Tensile shear strength and dynamic mechanical analysis of 6063 aluminium alloy and 304 stainless steel by spot welding

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Abstract: Mechanical properties of dissimilar metal of spot welding were tested and analyzed based on the variation in welding currents and welding times. From visual observation, the largest weld nugget recorded was 7.43 mm at 5 kA, meanwhile the smallest was 6.4 mm at 3 kA. It was found that weld nugget size increase with the increment of weld current and extension of weld time. Based on tensile result, the largest weld nugget size of 7.43 mm produced the highest tensile strength, 31.99 N/mm^2 mean while the smallest weld nugget 6.4 mm produced 29.40 N/mm^2. The results show that weld nugget size affect the tensile shear strength, and with the increment of weld current and extension of welding time, tensile shear strength increase. Dynamic mechanical properties defined the storage modulus, loss modulus and damping capacity of dissimilar metal spot welded. It was found that at 10 Hz frequency between 70°C to 350°C, with heating rate of 10°C/minute, the storage modulus increase with increment in weld current and the extension of weld time to 8 s. Meanwhile the loss modulus decrease with the increased of weld current and weld time. Same pattern happen to damping capacity, the value dropped with the increases of welding current and welding time.

Keywords: spot welding, dissimilar metal, 6063 aluminium alloy, 304 stainless steel, dynamic mechanical analysis.

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Introduction

Dissimilar metal welding is where both metal use for welding is different from the compositions or thickness. There's is a few disadvantages of aluminum and stainless steel dissimilar welding due to the clear difference between the aluminum and stainless steel sheets melting points and weldability between these two metals. Spot welding is often use because of the advantages such as low manufacturing cost and the probability to reduce the operations costs [1]. The process of dissimilar metal spot welded used extensively to join low carbon steel components, high strength low alloy steel, stainless steel, nickel, aluminium, titanium, copper alloys [2]. Spot welding make the changes in metallurgical and mechanical properties of the spot welded area and heat affected zone [3]. Dissimilar welded joint have some complex issue because of the large difference in physical and thermal properties and will cause defect in weldment [4]. Damping capacity (tan φ) used to measure material's ability to dissipate elastic strain energy during mechanical vibration or wave propagation [5]. The objective of this finding are to study the tensile strength and dynamic mechanical properties of 6063 aluminium alloy and 304 stainless steel by spot welding.

Experimental procedures

The raw materials were 6063 aluminium alloy and 304 stainless steel with thickness of 0.36 mm and 1.00 mm respectively. Lap joint are the common weld joint for spot welding other than T-peel joint or corner joint. In this study, lap joint were used according to the AWS C 1.1 standard for spot welding procedure. The sample were cut with the dimension of 130 mm length and 30 mm width. The dimension of the sample were shown specifically in Table 1.0.

Table 1: Dimension of the spot welding specimen.

Material	Dimension, mm		
	Length	Width	Thickness
6063 aluminium alloy	130	30	0.36
304 stainless steel	130	30	1.00

Welding process requires the essential detail such as welding parameter. In this study the welding parameters were varied in term of welding currents and welding times, while the other parameters were fixed such as electrode forces, (1.8 kN) and welding cycles(10 cycles). The welding parameters used were shown in Table 2 and welding joint (lap joint) design was shown in Figure 1.

Table 2: Welding parameters of spot welding.

Parameter		Welding time, s	Overlap, mm
Welding current, kA	3	6	30
		8	
	4	6	30
		8	
	5	6	30
		8	

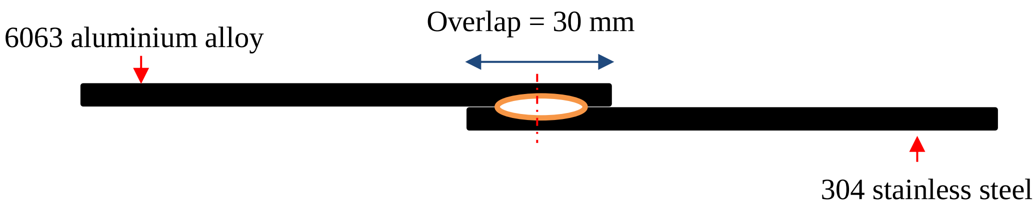


Figure 1: Design optimization for lap joint spot welding

Weld nugget is a crucial part in spot welding, the strength of spot weld joint highly depends on the weld nugget quality. The quality of weld nugget can be determined by its size or diameter. In this study sizes of weld nugget were measured using vernier caliper and ruler. The differences of weld nugget surface or indication between 6063 aluminium alloy and 304 stainless steel were observed.

The tensile properties of any weld joint was determined by tensile test. In this study, tensile shear strength was influenced by the variations of weld nugget sizes. The testing were conducted according to AWS C 1.1 standard with the specification of sample dimension as shown in Table 1.0 using the universal testing machine (UTM Instron, 5569 model) at cross head speed of 1 mm/minute.

Dynamic mechanical analysis

Dynamic mechanical properties were determined by using the dynamic mechanical analyzer (DMA). The dimension of dynamic mechanical analysis sample were shown in Table 3 and were cut using shear machine. The thickness of the raw material must be reduced, therefore grinding machine were used to reduce the thickness of the sample, the detail shown in Table 4.

Table 3: Dynamic mechanical analysis specimen dimension

Material	Dimension, mm		
	Length	Width	Thickness
6063 aluminium alloy	50	10	0.36
304 stainless steel	50	10	0.55

Table 4: Details of specimen thickness reduction using grinding machine

Material	Original thickness, mm	Desired thickness, mm	Remarks
304 stainless steel	1.00	0.55	Thickness were reduced by 0.45 mm using sand paper (grits 80) with 200 rotations per minute.
6063 aluminium alloy	0.35	0.35	N/A

Dynamic mechanical analysis test was performed using 3 point bending mode. The specimen were heated up at 10°C/minute from 70°C - 350°C at 10 Hz frequency.

Results and Discussions

Weld nugget quality

Weld nugget size were measured and recorded, and were categorized by welding current and welding time. Table 5 shows the weld nugget diameter changes with the changes of welding parameter. It was found that weld nugget sizes increased with the increases of weld currents and weld times accordingly. The largest weld nugget recorded was 7.45 mm at weld current of 5 kA, welding time of 8 s and the smallest weld nugget was 6.4 mm at weld current of 3 kA and welding time of 6 s.

Table 5: Weld nugget diameter for (a) tensile test specimen and (b) dynamic mechanical analysis specimen

No	***Parameter***		***Diameter (mm)***
	Current, kA	**Time, s**	
1	3	6	6.40
2	3	8	6.78
3	4	6	6.95
4	4	8	7.11
5	5	6	7.27
6	5	8	7.43

(a)

No	***Parameter***		***Diameter (mm)***
	Current, kA	**Time, s**	
1	3	6	6.42
2	3	8	6.53
3	4	6	6.93
4	4	8	7.02
5	5	6	7.18
6	5	8	7.45

(b)

The increment of weld current let more current pass through the welded area and consistently generated the heat around the weld nugget area (welded area) that melt both metal and fused together. The major factor that affect the weld joint strength and shear strength is the weld nugget diameter (fusion zone of spot welded). In some cases the weld nugget diameter decreased due to the excessive melting and splashing in the welding zone if the weld current or weld time area larger than it is critical value [10].

Figure 2(a) shows the weld nugget surface on the aluminium alloy side while Figure 2(b) shows the side of stainless steel at weld current of 3 kA. The surface show that weld nugget does not fully in oval shape, which is the normal shape for the weld nugget in spot welding. This may happened due to the short welding time or inappropriate cooling time. Non-round weld may occur when the weld current is low or short welding time [9]. The weld defect of non-round weld happen on both side of dissimilar metal.

In Figure 2(c) the surface of weld nugget at 5 kA of weld current and the weld nugget surface on 6063 aluminium alloy side show the oval shape of weld nugget. It consider as good weldability and heat transfusion. Figure 2(d) shows the surface of weld nugget at 5 kA of weld current and the weld nugget surface on 304 stainless steel side show that there is missing weld, and it reconsider due to poor and varying fit up [9] but it also may happened due to the differences of melting temperature between both dissimilar metal, therefore it consider as poor heat input through the 304 stainless steel.

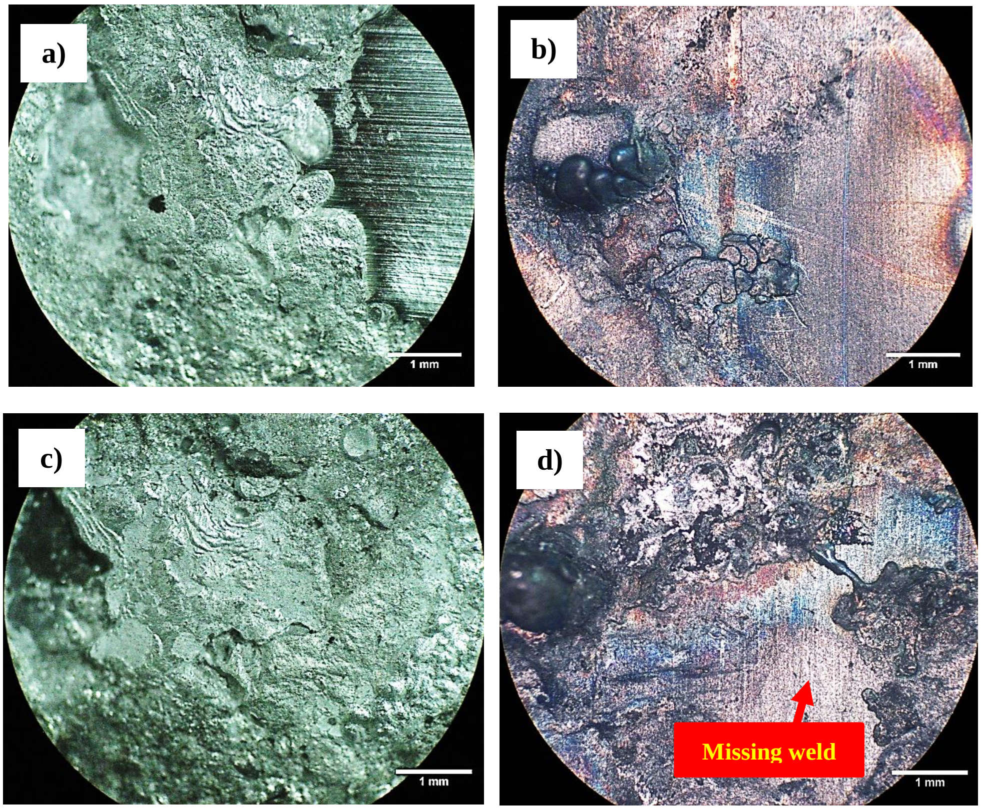


Figure 2: Macrographs of weld nugget surface on (a) & (c) 6063 aluminium alloy (b) & (d) 304 stainless steel with 50x magnifications.

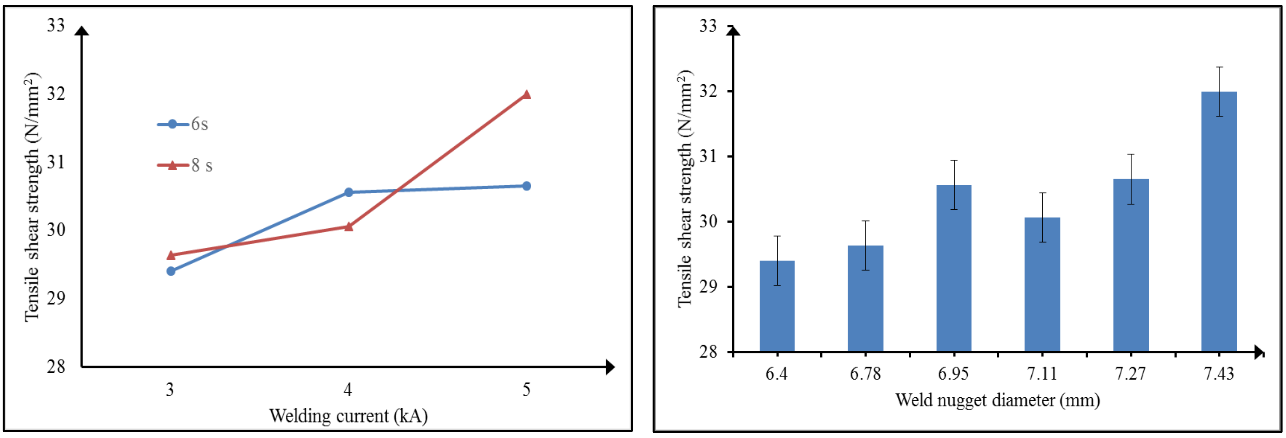
Tensile shear strength

There were different effects of weld current and weld nugget size on tensile shear strength, the graphs show every differences of each welding parameter. The cross section area in the table shows the cross section area of the weld nugget, which the diameter of weld nugget times by the thickness of dissimilar metal spot welded, (weld nugget diameter x 1.36 mm).

Table 6: Tensile shear strength of dissimilar metal spot welded.

Welding parameter		**Max load (N)**	**Diameter (mm)**	**Cross section area (mm^2)**	**Tensile shear strength (N/mm^2)**
Current, kA	**Time, s**				
3	6	255.88	6.40	8.70	29.40
3	8	273.16	6.78	9.22	29.63
4	6	288.00	6.95	9.45	30.56
4	8	290.67	7.11	9.67	30.06
5	6	303.08	7.27	9.89	30.65
5	8	323.11	7.43	10.10	31.99

Figures 3(a) shows the different of weld current resulted in different tensile shear strength, the increasing of weld current proportionally increase the tensile shear strength of the weld joint. The lowest average tensile strength of dissimilar metal spot welded recorded was 29.40 N/mm^2 at weld current of 3 kA for 6 s and the highest average tensile strength was 31.99 N/mm^2 at 5 kA for 8 s. The result showed that the tensile shear strength increased proportionally with welding current and improvement of tensile shear strength of the joint are due to the enlargement of weld nugget size. Figure 3(b) shows the raised up pattern of tensile shear strength with the increases of weld nugget size. The raised up pattern shows tensile shearing load bearing capacity increase with the increment of peak current are influence by the enlargement of weld nugget size. During the spot welding process, when the current was switched off, the melting metal solidified under the pressure of electrode force. In this process, stress hardening take places in the welding zone due to the rapid cooling of weld metal [8, 12].



(a) (b)

Figure 3: Graph of (a) tensile strength over welding current varies with weld time (b) tensile strength over weld nugget diameter.

The fracture analysis of weld nugget between dissimilar metal have to be reconsider to observe the crack initiations that occur with the welding type. Figure 4 shows the weld joint at 4 kA and 8 s, the tear called as button pull out or tearing fracture (TF) [7]. This tear occur when the weld joint has good bonds or weld joint between sheets, so it requires high tensile strength or load to break the joint. Metal sheet separation is one of the factors that influence the spot welding quality happen at surface due to the expansion and contraction on the weld nugget.

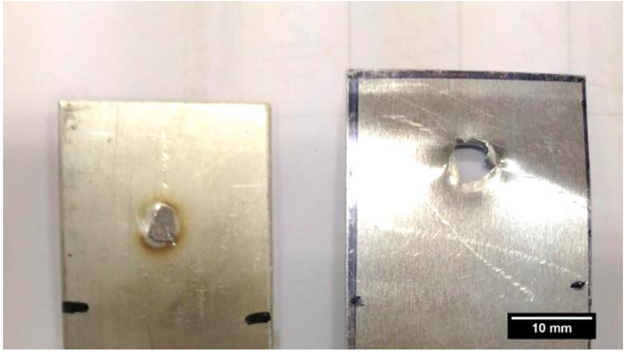


Figure 4: Image of tensile test sample after fracture (weld current = 4 kA, weld time = 8 s).

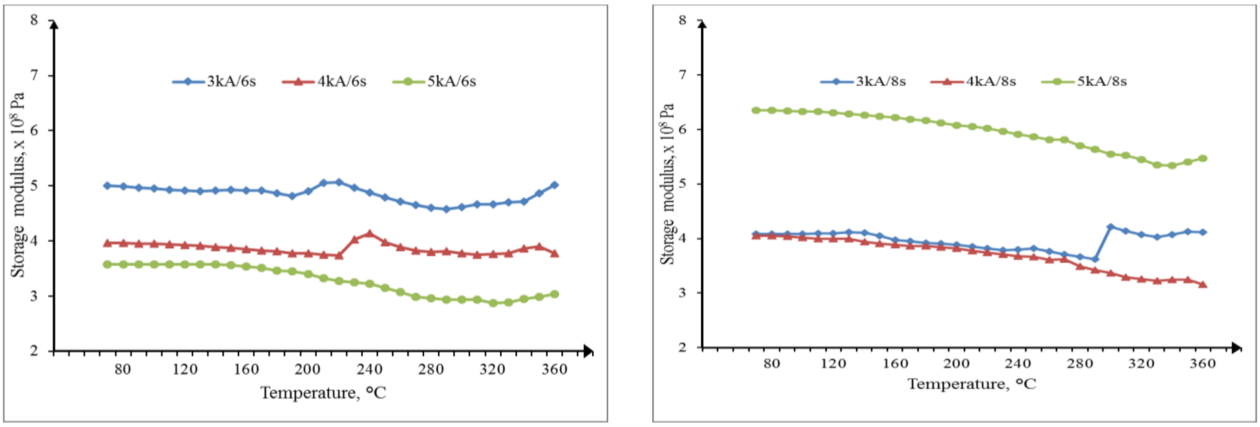
Dynamic mechanical properties

Dynamic mechanical analysis was used to analyze the dynamic mechanical properties of dissimilar metal spot welded. Temperature range during the analysis was from 70°C to 350°C and the heating rate was 10°C /min. The frequency used was 10 Hz.

Storage modulus and loss modulus of weld joint

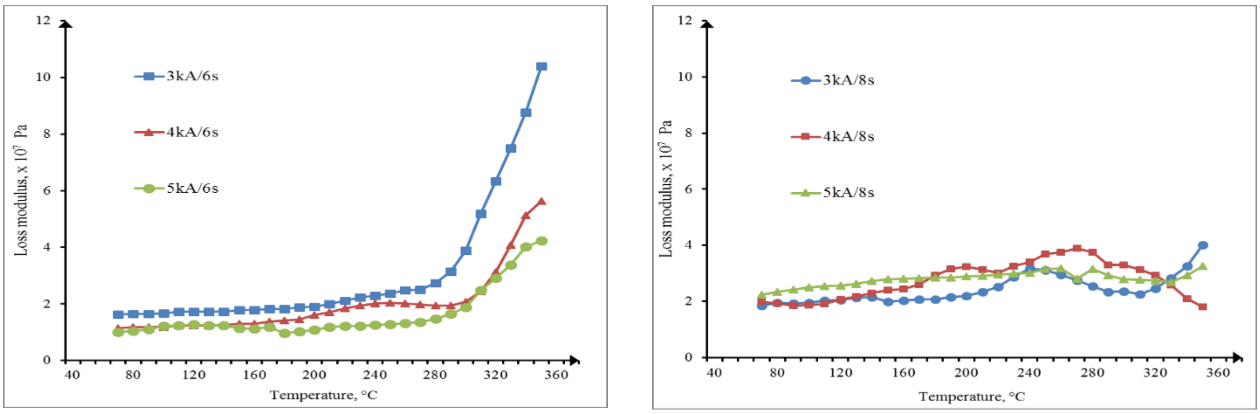
Figure 5 shows the storage modulus as function of temperature with various welding current and welding time. The increment of storage modulus show that storage modulus increased with the increment of weld current due to the enlargement of weld nugget. The storage modulus at 5 kA is more stable than 3 kA of weld current. From the observation, it can be concluded that enlargement of weld nugget size effects the storage modulus of dissimilar metal spot welded. At 3 kA and 4 kA between 210°C to 350°C, it can be observed that sample for 8 s have lower storage modulus value which were between 458 MPa to 506 MPa for weld current 3 kA, while at weld current 4 kA, the storage modulus value between 374 MPa to 414 MPa. From the observation at Figure 5, it can be concluded that storage modulus decreased with the increment of weld current and extension of weld time.

Figure 6 shows the loss modulus of temperature with various welding parameters at frequency of 10 Hz. As plotted in Figure 6, the loss modulus increased proportional to the temperature and at certain temperature and welding parameter the loss moduli dropped drastically. It was observed that between temperatures 70°C to 150°C, the loss modulus for all welding parameter were around 15.9 MPa to 27.9 MPa. At 5 kA and 8 s, the loss modulus increase from 18.6 MPa to 74.1 MPa while at 3 kA and 6 s the modulus increase from 11.8 MPa to 135 MPa. At the lowest weld parameter, 3 kA, the loss modulus start with low loss modulus, but end with the highest loss modulus, 135 MPa, but at the highest weld parameter, 5 kA, the loss modulus start with highest modulus and end lower than weld current 3 kA.



(a) (b)

Figure 5: Graphs of storage modulus of dissimilar metal spot welded at (a) 6 s and (b) 8 s of weld time, varies with weld current at 10 Hz frequency.



(a) (b)

Figure 6: Graph of loss modulus of dissimilar metal spot welded at weld times of (a) 6 s and (b) 8 s at 10 Hz frequency with the variation of welding currents.

Figures 7(a) to 7(c) show that loss modulus increase with the increment of temperature and loss modulus reduced with the extension of welding time. From Figure 2.15(a) it can be observed that at 240°C the loss modulus of 8 s weld time raised up to 31.8 MPa before it drop to 22.6 MPa at 310°C and drastically raised up again to 69 MPa at 390°C. It was the same curve with the current of 4 kA and 5 kA, it show the same pattern with different welding time.

Figure 7(a), shows the graph of loss modulus between 6 s and 8 s welding time start to overlap at 280°C, and the value for the loss modulus are 22.2 MPa. While Figure 7(b) shows the interception of loss modulus graph of 4 kA at 310°C with 30 MPa of loss modulus. It show that with the increment of current and the extension of welding time, the loss modulus has dropped slower than at lower current and time. It can be concluded that the extension of welding time reduces the loss modulus of weld nugget. Loss modulus increased at final temperature when then reduction of dislocation energy occur and lead to the dissipation of energy in material easily [8].

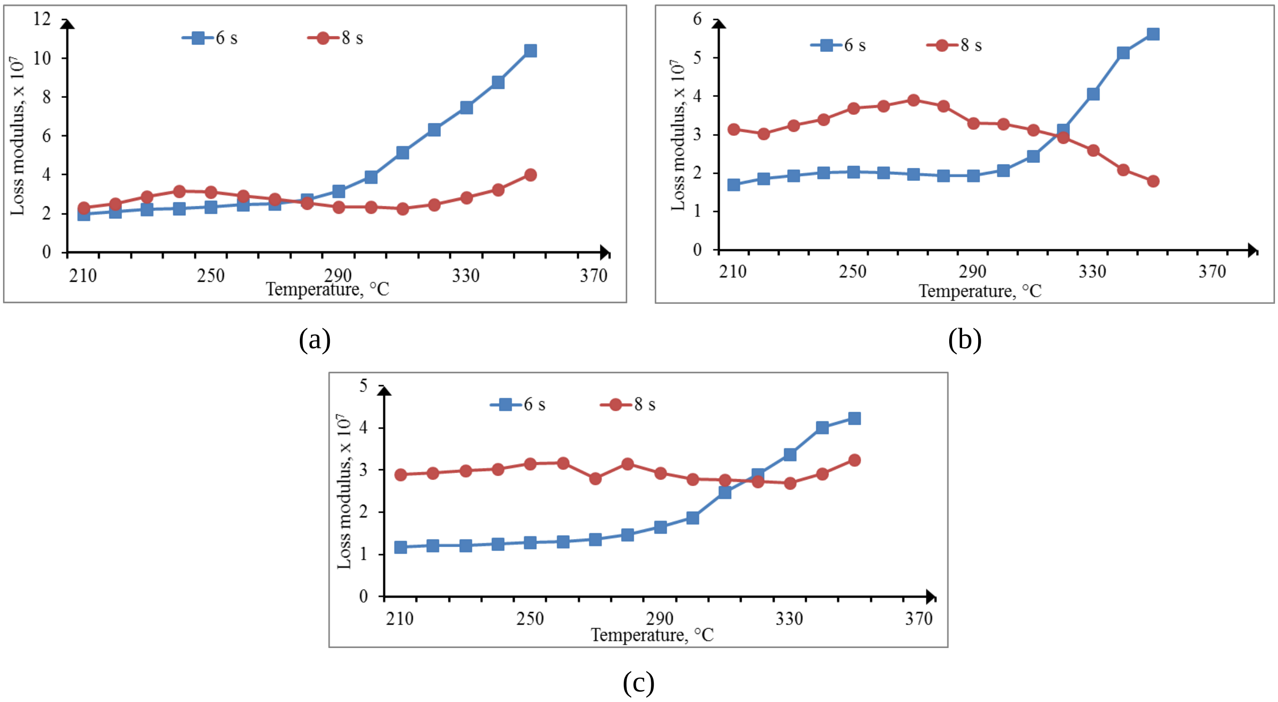
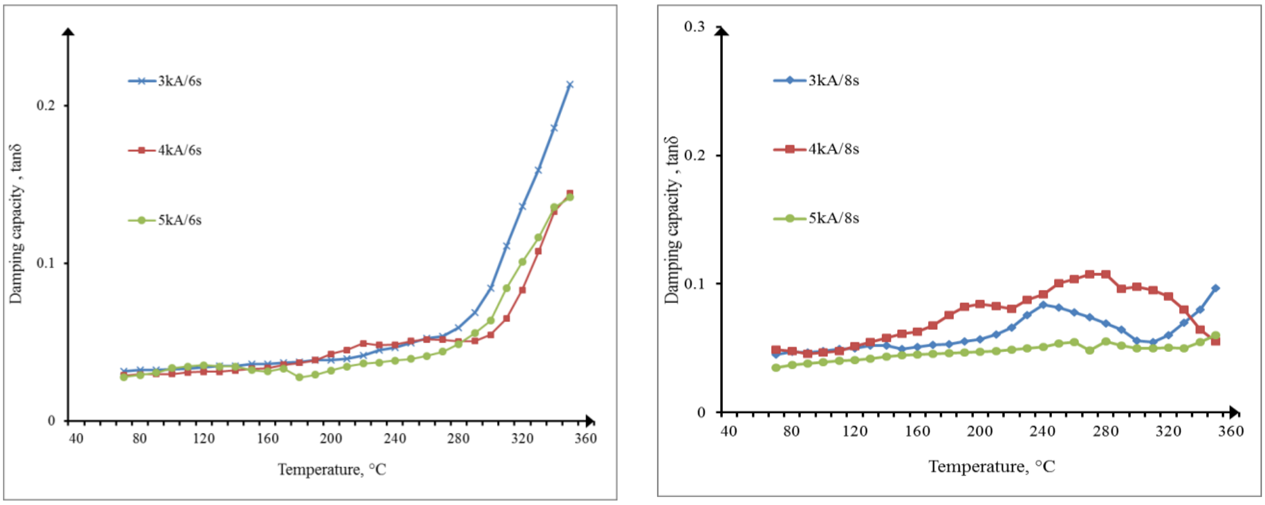


Figure 7: Graph of loss modulus at weld currents of (a) 3 kA, (b) 4 kA, and (c) 5 kA, varies with welding times at and 10 Hz.

Damping capacity of weld joint

As illustrated in Figure 8, the highest welding parameter with 5 kA weld current and 8 s, weld time has the highest damping capacity at the initial temperature, but at the final temperature it dropped. At the initial temperature, 70°C, the value for 3 kA and 5 kA were 0.0233 and 0.0339 respectively, but at the final temperature 350°C, the values were 0.2797 and 0.1249 respectively. The finding show that weld joint at higher weld current cannot withstand at high temperature relatively (above 350°C). It also shows that with the enlargement of weld nugget sizes, the damping capacity reduced. Lower current and shorter weld time produce smaller weld nugget. Therefore it can be concluded that the damping capacity was effected by the size of weld nugget. The enlargement of weld nugget reduced the weld joint damping capacity. The damping capacity of a material is determined by evaluating the energy dissipated in the material during mechanical vibration [5].



(a) (b)

Figure 8: Graph of damping capacity of dissimilar metal spot welded at weld times of (a) 6 s and (b) 8 s, varies with weld currents at 10 Hz frequency

Conclusions

i) The relationship between welding current and tensile shear load shows that tensile shear strength of the joints increases as the welding current increases. The enhancement of tensile shear strength of joints was due to the enlargement of the nugget diameter.

ii) The relationship between the weld nugget diameter and welding current reveals that tensile shear strength solely relies on the size of the welding nugget.

iii) The dynamic mechanical analysis shows the relationship between storage modulus and welding parameters. The increment of welding current decrease the storage modulus of weld nugget. Meanwhile loss modulus has decreased with the increased of welding currents and welding times accordingly.

iv) The damping capacity of weld nugget depends on the size of weld nugget.

References

[1] Saunders, F. I. & Wagoner, R. H. (1995). The use of tailor-welded blanks in automotive applications - Simulation of Materials Processing: Theory, Methods and Applications. Rotterdam: Shen & Dawson.

[2] Mazlee, M. N., Zhen, A. T. Y., Jamaludin, S. B., Hayazi, N. F., & Shamsudin, S. R. (2013).Joining of Dissimilar 6063 Aluminium Alloy–316L Stainless Steel by Spot Welding:Tensile Shear Strength and Heat Treatment. In Advanced Materials Research (Vol. 795, pp. 492-495). Trans Tech Publications.

[3] Sun DQ, Lang B, Sun DX, Li JB (2007). Microstructures and mechanical properties of resistance spot welded magnesium alloy joints. Mater SciEng A; 460– 461. 494–4.

[4] Qiu, R., Iwamoto, C. & Satonaka, S. (2009). The influence of reaction layer on the strength of aluminium/steel joint welded by resistance spot welding. Materials Characterization, 60, 156-159.

[5] M. N. Mazlee, J. B. Shamsul & H. Kamarudin. (2010). Comparison of dynamic mechanical properties of non-superheated and superheated A357 alloys. Kovové Materiály, 48, 1-6.

[6] Mazlee, M. N., Shamsul, J. B., &Ayusnida, S. (2010). Interfacial reaction layer and tensile shear strength of AI 6063 alloy/stainless steel 316L spot welded joint.

[7] Lee, Won Bae, et al. "Effect of friction welding parameters on mechanical and metallurgical properties of aluminium alloy 5052–A36 steel joint." *Materials science and technology* 19.6 (2003): 773-778.

[8] M. N. Mazlee, J. B. Shamsul, Y. Yasmin, S. R. Shamsudin, M. S. Risby and M. Afendi, (2015). The Effects of Rolling Deformation and Annealing Treatment on Damping Capacity of 1200 Aluminium Alloy, Materials Science Forum, Vol. 819, pp. 123-128.

[9] Brown, J., Cai, W., Clay, N., Faitel, B., Johnson D., Bilge, U., “Weld Help Program”, Auto Body Consortium Inc., 1999.

[10] Shamsul Baharin Jamaludin, Mazlee Mohd Noor, Muhammad Rifki Ismail, Khairel Rafezi Ahmad and Kamarudin Hussin. (2013). Effects of Spot Welding Current and Cycles on the Mechanical Properties of Welded Galvanised Steel Sheets, Advanced Materials Research. Vol. 795, pp. 88-91.

[11] Shamsul Baharin Jamaludin, Mazlee Mohd Noor, Shahzan Kamarul A. Kadir and Khairel Rafezi Ahmad. (2013). Mechanical Properties of Dissimilar Welds Between Stainless Steel and Mild Steel, Advanced Materials Research. Vol. 795, pp. 75-78.

[12] Shamsul, J. B., &Hisyam, M. M. (2007).Study of spot welding of austenitic stainless steel type 304. Journal of Applied Sciences Research, 3(11), 1494-1499.

[13] M. N. Mazlee, J. B. Shamsul, Y. Yasmin, S. R. Shamsudin, M. S. Risby and M. Afendi, (2015). The Effects of Rolling Deformation and Annealing Treatment on Damping Capacity of 1200 Aluminium Alloy, Materials Science Forum, Vol. 819, pp. 123-128.