Comparative Fatigue Life Study on the Indentation Levels of Resistance Spot Welds with Dual Phase Steel

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Abstract. This project is focused on the critical parameters affecting nugget formation through both electrical-thermal analysis and thermal-mechanical analysis during resistance spot welding (RSW) process. The object of this study is three stacked up sheets instead of conventional two sheets assemblies because of its wide application in automobile industry. It is analyzed that the nugget and the plastic ring region localized around nugget are more inclined to have fatigue failure such as cracks and fracture. Local indentation levels comprising of 10%, 30% and 50% of a sheet thickness are investigated under tensile shear load and cross tension load by fatigue experiments. It is proved that higher indentation level weld is more likely to have longer fatigue life than that of lower indentation level weld at the same load condition for both tensile shear loads and cross tension loads. Moreover, comparing with the results derived from DP material welds, it is obtained that the indentation levels for mild steel welds shows similar results on fatigue lives.

Introduction

With the increasing of global energy and environmental crisis, energy saving and emission reduction has become an inevitable topic in automobile design and manufacture. It is pointed that 50% of the fuel consumption is generated by the vehicle weight [1]. Therefore, reducing the weight of the car is an effective method for energy saving and emission reduction. Dual phase steel (DP steel) which has apparent advantages in lightweight, high strength is regarded as one of the most promising material in automotive industry [2]. Due to its low cost and high efficiency, resistance spot welding (RSW) is widely employed in automotive production and 4000~5000 solder joints are applied in each vehicle body. Based on the previous factors, DP steel is becoming a popular material joined in RSW process [3]. It is investigated that the nugget pullout and interfacial fractures are typical failure modes which greatly influences the static strength of the welds as well as dynamic fatigue life, hence waking the quality and reliability of welds [4]. Moreover, nugget fracture probability for DP steel is conventionally higher than that of mild steel (MS). Hence, the traditional welding quality evaluation standard system is inadequate for DP steel, which prevents the further application of DP steel for RSW. Therefore, it has great significance to study on the internal factors through both electrical-thermal analysis and thermal-mechanical analysis during RSW process. Two major failure modes which are pull-out and interfacial fracture are presented and the transition between interfacial and pull-out failure modes for AHSS RSW in terms of tensile shear loading test are analyzed by analytical approach in literature [5-6]. It is obtained that the servo gun has remarkable performance on the improvement of weldability for dual-phase steel and the electrode force can be flexibly adjusted during spot welding process [7]. Moreover, the microstructural change in DP600 steel after laser welding and its effect on the tensile and fatigue properties have been evaluated [8]. In literature [9], the effects of solid state phase transformations on the prediction of residual stresses are conducted and distortion during welding of DP600 steel is investigated.

However, most RSW process studies are limited to two sheet assemblies, Nevertheless, more than two sheets joints are frequently operated in practical during the RSW for vehicle body manufacture. Therefore, in this study, the critical control parameters for DP steel in RSW are conducted including electrical current, electrode force, cooling rate, phase change and so on during electrical-thermal analysis and thermal-mechanical analysis. Moreover, the fatigue lives of DP steel welds with various nugget indentations levels which are comprised of 10%, 30% and 50% of a sheet thickness are investigated and compared with each other. Furthermore, the fatigue life results derived from DP material welds are also compared with those of MS welds.

Theoretical Methodology

In the RSW process, four steps are endured including squeezing, heating, holding and cooling. It is indicated that following factors and nugget formation mechanism are the main reasons contributed to the quality and reliability for RSW of DP steel.

Electrical-Thermal Analysis

Squeezing and heating stages are critical in terms of heat control during RSW process. In the theoretical investigation, not only electrical current, electrode force, thermal conductivity but also contact resistivity, specific heat and phase change are taken into consideration for three sheets assemblies in RSW process. During heating stage, the heat generated by electrodes current in a certain period can be calculated by equation (1) shown as below:

$$Q = I^2 Rt \tag{1}$$

Where I is the electrical current, R is the electrical resistivity, and t is time.

The temperature generated by heat flow can be calculated by equation (2) represented below when equation (1) is obtained:

$$\frac{\partial T}{\partial t} = a \nabla^2 T + \frac{Q}{r c} \tag{2}$$

Where, r is density, T is temperature, c is heat capacity, and the thermal diffusivity is indicated by a, shown in equation (3):

$$a = \frac{l}{rc} \tag{3}$$

Where, l is thermal diffusivity.

The ∇ is Laplace operator explained in equation (4) which reveals the gradient of temperature for objects:

$$\nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \tag{4}$$

From above analysis, the temperature increases fast in a very short time during heat stage and the highest temperature distributed at the two faying surfaces between workpiece-workpiece. Thus the parent metal in the contacting region melts rapidly and nugget began to form in the zone. Moreover, solid material near the molten core absorbs high temperature energy and results in plastic ring because of plastic deformation under electrode force and recrystallization. However, if the melt liquid have not cooled down adequately during cooling stage, the liquid can be ejected from the molten core to the plastic ring under the action of the pressure thus the splash would be produced. The plastic ring localized around nugget region is more inclined to have fatigue failure such as cracks and fracture due to process controlling parameters. Therefore, to adjust the electrical current, electrode force and cooling rate correlated to each other scientifically is of great important affecting the nugget formation and weld life.

Thermal-Mechanical Analysis

The electrodes and workpiece are undertaken large deformation in critical contact interfaces because of extremely high temperature and large load in the process. Therefore, the following equitation is expressed considering the thermo-elastic-plastic relationship.

$$\{d\varepsilon\}=\{d\varepsilon_e\}+\{d\varepsilon_p\}+\{d\varepsilon_T\} \tag{5}$$

Where, $\{d\varepsilon\}$ is the full strain increment;

$\{d\varepsilon e\}$is the elastic strain matrix;

$\{d\varepsilon p\}$ is the plastic strain matrix;

$\{d\varepsilon T\}$ is the thermo strain increment matrix.

Hence, the stress-strain increment equation can be expressed as:

$$\{d\sigma\}=[D_e](\{d\varepsilon\}-\{d\varepsilon_p\}-\{d\varepsilon_T\}) \tag{6}$$

Where, $[De]$ is the elastic stress–strain matrix;

$\{d\sigma\}$ is the stress increment matrix.

In the project, the solution of above equation acquires the boundary condition, initial condition as well as material properties which have been applied for mechanical characteristics of RSW. These parameters are interrelated and interact on each other.

During the cooling stage, according to phase transition theory, the rate of martensite formation is speeded up when cooling rate is accelerated. In this way, the martensite content increases from the core to the outer spaces, which lead to the lower martensite in the core material than that in the base metal. Hence, fracture tends to occur in the zone of fusion core which is the nugget region.

Furthermore, when the columnar crystals grow quickly during the contact interfaces where nugget is formed finally, it is easy to introduce internal shrinkage, cracks and other defects because of uneven cooling speed and internal stress generation. Specifically, DP steel is comprised of certain amount of martensite which develops very fast during cooling stage and apparently it is more prone to result in defects. Consequently, fracture is more likely to happen around the nugget since these defects exists around these parts result in weaker strength than other areas of DP materials.

Less attention was paid to various nugget indentation levels of DP steel welds with multiple sheets to assess the fatigue life of spot welds. However, nugget indentation is one the most important indicators evaluating the quality of RSW since it possesses rich information on the electrode current, electrode force and other effective parameters. In the following session, the nugget indentations generated by electrodes are investigated and compared including 10%, 30% and 50% of a sheet thickness with DP material of three sheets stack up in RSW. Besides, the fatigue lives of DP steel welds under tensile shear and cross tension loads are also compared with those of mild steel welds.

Indentations Analysis

Experimental Models

Both tensile shear and cross tension loading samples are conducted for fatigue life evaluation shown in Fig.1 and Fig.2 respectively. Three sheets are stacked up and the length of each layer is 160 mm, the thickness of each sheet is 1.5 mm. The overlapping distance for tensile shear and cross tension specimen is 45 mm. The average nugget diameter is 5.2mm.The indentation levels are 10%, 30% and 50% of a sheet thickness. DP600 and Mild steel are employed and the Chemical compositions are shown in Table 1.

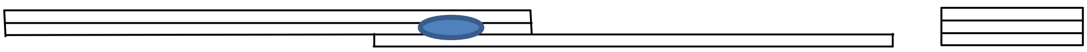

Fig. 1 tensile shear model

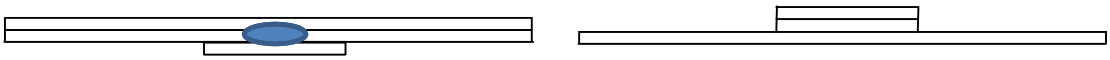

Fig. 2 cross tension model

Table 1 Chemical composition of the materials in weight percentage.

	C	Si	Mn	P	S	Cr	Mo	Ni
Mild Steel	<0.001	0.001	0.077	0.008	0.012	0.023	0.004	0.013
DP600	0.0759	0.01	1.894	0.014	0.006	0.181	0.175	0.014
	Al	**Cu**	**Nb/Cb**	**Ti**	**V**	**Sn**	**Fe**	**B**
Mild Steel	0.0264	0.032	0.01	0.0443	<0.001	0.001	99.748	<0.000
DP600	0.0427	0.031	0.006	0.0025	0.002	0.003	97.542	<0.000

Fatigue life results

Tensile Shear Load for DP Steel

From the fatigue behavior for dual phase welds under tensile shear load in Fig. 3, it shows that different nugget indentation levels of DP steel welds for three sheets stack up result in significant variations of life cycles. The fatigue lives for 50% indentation welds are much longer than 30% indentation welds, particular at the lower load levels. Comparing with the 30% and 10% indentation level welds, similar characteristics are derived as represented in Fig. 3.

Cross Tension Load for DP Steel

The fatigue behavior for dual phase welds under cross tension load in Fig.4 represents that the higher indentation level the welds have, the longer fatigue lives they have, which is similar to the results obtained from Fig. 3. However, the fatigue lives for 30% indentation welds are close to those of 30% indentation welds at low loads. Nevertheless, the differences of welds fatigue lives in Fig.4 are not as noticeable as the result shown in Fig. 3.

Tensile Shear Load for DP Steel and Mild steel

The fatigue life cycles for DP steel and mild steel under tensile shear load are taken into comparison displayed in Fig. 5. Apparently, DP steel welds lead to longer lives than mild steel welds at the same loads condition. Moreover, DP steel welds failed at relative higher loads than those of mild steel. However, mild steel are more inclined to conduct longer fatigue lives at lower load levels below 10KN and much shorter lives at loads above 20KN than DP steel welds.

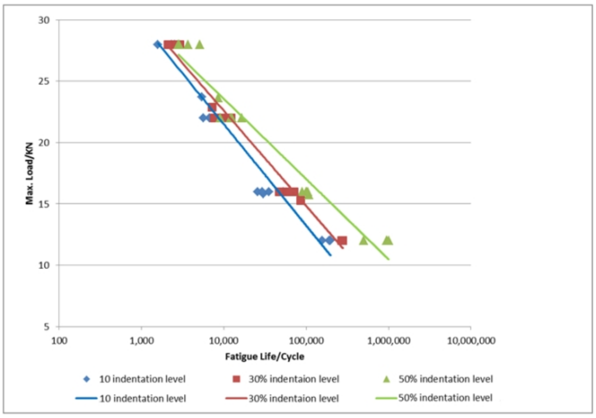

Fig. 3 Fatigue lives for DP welds under tensile shear load

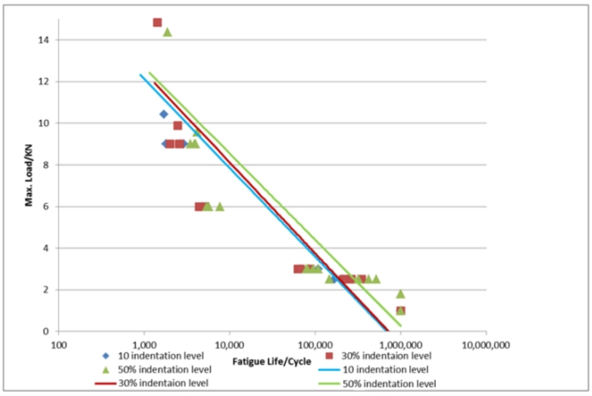

Fig. 4 Fatigue lives for DP welds under cross tension load

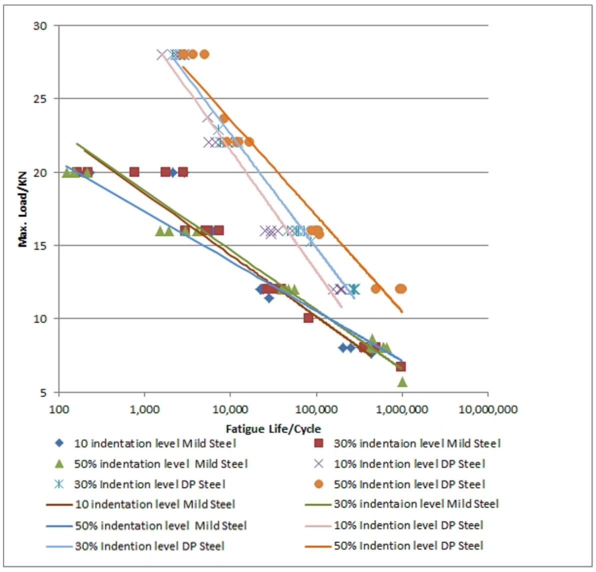

Fig. 5 Fatigue lives for dual phase welds & mild steel welds under tensile shear load

Conclusions

1. The nugget and plastic ring region are more inclined to have fatigue failure such as cracks and fracture. From the mechanism analysis of nugget formation during the RSW process, it is concluded that adjusting electrode force, electrical current and cooling rate are facilitated to control the average nugget size and its performance. Moreover, applying the carbon dilution method or the tempering process is effective for improving the welds quality.

2. It is found out that the fatigue lives of 50% indentation level welds are much longer than 30% indentation level welds for DP steel. Similar results can be obtained comparing 30% and 10% indentation level welds for both tensile shear loads and cross tension loads of DP steel.

3. DP steel welds lead longer lives than mild steel welds at the same load levels. Moreover, DP steel welds failed at relative higher loads than mild steel. However, mild steel are more inclined to conduct longer fatigue lives at lower loads below 10KN and much shorter lives at loads above 20KN than DP steel welds.

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