

Comparative Study of Fatigue Assessment Methods with and without Considering Residual Stress on Resistance Spot-Welded Unequal Sheet Thickness Stainless Steel

Triyono, Jamasri, M.N. Ilman, R. Soekrisno

Abstract—This paper compares various fatigue assessment methods with and without considering residual stress on resistance spot-welded unequal sheet thicknesses-austenitic stainless steels between sheet thicknesses of 3.0 and 1.0 mm. A set of fatigue data were obtained from fatigue tests that carried out at a room temperature using a sinusoidal wave input with a constant stress amplitude whereas the stress ratio and frequency used were 0.1 and 8 Hz respectively. The modified Goodman equation was used to calculate the stress amplitude with considering residual stress at the edge of the spot weld nugget. Both based on nominal and net-section stress, consideration of residual stress on fatigue strength shift the S-N curves toward lower stress. The S-N curves shifting based on the net section was higher than that based on the nominal stress.

Index Terms—austenitic stainless steel, fatigue, residual stress, resistance spot-welded, unequal sheet thickness.

I. INTRODUCTION

AUSTENITIC stainless steels are used for a very broad range of applications especially in automotive, railroad, and airplane structures when an excellent combination of strength and corrosion resistance in aqueous solutions at ambient temperature is required. These structures are generally in stiffened thin plate constructions where the thinner plates are reinforced by thicker plates called frame. They have been claimed as being a cost-effective way of achieving a high-performance vehicle structure [1]. Resistance spot welding (RSW) takes an important role for joining these structures. The advantages of using RSW are that it is a quicker joining technique, no filler material is required, and that the low heat input implies less risk for altered dimensions

during welding. However, the spot welded joints have a geometrical problem on the stiffened thin plate structures due to the thickness difference of joined materials. The spot welded joint provides a localized connection that it is a source of stress concentration, and thus fatigue cracks are easily initiated at this location under fluctuating loading [2]. This critical area is generally located around edge of nugget. In addition, the unbalance heating may produce physical, mechanical and metallurgical problems when unequal thickness plates are spot-welded together even though the same metal [3].

Fatigue is one of the major concerns in spot welded of the automobile structures, because they are exposed to variable loads [4]. There are a lot of scientific papers dealing with fatigue strength assessments of spot welded joints, but only a few studies have been published concerning fatigue assessments that consider welding residual stress especially on spot-welded unequal sheet thickness. Therefore, welding residual stress should be properly considered in the fatigue design of actual spot welded thin sheet structures since it affects fatigue crack initiation and propagation at the nugget edge of a spot weld [5]. It is well known that during the resistance spot welding process, expansion and shrinkage of the material occurs due to the thermal cycle. Thus, welding residual stress and electrode indentation remain at the spot weld after the spot welding process.

Nordberg [6] has proposed a line load method when fatigue data of spot welded joints of dissimilar sheet thickness have been analyzed. Alenius [7] has used this method to evaluate sheet thickness effects on the fatigue strength of spot-welded joints. 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 $t_1 > t_2$. Dividing the line load with the thickness of the sheet gives the net section stress.

The quantitative effects of residual stresses on fatigue life have not been clearly explained yet. Some studies show the tensile residual stresses in welded structures can be as high as the yield strength of the material and have a detrimental effect

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Triyono is Ph.D student at Mechanical Engineering, Gadjah Mada University, Yogyakarta, Indonesia. (e-mail: tyon_bila@yahoo.co.id).

Jamasri is with the Department of Mechanical Engineering, Gadjah Mada University, Yogyakarta, Indonesia. (e-mail: jamasri@ugm.ac.id).

M.N. Ilman is with the Department of Mechanical Engineering, Gadjah Mada University, Yogyakarta, Indonesia.

R. Soekrisno is with the Department of Mechanical Engineering, Gadjah Mada University, Yogyakarta, Indonesia.

on the fatigue behavior. Conversely, compressive residual stresses could have a favorable effect on fatigue life [8]. One of the fatigue strength assessment with consideration to welding residual stress at the spot-weld nugget edge has been proposed by Bae [5] using the modified Goodman equation as follows

$$\frac{\sigma_{a-res}}{S_e} + \frac{(\sigma_{mean} + \sigma_{res})}{S_u} = 1 \quad (2)$$

where σ_{a-res} and σ_{res} are the stress amplitudes which consider welding residual stress and welding residual stress at the nugget edge of the spot weld, respectively. When the load ratio, $R = 0.1$, then $\sigma_{mean} = 1.1\sigma_{max}/2$. Therefore the stress amplitude which considers welding residual stress can be written as

$$\sigma_{a-res} = S_e \left[\frac{2S_u - (1.1\sigma_{max} + 2\sigma_{res})}{2S_u} \right] \quad (3)$$

σ_{max} is maximum stresses; S_e and S_u are fatigue strength at a given number of cycles and ultimate stress respectively. The calculated stress amplitude (σ_{a-res}) replaced the fatigue stress range ($\Delta\sigma$) obtained from the fatigue test to generate the stress amplitude (σ_{a-res})-fatigue life (N_f) relation.

The applied external loads relieve the residual stresses and then the mean stresses of spot-welded structures can be changed. It is very important to consider not only the initial residual stress but also the relaxation of residual stress in assessing fatigue strength. The following residual stress relaxation formula for austenitic stainless steel has been proposed by Lee [9].

$$\sigma_{res-relax} = \sigma_{res-ini} \times N^{-0.004} \quad \text{if}$$

$$\sigma_{app} + \sigma_{res-ini} < \sigma_{yield} \quad (4)$$

Remaining residual stress after N cycles ($\sigma_{res-rem}$) is the difference between initial residual stress and relaxed residual stress. The stress amplitude which considers the remaining residual stress can be obtained from the modification of equation (3). In general, since fatigue crack initiation occurs at the nugget edge on the inner surface of the loading side, it would be reasonable to look at the stress at the fatigue crack initiation location to assess the fatigue strength of spot welds [5]. The welding residual stress at the nugget edge on the inner surface of spot-welded unequal sheet thicknesses-

II. EXPERIMENTAL PROCEDURE

A. Materials and welding processes

Austenitic stainless steels SUS304 with the thickness of 3.0 mm and 1.0 mm were joined in a lap joint by resistance spot weld (RSW). The chemical composition and mechanical properties of test materials are given in Table I and II respectively. Mobile Spot Welding Machine WT-300SB equipment produced by Mitsubishi Electric Corporation Japan was used in the spot welding studies. RSW's electrode had diameter of 25 mm and curved surface with a radius of 100 mm. The welding conditions used including weld current, weld time and electrode force were 4.7 kA, 20 cycles and 6 kN respectively.

B. Metallography

The transverse section of weld passing through the weld nugget was 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 and scanning electron microscopy.

C. Fatigue tests

The fatigue testing was 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 Fig.1. These samples were similar to the samples used in a work which was carried out by Gean [1]. 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 constant load amplitude was selected whereas the stress

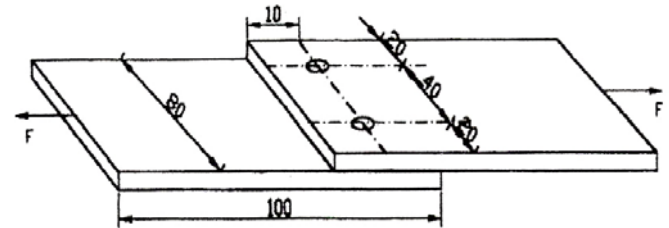


Fig. 1. Fatigue specimen (dimension in mm)

TABLE I
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

austenitic stainless steels between sheet thicknesses of 3.0 and 1.0 mm was +75.5MPa [11]. The present paper aims to evaluate various methods of fatigue assessment associated with the presence of residual stress and thickness differences on the spot-welded joints.

TABLE II
THE MECHANICAL PROPERTIES OF TEST MATERIALS

Material	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Electrical Resistivity ($\mu\Omega$ cm)
SUS304	305	670	55	72

ratio and frequency used were 0.1 and 8 Hz respectively. Specimens were exposed to constant load amplitude until fracture occurred or to a maximum 2×10^6 cycles. Specimens that survived 2×10^6 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.

III. RESULTS AND DISCUSSION

The optical macrograph of the spot welded austenitic stainless steel with significant difference in thickness is shown in Fig. 2. As seen in Fig. 2, surface indentation was very slight. Separation of the sheets was also small. Penetration

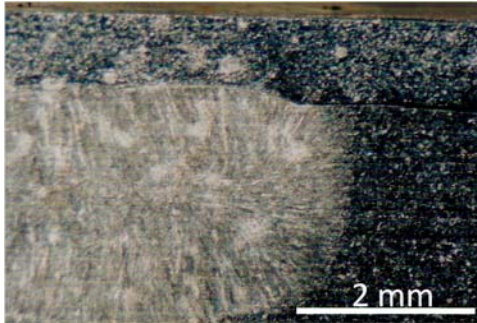


Fig. 2. Macrostructure of spot welded unequal sheet thickness

was asymmetric because of the unbalanced heat resulting from unequal thickness of the joined materials. Heat will be generated more rapidly in the thick plate because it has higher electrical resistance than the thin plate [3]. This condition caused penetration was almost 100% on the thick plate and very slight on the thin plate. In general, the penetration should be 20–80% of the thickness of the sheet [10]. However, it did not cause defects and other metallurgical problems in the interface zone, heat affected zone (HAZ) and weld nugget. This condition ensured that the fatigue failure would be not caused by metallurgical defects but by the stress concentration at the spot weld geometry where the residual stress would take a role.

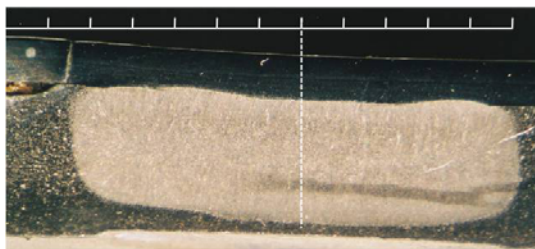


Fig. 3. The fatigue crack location of fatigue test samples

During fatigue tests, cracks initiated at the nugget edge on the inner surface of the loading side which had a distance of 5–6 mm from the nugget center as seen in Fig. 3. Then cracks propagated through the thickness of the thinner sheets as shown in Fig. 4. This phenomenon was in accordance with the result of the work conducted by Bae [5]. It will be reasonable to investigate the residual stress at the fatigue crack initiation location to assess the fatigue strength of spot welds. The

residual stress in hoop direction became a major concern because its direction and the direction of applied stresses on the fatigue tests were the same. Triyono et al. [11] have measured the residual stress in hoop direction at the edge of nugget using neutron diffraction method. They found that the welding residual stress at the nugget edge of spot-welded

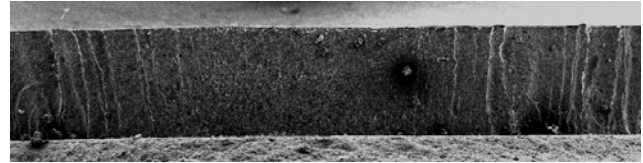


Fig. 4. Initial crack and crack propagation zone

unequal sheet thicknesses-austenitic stainless steels between sheet thicknesses of 3.0 and 1.0 mm was +75.5MPa.

Based on measured residual stress, the obtained fatigue data were assessed with and without considering the initial residual stress and relaxed residual stress. The stress amplitude which considers initial residual stress was calculated using the modified Goodman equation which expressed in equation (3). In present study, sum of applied stress and initial residual stress was smaller than the yield stress of material ($\sigma_{app} + \sigma_{res-ini} < \sigma_{yield}$), therefore the stress amplitude which considers the relaxed residual stress was calculated using a combination of equation (4) and (3). Together with residual stress consideration, net-section stress due to the nature of unequal sheet thicknesses which expressed in

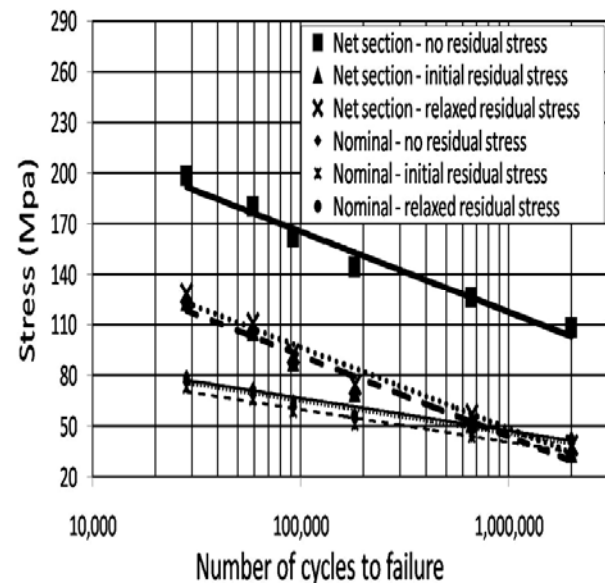


Fig. 5. Comparison S-N-curves based on nominal stress and net-section stress

equation (1) was considered for fatigue strength assessment. The S-N curves, the results fatigue test of the spot welded joints represented by stress amplitudes with and without consideration of initial and relaxed residual stresses based on nominal and net-section stress are presented in Fig. 5. The difference of each fatigue assessment by taking the fatigue strength based on nominal stress without considering the

residual stress as a reference is shown in Table III.

In general, fatigue strength without residual stress consideration based on net-section stress was higher than that based on nominal stress. The slope of S-N curves based on net-section stress differed from that based on nominal stress. The fatigue strength based on net section stress at fatigue limit was 149% higher than that the nominal fatigue strength, while in higher stress and shorter life ranges the difference of them was more than 149%. The fatigue strength without considering the residual stress based on net-section and nominal stresses at fatigue limit were 108.3 and 43.5 MPa respectively. If the residual stress, both initial and relaxed residual stress, was considered, the difference in fatigue strength based on net section and nominal stress will become smaller even the same in low stress range. In higher stress and shorter life range, the fatigue strength based on the net-section stress was higher than that based on the nominal stress, at fatigue limit vice versa. The fatigue limit based on the net-section and nominal stress that considers initial residual stress were about 34 and 37 Mpa respectively, while that considers relaxed residual stress were about 41 and 39 Mpa respectively. Referring to these data, it can be seen that the fatigue limit with initial residual stress consideration was lower than that with relaxed residual stress consideration. Both based on nominal and net-section stress, initial and relaxed residual stress consideration parallel shifted the S-N curves toward lower stress. This result was in accordance with the calculations performed by Bae [5].

In each stress category, nominal stress or net-section stress, the S-N curves shift in the same slope since the sum of applied stress and initial residual stress was smaller than the yield stress of material. The effect of residual stress depended on the sum of applied stress and initial residual stress. When it was smaller than yield stress, then the applied stress played as a mean stress. Therefore, initial residual stress consideration causes the S-N curves shifted in the same slope which may go upward or downward. Conversely, when it was higher than yield stress, then the initial residual stress was relaxed by the applied loading in certain stress range especially in higher loads and shorter life ranges. Therefore, the slope of the shifted S-N curve and the original curve in this condition are different. The S-N curves in both conditions, the sum of applied stress and initial residual stress were smaller and higher than the yield stress of material, will intersect at a point where the sum of applied stress and initial residual stress was equal to the yield stress of material [9].

TABLE III
FATIGUE LIMIT VALUE WITH VARIOUS CONSIDERATIONS

Stress categories	Consideration	Fatigue limit (MPa)
Nominal stress	No residual stress	43.50
	Initial residual stress	36.90
	Relaxed residual stress	41.50
Net section stress	No residual stress	108.3
	Initial residual stress	34.35
	Relaxed residual stress	38.98

Referring to the results of the above discussion, each fatigue assessment method had different interpretations. This indicated that fatigue strength of spot-welded joints could be greatly overestimated or underestimated by neglecting presence of welding residual stresses and sheet thicknesses difference. Therefore, for determining more reasonable fatigue design criterion of the spot-welded structures, the welding residual stresses generated in the welding process and dissimilar sheet thicknesses joints should be considered in fatigue strength assessment [5].

IV. CONCLUSION

The fatigue strength of resistance spot-welded dissimilar sheet thicknesses-austenitic stainless steels was assessed using various methods with and without considering the initial and relaxed residual stress based on nominal and net-section stress. Each fatigue assessment method has different interpretations. The following conclusions are made:

1. The fatigue strength without considering the residual stress based on net-section stress was 149% higher than that based on nominal stress, the percentage difference becomes smaller by considering the residual stress, even vice versa in lower stress range.
2. The fatigue limit with initial residual stress consideration was lower than that with relaxed residual stress consideration.
3. The increasing the initial residual stress at the nugget edge decreases the fatigue limit of spot-welded joints.

Based on the conclusions, it is important to carry out the fatigue tests on the specimens with the same geometry and dimensions but different residual stress.

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