: nugget zone, thermo-mechanically affected zone (TMZ), heat affected zone (HAZ), flow arm and base metal (BM) [8, 9]. The heat certainly increases the temperature in the base metal and this increased base metal temperature forms nugget zone, which can be analogized by a lump of clay. Nugget zone, also known as stirred zone or dynamically recrystallized zone (DRZ), can be identified by the presence of fine equiaxial grain when the FSW process has been completed. The stirred zone refers to the area where the pin movement has direct effects. The pin movement causes high temperature, strain and deformation which lead to grain recrystallization. It was found that this new grain is finer than initial base metal. Since the recrystallization is due to plastic deformation it is called as DRZ [7, 10]. The mixing forces due to friction, centrifugal and centripetal forces act as forces to mix two lumps of clay. With this mixing forces in the nugget zone, finally mechanical bonding is formed.

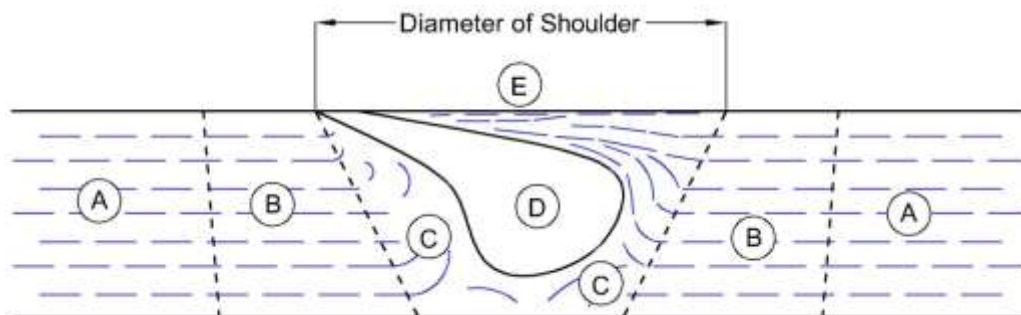


Figure 2. Schematic cross-section of a typical FSW weld: (A) base metal, (B) heat affected zone, (C) thermo mechanically affected zone, (D) nugget Zone and (E) flow arm [9]

The friction tool and its component clearly are the most important instrument in FSW process. In figure 3 is shown the friction tool and nomenclature of its element. Dimensions of tool's element which was used for this research are also attached and all measurements are in mm.

Considering the principle of how mechanical bonding is formed in FSW, it is plausible to consider feed rate, rotating speed and pin angle as important parameters that influence the quality of the joint. With a different feed rate while other parameters are constant varied heat is embedded in the base metal which creates different volume and temperature distribution of nugget zone. Variations on rotating speed determine the amount of heat and the value of forces. These forces mix the nugget area and creates mechanical bonding. Since forces as a vector are not only determined by its value, but also its direction, the pin angle influences the mechanical bonding by means of alternating the force's direction. In short, it can be said that, the objective of this research is observing the effect of feed rate, rotating speed and pin angle to the final resulted joint's strength (i.e. tensile strength).

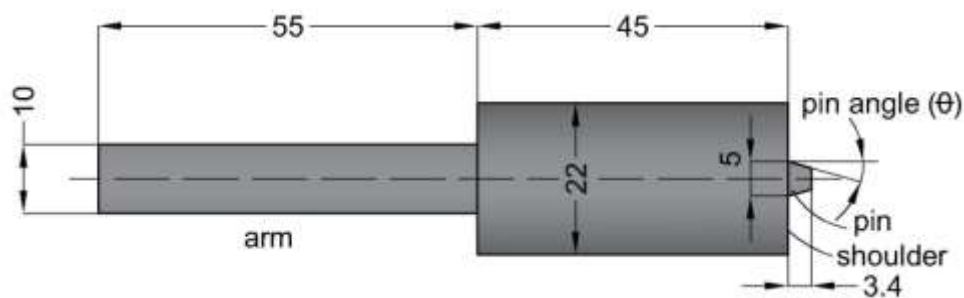


Figure 3. The nomenclature of friction tool and its dimensions

2. Experiment set up

There are three ways to understand a phenomenon, especially welding: analysis, modelling and experiment [11, 12]. Those methods enhance each other. This paper discusses true experiment method of FSW phenomenon. The experiment was carried out in Manufacturing Processes Laboratory of Mechanical Engineering, Brawijaya University. The FSW was performed on modified vertical milling machine. The feeding speed was varied using the available variation which is provided by the machine, those are: 24, 42, 55 and 74 mm/minute. The rotating speed was determined by belt and pulley installation and the provided rotating speed are: 1842, 2257 and 2904 rpm. Tools were made from EMS 45 hardenable tool steel. After pin, shoulder and arm have been formed from rod steel using turning machine the tool was hardened. For practical production reason the pin angle was varied at 0° , 4° , 8° and 12° . These angles were considered will give enough data to know the effect of pin angle on join's strength. In figure 4 is shown the tools before they are hardened. The hardening was done by heating the tools in furnace up to 1100°C and suddenly quenched in oil. After the tool cooled down to room temperature the tempering was applied by heating the tool in furnace up to 300°C and naturally cooled down to room temperature by exposing the tool in ambient temperature.



Figure 4. Friction tools with varied pin angle, from left: 0° , 4° , 8° and 12°

The base metal is a commercial A1090 Aluminum sheet with thickness equal to 3.5mm. First, the sheet is cut in a 70mm x 125mm rectangular, then friction stir welded on the 70mm side as shown in figure 5. How the FSW was carried out on milling machine is shown in figure 6.

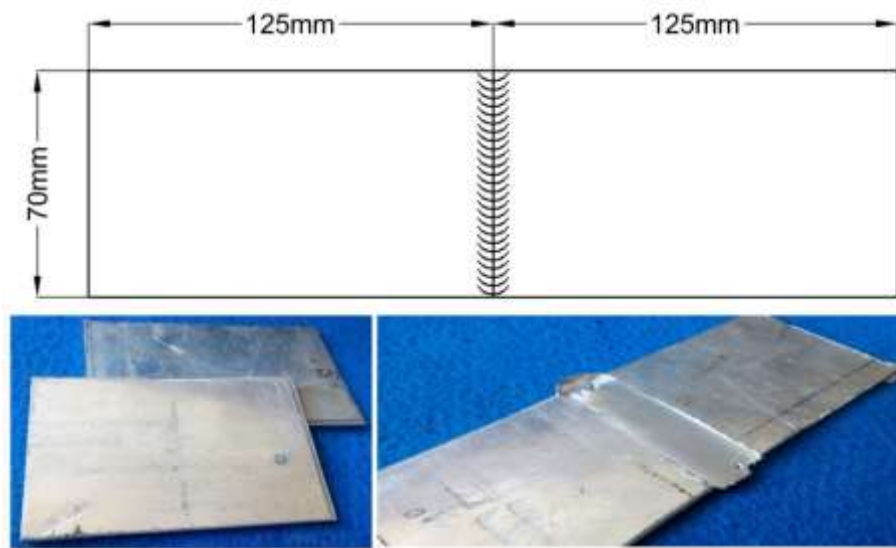


Figure 5. Aluminum plate as friction stir welded

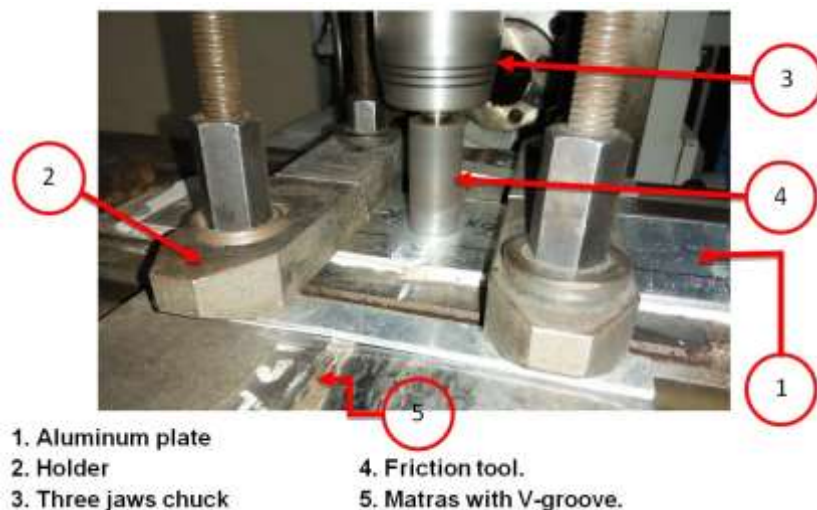


Figure 6. Aluminum plate as friction stir welded

After the join has been formed the welded sheet was cut as a tensile specimen following AWS B4.0; 2007 as shown in figure 7. The tensile specimen, then is attached at Kai Wei universal testing machine to obtain ultimate tensile stress. These ultimate tensile stress for alternated parameters (feed rate, rotating speed and pin angle) which are considered to have significant influence on quality of resulted join, then tabulated and presented in graphics.

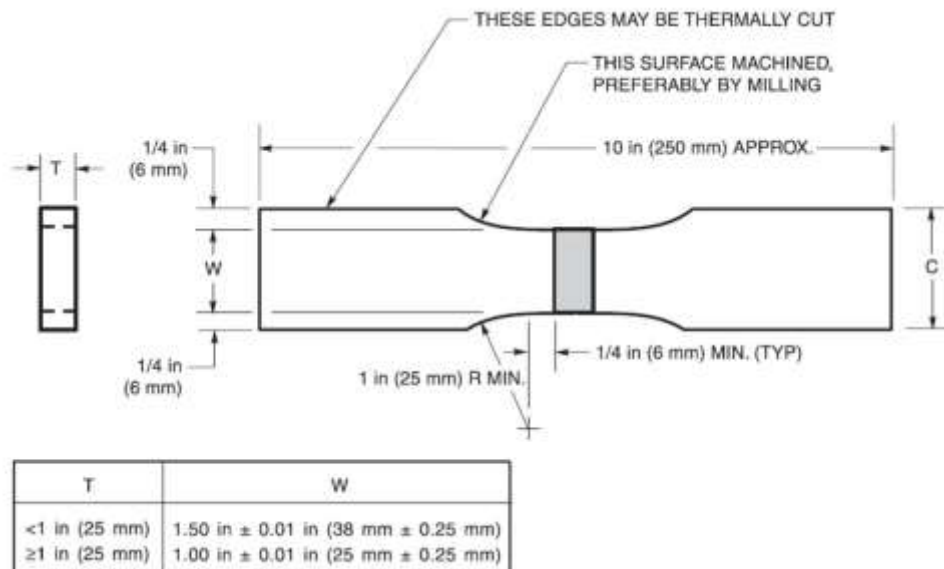


Figure 7. Tensile test specimen

3. Results and discussion

Table 1 shows the results for varied feed rate (24, 42, 55 and 75 mm/minute) with rotating speed equal to 1842, 2257 and 2904 rpms. The numbers in table 1 are presented in graphic as shown in figure 8. figure 8 shows normalized ultimate tensile strength for the miscellaneous parameters means the obtained tensile strength are compared to base metal ultimate tensile strength and presented in percent. The tensile strength of the FSW join for sundry parameters is below a hundred percent.

The maximum tensile strength is equal to 89.81% for specimen no. 3 which is obtained for feed rate equal to 24 mm/minute and rotating speed is 2904 rpm. As it is expected, the higher feed rate decreases the ultimate tensile stress. The lower feed rate means higher heat produced by friction force is embedded in the base metal which in turn increases ultimate tensile stress. In contrast, the embedded heat to the base metal is proportionate to the rotating speed means with higher rotational speed the bigger heat is embedded into base metal. On the other hand, higher rotating speed also means higher centrifugal and centripetal force. These forces analogous to mixing force of joining two lumps of clay and with higher centrifugal and centripetal forces better mechanical bonding will be produced. These two reasons, higher heat and forces, together contribute to higher ultimate tensile strength of the resulted FSW join. The second order polynomial for regression lines also attached in figure 8. For 1842 rpm the regression line follows the expression: $0.003f^2 - 0.978f + 101.3$ (%) with f is feed rate. The R^2 for the line is 0.952 which means the expression can very well represent the data. For 2257 rpm the mathematical expression for regression line and the value of R^2 are $0.006f^2 - 1.231f + 110.8$ (%) and 0.988 respectively again describes the equation very well represents the data. For 2904rpm the equation for normalized ultimate strength and R^2 are $0.007f^2 - 1.21f + 113.3$ (%) and 0.999 respectively. The R^2 describes the equation well match the data.

Table 1. The resulted ultimate tensile strength for varied feed rate.

No.	Feed rate (mm/min)	Rotating speed (rpm)	Spec	σ_{ult} (MPa)	Means (MPa)
1	24	1842	1	55.14	59.21
			2	58.36	
			3	64.14	
		2257	1	65.43	63.55
			2	59.86	
			3	65.36	
		2904	1	65.21	66.36
			2	66.50	
			3	67.36	
2	42	1842	1	51.32	52.54
			2	51.89	
			3	54.41	
		2257	1	54.84	54.43
			2	52.64	
			3	55.82	
		2904	1	55.14	56.83
			2	57.71	
			3	57.64	
3	55	1842	1	38.50	40.98
			2	46.14	
			3	38.29	
		2257	1	46.43	46.33
			2	44.64	
			3	47.93	
		2904	1	49.64	51.57
			2	52.07	
			3	53.00	
4	74	1842	1	38.50	36.76
			2	35.21	
			3	36.57	
		2257	1	42.14	42.57
			2	43.57	
			3	42.00	
		2904	1	47.14	48.10
			2	48.43	
			3	48.71	
Base metal					75MPa

Table 2 shows the result for various pin angles (0° , 4° , 8° and 12°) with rotating speed equal to 1842 and 2257 rpms. The maximum ultimate tensile strength is 70.52 MPa for specimen 1 with pin

angle 8° and rotating speed 2257 rpm. For rotating speed equal to 1842 rpm the maximum ultimate tensile strength is 61.98 MPa for specimen 3 with pin angle again equal to 8° .

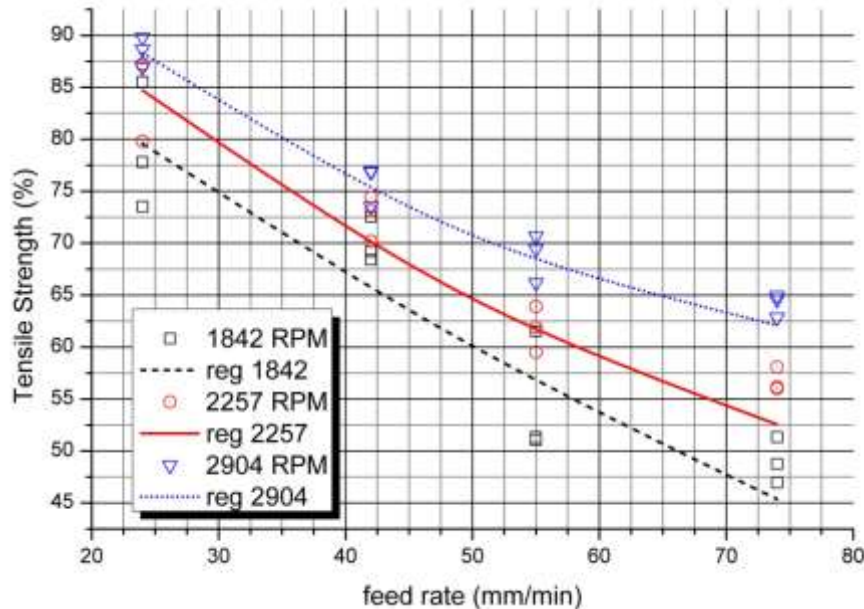


Figure 8. The effect of feeding speed on ultimate tensile strength

The numbers in table 2 are presented in a graphic as shown in figure 9 in which the ultimate strength is presented as normalized strength. The third order polynomial for regression line also included. For 1842 rpm the normalized tensile strength can be expressed as pin angle $-0.150^3 + 1.9840^2 - 5.0120 + 70.05$ and for 2257 rpm the normalized tensile strength is $-0.1970^3 + 2.7310^2 - 6.9840 + 72.5$. The ultimate tensile strength for specimen 1 with pin angle 8° and rotating speed 2257 rpm in figure 9 is presented as normalized strength: 94.02% whilst for specimen 3 with rotating speed equal to 1842 rpm and the 8° pin angle is 82.64%. As previous results (figure 8), the higher the rotating speed also yields stronger FSW join. Pin without angle (0°) generates lower ultimate tensile strength of FSW join. Pin with angles exhibits more complex force's direction that mixes the nugget zone more intensive as shown schematically in figure 10. This intensive force generates more homogeneous and stronger mechanical bonding. Generally, the pin angle increases the resulted tensile strength.

However, the 12° pin angle generates lowest tensile stress. As shown in figure 10 the higher pin angle tends to push the nugget zone downward. This phenomenon may cause a part of nugget zone is pushed out of the bonding area, especially if the pin angle is too high (12°). The macro photos of 8° and the 12° cross section as shown in figure 11 proved this assumption. Since a part of the nugget zone for 12° is driven out of bonding area, small holes found in the joint area which in turn severely decrease the ultimate strength of the FSW join.

Table 2. The resulted ultimate tensile strength for varied pin angle.

No.	pin angle	Rotating speed (rpm)	Spec	σ (MPa)	means (MPa)
1	0°	1842 rpm	1	51.32	52.54
			2	51.89	
			3	54.41	
		2257 rpm	1	54.84	54.43
			2	52.64	
			3	55.82	
2	4°	1842 rpm	1	53.07	54.10
			2	53.80	
			3	55.41	
		2257 rpm	1	56.68	56.79
			2	55.74	
			3	57.94	
3	8°	1842 rpm	1	58.76	59.93
			2	59.04	
			3	61.98	
		2257 rpm	1	70.52	67.86
			2	64.75	
			3	68.31	
4	12°	1842 rpm	1	28.55	26.69
			2	25.31	
			3	26.21	
		2257 rpm	1	29.99	30.81
			2	31.35	
			3	31.09	
Base metal					75MPa

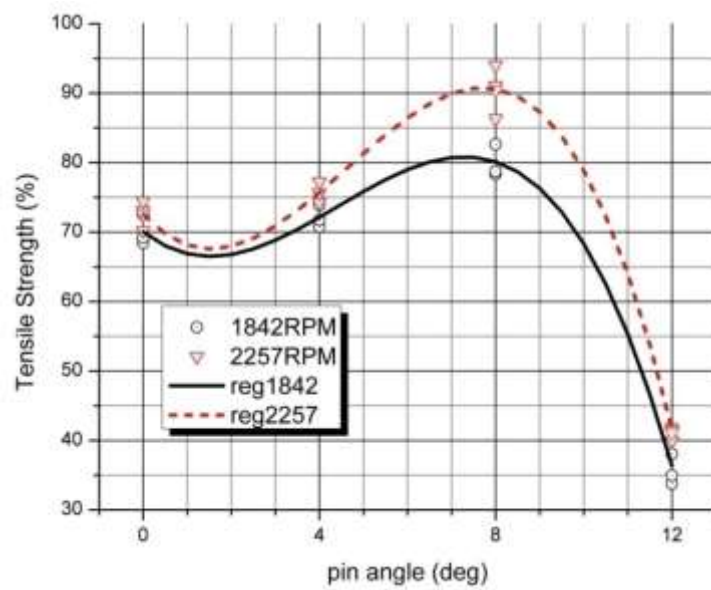


Figure 9. The effect of pin angle on ultimate tensile strength

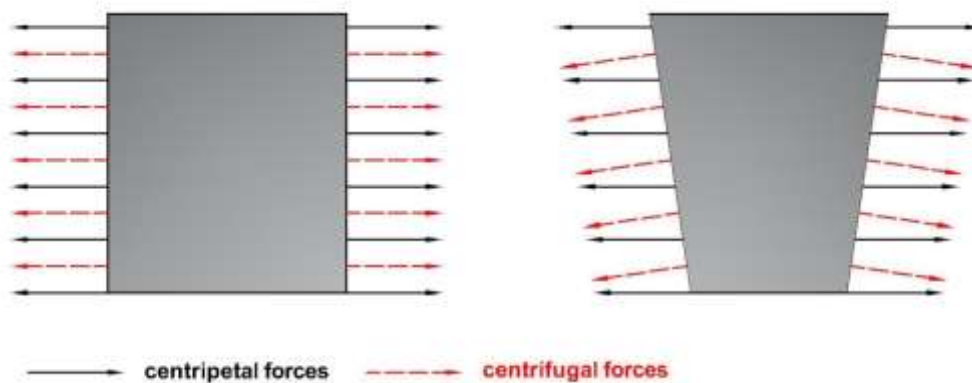


Figure 10. Force vectors for a pin without angle (left) and with angle (right)

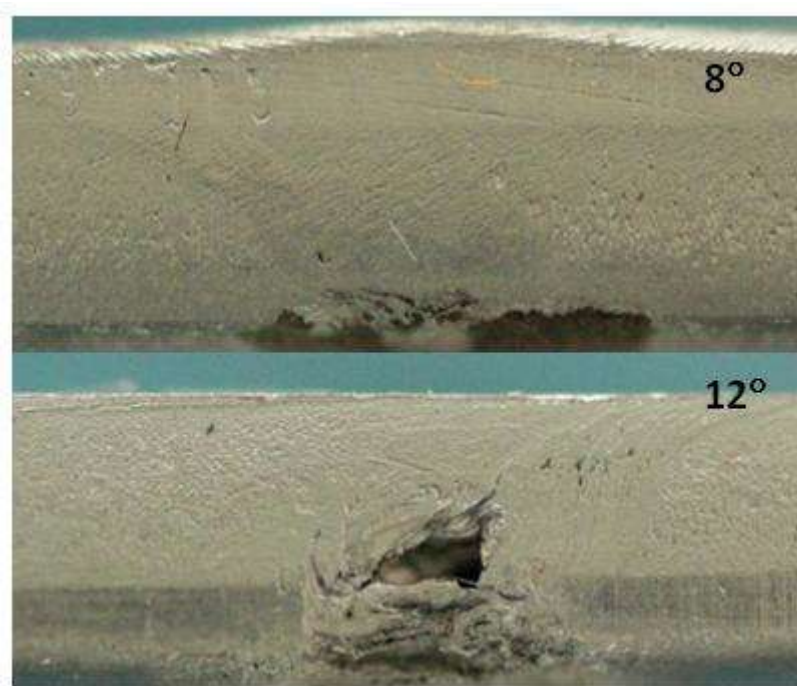


Figure 11. Macrophoto for 8° and 12° cross sections

4. Conclusions

Two factors determine the quality of FSW join are temperature and force. In terms of temperature, the feed rate and rotating speed have significant influence on resulted ultimate stress of FSW join. Lower feed rate and higher rotating speed increase the joint strength. The rotating speed also increases the value of centrifugal and centripetal forces whilst the pin angle determines the direction of centrifugal force. With the increasing value of forces the strength of the FSW will be improved. With higher pin angle, a better joint strength is provided. This phenomenon is correct for pin angle up to 8° since 12° pin angle drives out nugget zone cause holes in join area which in turn decreases tensile strength of the FSW join.

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