Fatigue Behavior of Resistance Spot-Welded Unequal Sheet Thickness Austenitic Stainless Steel

Triyono[1], Jamasri[2], M. N. Ilman[2] & R. Soekrisno[2]

[1] Mechanical Engineering Department, Sebelas Maret University, Indonesia

[2] Mechanical and Industrial Engineering Department, Gadjah Mada University, Indonesia

Correspondence: Triyono, Mechanical Engineering Department, Sebelas Maret University, Jl. Ir. Sutami 36A Surakarta, Indonesia. Tel: 62-27-163-2163. E-mail: tyon_bila@yahoo.co.id

Received: December 5, 2011 Accepted: April 7, 2012 Online Published: May 1, 2012

doi:10.5539/mas.v6n5p34 URL: http://dx.doi.org/10.5539/mas.v6n5p34

The research is financed by the Ministry of Research and Technology of Indonesia and Indonesian Railway Industry

Abstract

This paper presents a comparative study on the fatigue strength of resistance spot-welded unequal and equal sheet thickness austenitic stainless steel. Lap joints of 3.0-1.0 mm and 1.0-1.0 mm thick austenitic stainless steel were made using the same resistance spot welding schedule with current, weld time and electrode force of 4.7 kA, 20 cycles and 6 kN respectively. The sinusoidal wave form with a constant stress amplitude was selected in the fatigue tests whereas the stress ratio and frequency used were 0.1 and 8 Hz respectively. Fatigue strength and tensile-shear load bearing capacity of 3.0-1.0 mm joint were higher than that of 1.0-1.0 mm joint, although its nugget diameter was smaller. The joint stiffness was the controlling factor of the fatigue strength of resistance spot-welded unequal sheet thickness austenitic stainless steel.

Keywords: resistance spot welding, unequal sheet thickness, fatigue, austenitic stainless steel

1. Introduction

Austenitic stainless steels are used for a very broad range of applications especially in automotive, railway vehicle, ship body, and airplane structures when an excellent combination of strength and corrosion resistance in aqueous solutions at ambient temperature is required. Stiffened thin plate construction where the thinner plate is reinforced by thicker plate called a frame, is generally applied to the structures. Gean et al. (1999) have claimed that it is a cost-effective way of achieving a high-performance vehicle structure because it remains suited to low-volume manufacture. This structure is typically joined by the resistance spot welding (RSW) process. The advantages of using RSW are that it is a quicker joining technique, suitable for automation, no filler material is required, and that the low heat input implies less risk for altered dimensions during welding.

Many standards and recommendations are developed by individual companies, such as Ford Motor Company and General Motors. Professional organizations such as the American Welding Society (AWS), Society of Automotive Engineering (SAE), the American National Standards Institute (ANSI), and International Organization for Standardization (ISO) also contribute to a significant portion of the standards. Because of the drastic differences in design, understanding and perception of weld quality, automobile manufacturers and others tend to have very different requirements on weld quality. Zhang and Hongyan (2006) have concluded that in general, spot weld size is enveloped between $3\sqrt{t}$ and $6\sqrt{t}$ (t is the thickness of the sheets in millimeters). This recommendation is very useful in finding good weld schedules for equal sheet thickness welding. However, in automotive body application, the majority of welds are between two dissimilar thicknesses. In this case, schedules for welding unequal sheet thickness are generally developed by and practiced within individual manufacturers. Some researchers also have proposed the spot welding unequal sheet thickness researches to evaluate these recommendations. The joint of unequal thickness of the same metal may produce a strength problem due to the heat unbalance (Hasanbasoglu & Kacar, 2007) and have the unique failure mechanism (Pouranvari & Marashi, 2010).

Despite various applications of spot welded unequal thickness in automotive body, reports in the literature dealing with its mechanical behaviors, especially the fatigue behaviors are limited. In fact, Gean et al. (1999)

have found that the spot welded joint provides a localized connection which it is a source of stress concentration, and thus fatigue cracks are easily initiated at this location under fluctuating loading. Therefore, the objective of the present work is to investigate and analyze fatigue behavior of the unequal sheet thickness resistance spot welding austenitic stainless steel.

2. Experimental Procedure

2.1 Materials and Welding Processes

Two types of austenitic stainless steel joints, one is the joint between 3.0 mm and 1.0 mm thick hereinafter called 3.0-1.0 mm joint and the other is 1.0 mm and 1.0 mm thick joint called 1.0-1.0 mm joint, were lap joined by resistance spot welding (RSW). The chemical composition and mechanical properties of test materials are given in Table 1 and 2 respectively.

Table 1. The chemical composition of test materials, Wt-%

Material	C	Ni	Cr	Mn	P	Si	Cu	Mo	V
SUS304	0,076	8,183	18,107	0,252	0,031	0,389	0,209	0,486	0,22

Table 2. The mechanical properties of test materials

Material	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Electrical Resistivity (μΩ cm)
SUS304	305	670	55	72

A mobile spot welding machine WT-300SB equipment produced by Mitsubishi Electric Corporation Japan was used with the electrode diameter of 25 mm and a curved surface radius of 100 mm. Based on the recommendations, the spot-weld nugget diameter was selected between 3 and 10.4 mm. The welding parameters called welding schedule required to produce a weld nugget size was determined. This was done using the highest current possible without causing expulsion both in the 3.0-1.0 mm joints and 1.0-1.0 mm joints samples. The determined welding schedule used for making the test samples including weld current, weld time and electrode force were 4.7 kA, 20 cycles and 6 kN respectively. Fortunately, this welding schedule was in accordance with the actual conditions in the Indonesian Railway Industry.

2.2 Metallography and Microhardness Measurements

The transverse sections of weld passing through the weld nugget were prepared by standard metallographic procedure. The microstructure of austenitic stainless steel was revealed by using 10 ml nitric acids, 20 ml hydrochloric acid and 30 ml water. Microstructure investigations were carried out using an optical microscopy.

The Vickers microhardness measurements across the weld nugget, HAZ, and the base metal were carried out on the metallographic specimens with a load of 500 g.

2.3 Tensile-Shear Tests

The tensile test of base metal and tensile-shear tests of the spot-welded joint were performed using a servo-hydraulic SHIMADZU universal testing machine. The geometry and dimensions of a typical RSW specimen are illustrated in Figure 1.

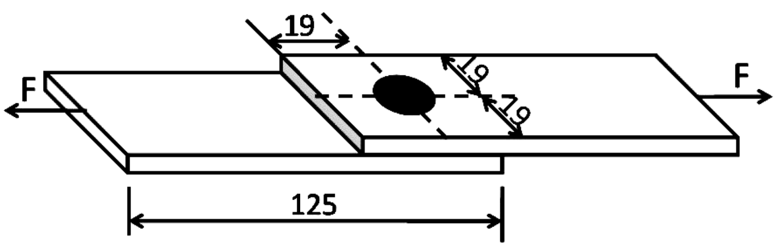


Figure 1. Dimension of tensile-shear test specimens (in mm)

These samples were similar to the samples used in a work which was carried out by Gean et al. (1999). The dark region at the center of the assembly represents the nugget. The overlap is equal to the width of the metal sheet. In order to provide a tensile-shear loading condition, 38 mm long shims were attached at both ends of the specimen.

2.4 Fatigue Tests

The fatigue tests were performed at room temperature in laboratory conditions using a 40 kN servo-hydraulic SHIMADZU testing machine with a software package specifically designed for running fatigue tests. The double spot-welded test samples were made according to the French standard A03-405 as shown in Figure 2.

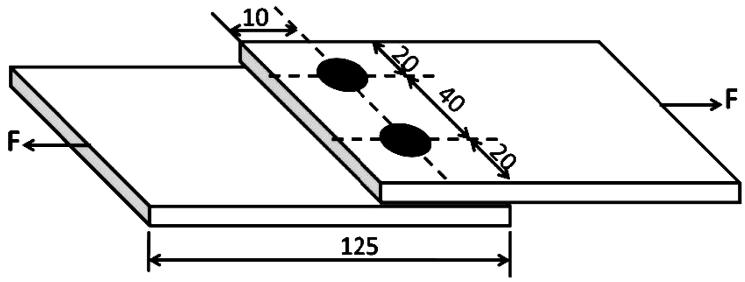


Figure 2. Dimension of fatigue test specimens (in mm)

These samples were similar to the samples used in a work which was carried out by Gean et al. (1999). In order to provide symmetry and to prevent a moment being applied at the weld, 60mm long shims were glued at both ends of the specimen. A sinusoidal wave input with a constant load amplitude was selected whereas the stress ratio and frequency used were 0.1 and 8 Hz respectively. Specimens were exposed to a constant load amplitude until fracture occurred or to a maximum $2x10^6$ cycles. Specimens that survived $2x10^6$ cycles are called run outs. Applied force range and number of cycles to failure were recorded and S-N curves for the joints were obtained.

3. Results and Discussion

The weld profile of 3.0-1.0 mm joint is shown in Figure 3.

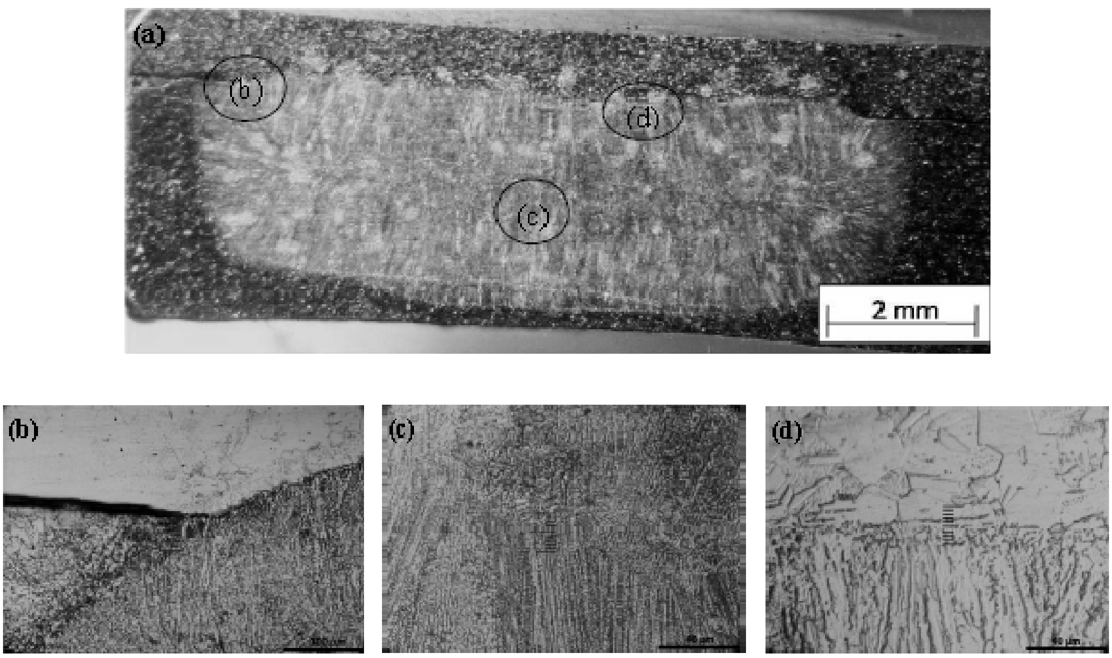


Figure 3. Weld profile of 3.0-1.0 mm thick joints (a) macrograph (b) nugget corner (c) nugget (d) interface

It can be seen from Figure 3(a) that the nugget is asymmetric where its centre leans to the thicker workpiece. Because of the unbalanced heat resulting from unequal thickness of the joined materials, more thermal will be generated in the thicker plate (Hasanbasoglu & Kacar, 2007). Heat loss in thicker plate is smaller than that in thinner plate. This condition causes penetration is almost 100% on the thicker plate and very slight on the thinner plate. Further evaluation of Figure 3(a) shows that separation of the sheets is about 20 mm (Figure 3(b)) and surface indentation was very slight. The asymmetry of temperature field distribution in spot welded unequal thickness causes the edge of sheets warp to the thinner sheet and makes the sheet separation is high enough (Wang et al., 2010). The microstructure of weld nugget has a columnar structure in which the grains are found to be elongated parallel to irregular direction as shown in Figure 3(c). It shows that solidification occurs in non-uniform manner from all the sides of the surrounding solid, in both the electrode and sheet directions. Figure 3(d) shows interface microstructure where the base metal and the nugget are separated by very narrow heat affected zone (HAZ).

Different from the microstructure of spot welded unequal sheet thicknesses, the microstructure investigation of spot welded equal sheet thickness austenitic stainless steel shows that the nugget is symmetry, there is no sheet separation, nugget microstructure has regular direction and wide heat affected zone (HAZ) band appears at the interface of nugget and base metal as seen in Figure 4.

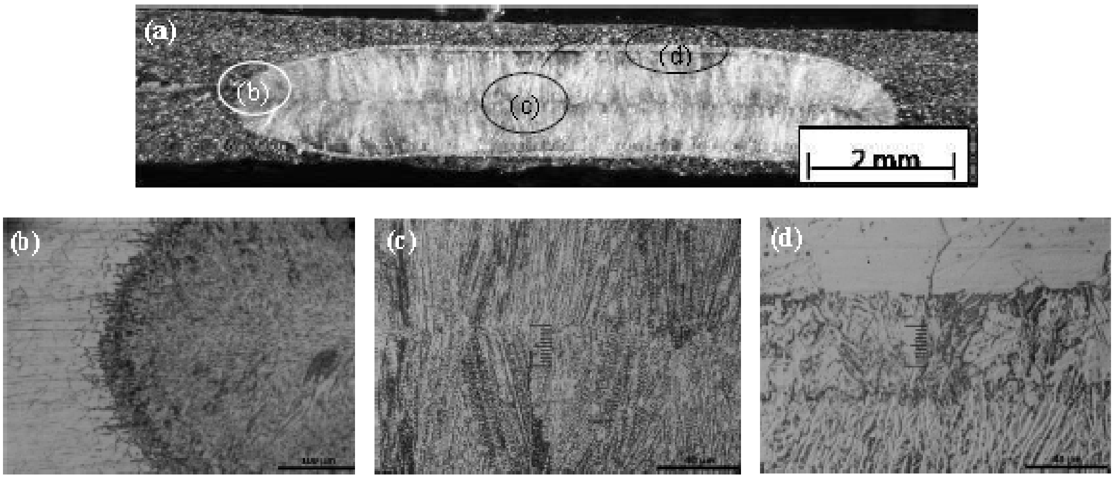


Figure 4. Weld profile of 1.0-1.0 mm thick joints: (a) macrograph (b) nugget corner (c) nugget (d) interface

In addition, according to the macroscopic examination (Figure 3 and Figure 4) when the 3.0-1.0 mm and 1.0-1.0 mm joints were spot welded using the same welding schedule, the nugget diameter at center of total thickness were also the same, however that at the joint interface were 8.3 mm and 8.9 mm respectively. This difference is primarily attributed to the asymmetry nugget of 3.0-1.0 mm joint. The measured weld nugget sizes for all welded materials were found to be much higher than a minimum nugget diameter of the 3-6 times the root of the sheet thickness (Zhang & Hongyan, 2006). Therefore, the weld nugget sizes of all welded materials were acceptable.

The hardness profiles of weld nugget, HAZ (heat affected zone), and the base metal are shown in Figure 5.

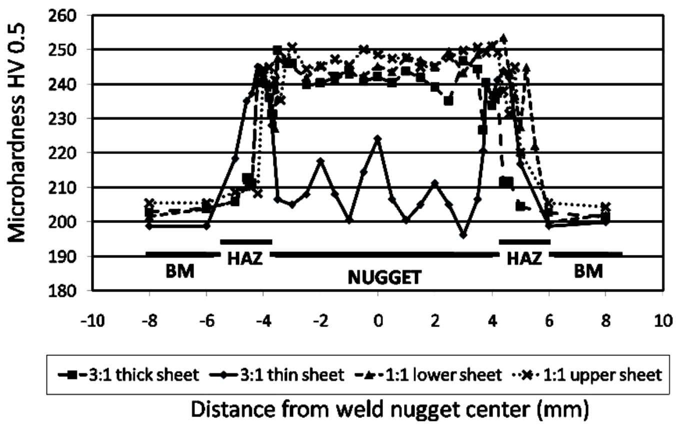


Figure 5. Microhardness distribution of the spot welded equal and unequal thickness austenitic stainless steel

The hardness of nugget for both 3.0-1.0 mm and 1.0-1.0 mm joint was found to be higher than that of base metal. The highest hardness value of weld nuggets was over 250 HV 0.5 which was observed on the edge of nugget. However, hardness of the nugget of 3.0-1.0 mm joint did not show many differences compared to that of 1.0-1.0 joint because of the chemical composition of base metals in which there is not so much alloying elements such as carbon, manganese that affects the hardenability. Spot welds in thin sheet can have relatively high hardness when the carbon content exceeds about 0.08% (AWS, 1982; Ozyurek, 2008). As seen in Table 1, base metals that had been used in this study had less than that of percent carbon. In addition, there was no significant change in hardness of the thinner sheet of the 3.0-1.0 mm joint compared to base metal because there was no change in its microstructure.

Interesting phenomenon occurs in a thin sheet of the 3.0-1.0 mm joint where there was no significant change in hardness compared to base metal unless the nugget edge in which its hardness value was similar to nugget hardness. This could be attributed to the asymmetric nugget that occurred on the unequal sheet thickness joint. Hardness profile of thin sheet was more influenced by strain hardening due to electrode indentation.

In order to determine the load range on the fatigue tests, the strength of weldment was also determined. In this study, the tensile shear load bearing capacity of spot welded equal and unequal sheet thickness austenitic stainless steel are compared and results are given graphically in Figure 6.

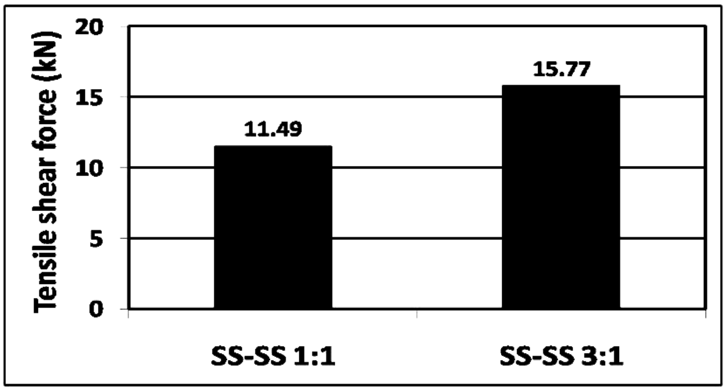


Figure 6. Tensile shear load bearing capacity of spot welded materials

As can be seen from Figure 6, the tensile shear load bearing capacity of 3.0-1.0 mm joint is higher than that of 1.0-1.0 mm joint even though its nugget diameter at the joint interface is smaller and it fail on the thin sheet. This result differs from the results obtained from a work which was carried out by Vural and Akkus (2004) and Ozyurek (2008). They found that increasing of the nugget diameter increased tensile-shear strength of the spot welded joint.

It seems that the enhancement in tensile shearing load bearing capacity of 3.0-1.0 mm joint is attributed to its stiffness. As known when tensile load was applied in a lap joint, the eccentricity of the load path resulted in a rotation of the joint. Figure 7 shows the deformation mechanism of lap joint during loading.

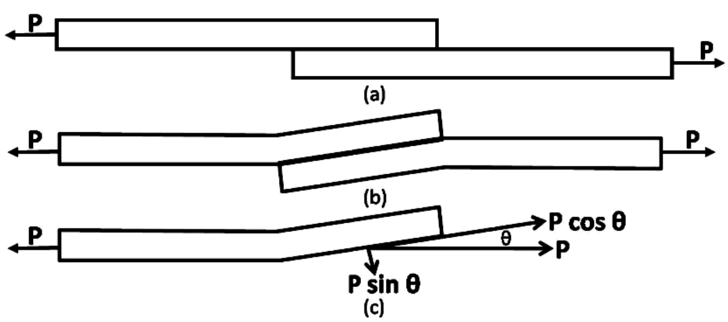
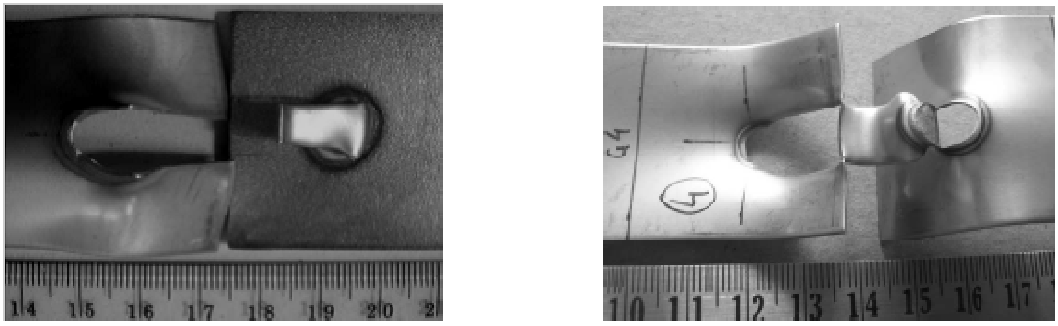


Figure 7. Deformation mechanism of lap joint during loading, (a) low load level, (b) plastic hinges, (c) schematic load distribution in a lap joint

When there was certain amount of rotation, the tensile stress called peeling stress (i.e. the normal stress acting in the through-thickness direction of the joint, expressed as P sin θ) formed around the nugget and caused plastic deformation in sheet thickness direction. Increasing of the joint rotation increased peeling stress that led necking at the nugget circumference (Nordberg, 2006). Due to the higher stiffness, joint rotation and consequently, peeling stress of 3.0-1.0 mm joint was smaller than that of 1.0-1.0 mm joint as shown in Figure 8.



(a) (b)

Figure 8. The fracture mode of tensile shear test samples: (a) 3.0-1.0 mm joint (b) 1.0-1.0 mm joint

Since load bearing capacity of spot welds under coach-peel test is much lower than that of under tensile-shear test (Nordberg, 2006) this mechanism can explain why 3.0-1.0 mm joint has a higher tensile shearing load bearing capacity than 1.0-1.0 mm joint.

The *S-N* curves, the results of fatigue test of the spot welded joints are presented in Figure 9.

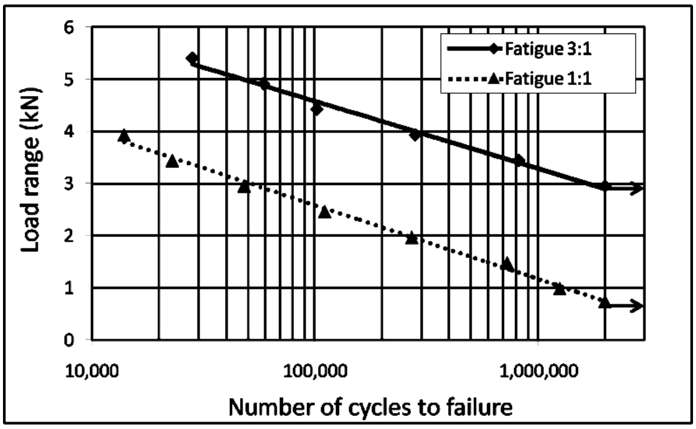


Figure 9. Comparison of fatigue strength of 3.0-1.0 mm and 1.0-1.0 mm joint based on the load range

All data points belonged to a mean value of three tests. As shown in Figure 9, while the load range decreases, the fatigue life of the specimens increases as expected. The 3.0-1.0 mm joints exhibited much higher fatigue strength than 1.0-1.0 mm joints. The endurance limit of 3.0-1.0 mm joints was 2.9 kN whereas that of 1.0-1.0 mm joints was 0.7 kN.

Nordberg (2006) has proposed a line load method when fatigue data of discontinuous joints like spot welding have been analyzed. Line load is the load divided by the width of the joint, and the width of the joint, e, is calculated as follows:

$$e = (14 \times t_2 + 3) \times \sqrt[3]{\frac{t_1}{t_2}} \quad (1)$$

where $t_1 > t_2$. The S-N curve in Figure 9 will has slightly different pattern if it is displayed in line load range-cycle relation as seen in Figure 10. At high loads fatigue strength of the 3.0-1.0 mm joint was slightly higher and increasing to much higher at lower loads than that of the 1.0-1.0 mm joint.

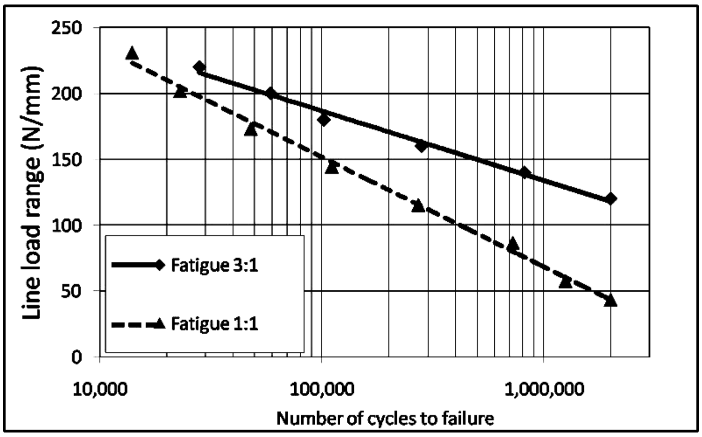
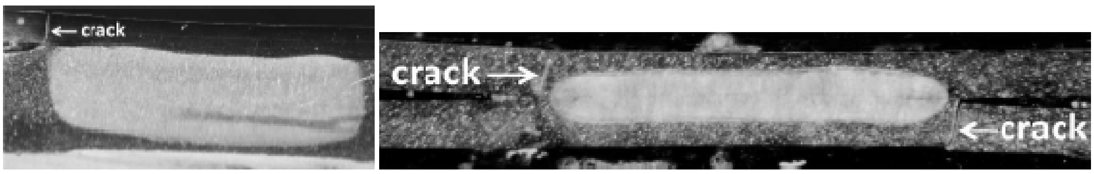


Figure 10. Comparison of fatigue strength of 3.0-1.0 mm and 1.0-1.0 mm joint based on the line load range

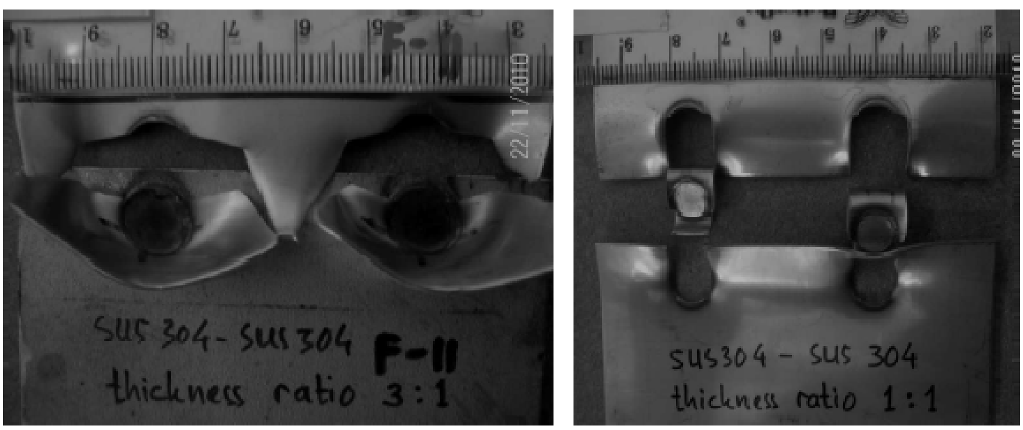
Similar to tensile shearing load bearing capacity, the enhancement in fatigue strength of 3.0-1.0 mm joint was also attributed to its stiffness. The explanation of the enhancement in tensile shearing load bearing capacity of 3.0-1.0 mm joint can be used to explain that in fatigue strength. Due to the higher stiffness, rotation of joint occurred just on thin sheet and it was smaller than that of 1.0-1.0 mm joint which rotated on both sheets. Consequently, crack of 3.0-1.0 mm joint initiated just on the thin sheet side whereas that of 1.0-1.0 mm joint initiated on both sheet side as shown in Figure 11. For both 3.0-1.0 mm and 1.0-1.0 mm joint specimens, cracks started in the base metal adjacent to the HAZ area.



(a) (b)

Figure 11. Initial crack location: (a) 3.0-1.0 mm joint (b) 1.0-1.0 mm joint

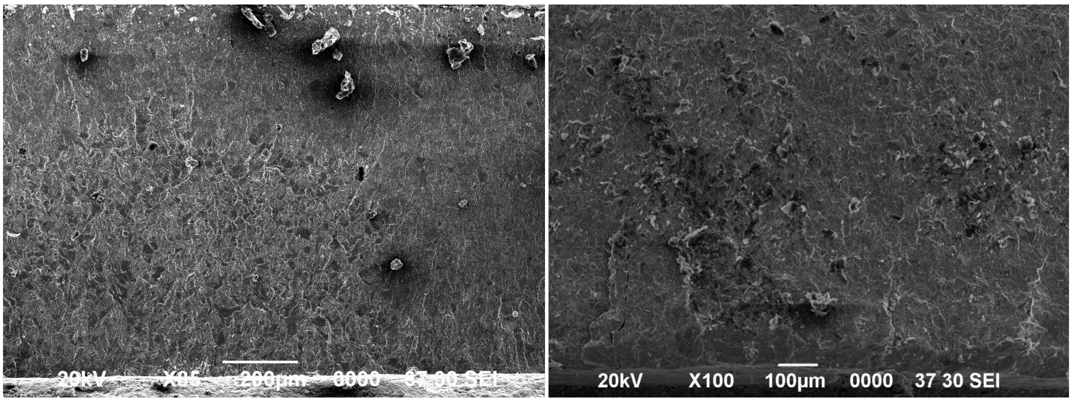
After initiation, the crack propagation of 3.0-1.0 mm joint occurred through the thickness and continued propagating through the width of the thin sheet. Finally, this mechanism led to the tearing fracture mode as seen in Figure 12(a). Different from fracture of 3.0-1.0 mm joint, cracks of 1.0-1.0 mm joint propagated at the nugget circumference due to high peel stress and led to the pull out fracture mode as shown in Figure 12(b). This behavior is similar to fracture of coach peel samples at high load that reported in a previous study (Long & Khanna, 2007).



(a) (b)

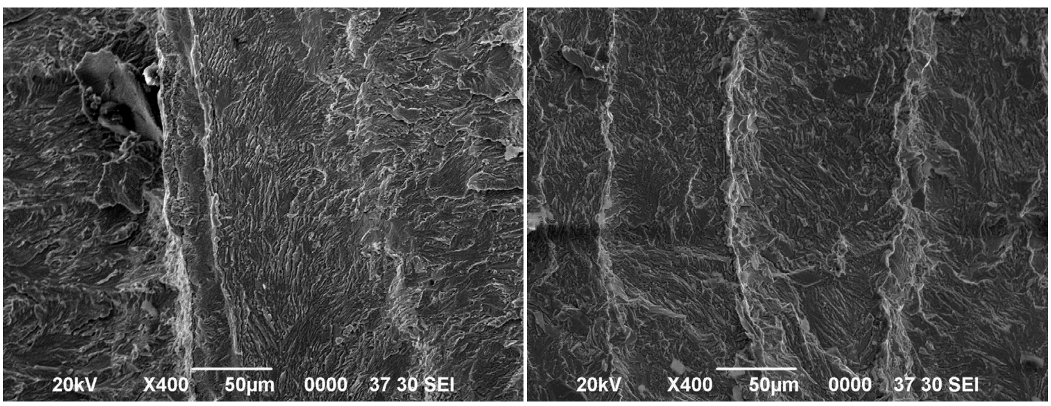
Figure 12. The fracture mode of fatigue test samples: (a) 3.0-1.0 mm joint (b) 1.0-1.0 mm joint

Given SEM views in Figure 13 and Figure 14 are the comparison of the last fracture surfaces of the 3.0-1.0 mm and 1.0-1.0 mm joint specimens which were subjected to same load of 3.4 kN. As seen in Figure 13(a), crack of 3.0-1.0 mm joint initiated on the inside of thin sheet. On the more half of thickness, it propagated slowly due to low peel stress and induced ductile fracture characterized by intergranular cracking. Ductile fracture changed to brittle fracture characterized by transgranular cracking on the remaining thickness due to increased peel stress. The embrittlement of stainless steel was attributed to strain-induced martensite forming during the fatigue tests (Vural et al., 2006). Different view was given by fracture surface of 1.0-1.0 mm joint specimen as shown in Figure 13(b). It displayed brittle fracture characterized by transgranular cracking on the entire thickness due to high peel stress.



(a) (b)

Figure 13. Initial crack of fatigue test samples: (a) 3.0-1.0 mm joint (b) 1.0-1.0 mm joint



(a) (b)

Figure 14. Crack propagation zone: (a) 3.0-1.0 mm joint (b) 1.0-1.0 mm joint

On the crack propagation zone, brittle fracture characterized by transgranular cracking was observed on both 3.0-1.0 mm and 1.0-1.0 mm joint specimens. They displayed wave of plastic deformation as shown in Figure 14. However, plastic deformation intensity of 1.0-1.0 mm joint was higher than that of 3.0-1.0 mm joint. It was indicated by the number of waves in the same observation area as seen in Figure 14.

4. Conclusions

Fatigue of resistance spot welded unequal sheet thickness austenitic stainless steel has been studied. Due to significant thickness difference, the asymmetric weld nugget, high microhardness on the edge of nugget and tearing fatigue fracture mode were observed. The fatigue strength of 3.0-1.0 mm joint was higher than that of 1.0-1.0 mm joint, although its nugget diameter was smaller. The endurance limit of 3.0-1.0 mm and 1.0-1.0 mm joint were 2.9 kN and 0.7 kN respectively. Ductile and brittle fractures were observed on 3.0-1.0 mm fatigue specimens whereas 1.0-1.0 mm fatigue specimens failed to fully brittle fracture mode. The joint stiffness was the controlling factor of the fatigue strength of resistance spot-welded unequal sheet thickness austenitic stainless steel.

5. Acknowledgments

The authors would like to express their sincere gratitude for the financial support of the Ministry of Research and Technology of Indonesia and Indonesian Railway Industry.

References

American Welding Society. (1982). *Metals and their weldabilty, Welding handbook(7th ed.), 4*. United States of America.

Gean, A., Westgate, S. A., Kucza, J. C., & Ehrstrom, J. C. (1999). Static and Fatigue Behavior of Spot Welded 5182-0 Aluminium Alloy Sheet. *Welding Journal*, *78*(3), 80s-86s.

Hasanbasoglu, A., & Kacar, R. (2007). Resistance Spot Weldability of Dissimilar Materials (AISI 316L-DIN EN 10130-99 Steels). *Material and Design, 28*, 1794-1800. http://dx.doi.org/10.1016/j.matdes.2006.05.013

Long, X., & Khanna, S. K. (2007). Fatigue properties and failure characterization of spot welded high strength steel sheet. *International Journal of Fatigue, 29,* 879-886. http://dx.doi.org/10.1016/j.ijfatigue.2006.08.003

Nordberg, H. (2006). Fatigue Properties of Stainless Steel Lap Joints. *SAE Transactions: Journal of Materials & Manufacturing, 114,* 675s-690s.

Ozyurek, D. (2008). An effect of weld current and weld atmosphere on the resistance spot weldability of 304L austenitic stainless steel. *Materials and Design, 29,* 597-603. http://dx.doi.org/10.1016/j.matdes.2007.03.008

Pouranvari, M., & Marashi, P. (2010). Resistance Spot Welding of Unequal Thickness Low Carbon Steel Sheet. *Advanced Materials Research, 83,* 1205-1211. http://dx.doi.org/10.4028/www.scientific.net/AMR.83-86.1205

Vural, M., & Akkus, A. (2004). On the resistance spot weldability of galvanized interstitial free steel sheets with austenitic stainless steel sheets. *J. Mater. Proc. Technol., 153-154*, 1-6. http://dx.doi.org/10.1016/j.jmatprotec.2004.04.063

Vural, M., Akkuş A., & Eryürek, B. (2006). Effect of Welding Nugget Diameter on The Fatigue Strength of The Resistance Spot Welded Joints of Different Steel Sheets. *J. Mater. Proc. Technol., 176*(1-3), 127-132. http://dx.doi.org/10.1016/j.jmatprotec.2006.02.026

Wang, Y., Zhang, P., Wu Y., & Hou, Z. (2010). Analysis of the Welding Deformation of Resistance Spot Welding for Sheet Metal with Unequal Thickness. *Journal of Solid Mechanics and Material Engineering, 4,* 1214-1222. http://dx.doi.org/10.1299/jmmp.4.1214

Zhang, H. Y., & Senkara, J. (2006). *Resistance welding: fundamentals and applications.* Boca Raton: Taylor & Francis Group.