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Effect of fatigue loading and residual stress on microscopic deformation mechanisms in a spot welded joint

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Abstract

The microstructure evolution in as welded and post-heated residual stress relived spot welded steel sheets during fatigue testing has been studied. The relationship between microstructure evolution and residual stress during fatigue loading has been considered. It has been found that under high fatigue load, dislocation density in spot nugget edge is much higher than that in nugget center area, which indicates significant plastic deformation occurred at the edge of spot nugget during fatigue testing. Under low fatigue load, dislocation density is quite low in both the edge and center area of spot nugget. The effect of post-heating is that more dislocations could be generated during fatigue testing for both high and low loading conditions. Post-heating results in lower strength of spot welded joint while it releases the residual stress in it, which reduces the fatigue life of the spot welded sheet.

Keywords: Spot welds; Residual stress; Fatigue; Dislocation structures

1. Introduction

Spot welding, or resistance spot welding, is a frequently used technique to fabricate sheet metal structures. The process involves joining two or more pieces of sheet metal in localized areas or spots where melting and coalescence of a small volume of material occurs from heating caused by resistance to the passage of an electric current. This process is typically used to obtain a lap joint of sheet metal parts. A common example is the mass production of automobiles, where a typical automobile may contain more than 5000 spot welds.

When the current is turned off, this volume of molten metal cools down and solidifies, beginning from its outer edges. The volume of metal from the work pieces that has undergone heating, melting, fusion, and resolidification is called the weld nugget. The grain structure in the nugget is considerably coarser than the parent metal. Evidently a spot weld cools down to room temperature non-uniformly. The large temperature gradients created by the intense local heating during the welding process followed by rapid cooling, and also phase changes in the solidifying metal, induce heterogeneous deformations in the metal resulting in the development of internal stresses. These internal or remaining stresses are known as residual stresses.

In order to increase the reliability of products, studies on the mechanical properties (including fatigue properties) of the spot welded joint has been attracting a lot of interest [1–6]. It is known that the mechanical properties of a welded joint are not only determined by the microstructure of weld zone metal, but also by the residual stresses introduced by the heterogeneous thermal cycle during welding. Residual stresses play an important role in influencing the fatigue life and other mechanical properties of the spot welded structure. For instance, when the interaction between residual stresses and external loads occurs, the local area that has the highest tensile residual stress is a potential source for crack initiation and growth in the weld or heat affected zone (HAZ).

The fatigue process in a metal is usually associated with microstructural changes, such as dislocations generation and motion, during the initiation period of a fatigue crack. For example, numerous sub-grains form in parent grains in metal during cyclic stressing [7]. The boundaries of those sub-grains are made up of heavily jogged, scalloped and tangled dislocations. The

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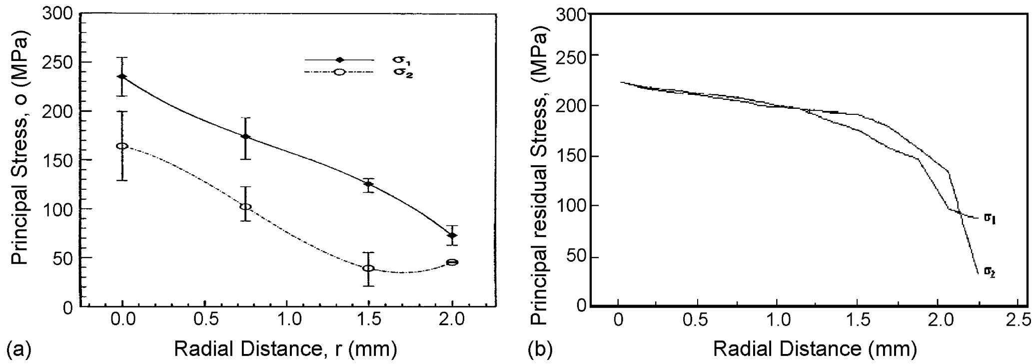

Fig. 1. Residual stress distribution in a spot weld in mild steel sheet, obtained using: (a) Moiré.

density of dislocations within the boundaries tends to increase as the fatigue test progresses. Thus, fatigue behavior, residual stress and microstructure of a spot weld are all interrelated. That is the basis for the present study. The objective of this study was to qualitatively determine dislocation density and dislocation redistribution in the spot weld as a function of fatigue cycles. When a spot welded sample is subjected to tensile shear fatigue loading there is a redistribution of residual stresses and this occurs in conjunction with dislocation generation and motion as a function of the number of fatigue cycles at various depths in the thickness direction of the spot weld. It is hypothesized that changes in the dislocation distribution are related to the residual stress distribution in the spot weld, which in turn affect final failure.

2. Brief review of experimental and numerical investigation of residual stress distribution in a spot weld

Residual stresses are defined as self-equilibrating stresses existing in materials under uniform temperature conditions without external loading. Such stresses being self-equilibrating, the resultant force and the resultant moment produced by them is zero. Residual stresses can be also generated due to elastic–plastic loading, machining, welding, forming, heat-treating, coatings, etc.

Generally, we can distinguish three main kinds of residual stress according to the distance over which they can be observed [8]. The first kind of residual stress, termed macroscopic, is long-range in nature, extending over at least several grains of the material. The second kind, often called structural micro stress, covers a distance of one grain or a part of the grain. It can occur between different phases and have different physical characteristics, or between embedded particles, such as inclusions and the matrix. The third kind of residual stress ranges over several atomic distances within the grain, and is equilibrated over a small part of the grain. In this study we are concerned with the second kind of residual stress or the micro-residual stress field.

A significant effort has been devoted to the measurement of residual stresses in different kinds of welds such as butt weld, fillet weld, etc., in medium to thick plates of various steels [9]. The first series of techniques consist of nondestructive methods, such as X-ray diffraction, neutron diffraction method, ultrasonic method, and the magnetic method. These are based on the relationship between the physical or crystallographic parameters and the residual stress state. The other series of techniques consist of the mechanical methods. These methods mainly involve the measurement of macroscopic engineering strains which are released when material is removed mechanically or by etching from parts loaded by residual stress and subsequent calculation of the residual stress as a function of the strain measured using elasticity theory. The main techniques are the hole drilling method, ring core method, bending deflection method, and sectioning method. These methods have been widely used for measuring residual stresses through the thickness of welds. All these methods are sensitive to the macroscopic residual stress.

However, due to the small size of a spot weld, it is very difficulty to measure the residual stress experimentally. High sensitivity Moiré interferometry with hole drilling [9] and X-rays [10–13] have been tried to measure residual stress in spot welded joint. With Moiré methods in conjunction with hole drilling, the average through thickness residual stresses are obtained, while the X-ray method gives the residual stresses in the surface layers of the weld, though etching techniques have been used for through thickness stress measurement using X-rays.

In addition to experimental methods, numerical study of residual stress by finite element analysis (FEA) has been developed with the advances in computer hardware and finite element method software. In 1984, a thermal-electro-mechanical coupled model was introduced by Nied [14]. Since then, coupled spot welding models have been developed by many researchers to focus on different aspects of the spot welding process, such as temperature distribution, nugget growth, electrode design, welding parameters optimization, etc. [14–20]. Fig. 1 shows the comparison between experimental and simulated residual stress distribution in mild steel spot welded joints [9,20]. It can be seen that the highest tensile residual stress occurs at the center of the nugget and the residual stresses decrease towards the edge of the nugget. Similar results can also be found in Refs [10–13]. Khanna et al. [9] also found that after high amplitude loading (that is low cycle fatigue), residual stress decreases in the center of spot nugget and increases at the edge of spot nugget such that the final residual stress in the edge area is nearly equal to that in center region, as listed in Tables 1 and 2.

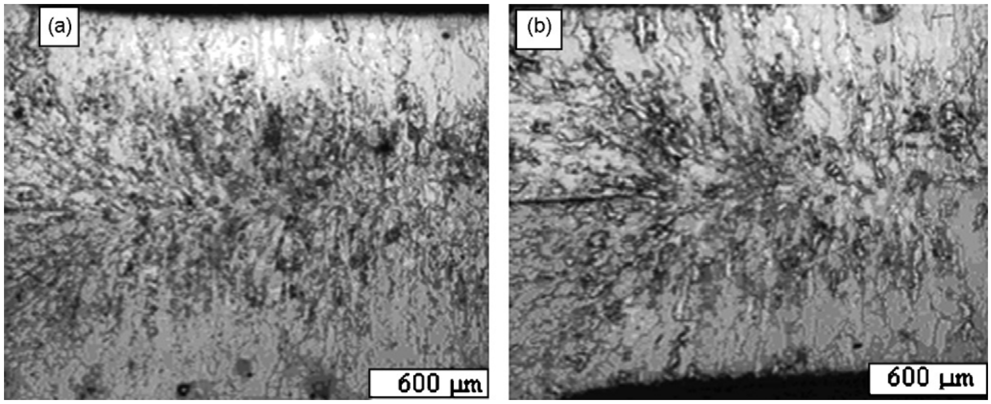

Fig. 2. Microstructure of (a) as welded specimen and (b) post-heated specimen.

Table 1
Residual stress in as welded spot weld nugget [9]

Type of spot welded sample	At center	At edge
Single face	252.0 199.6 254.7	63.2 83.2
Average	235.4	73.2
Double face	247.3 236.0	75.2 87.5 69.1
Average	241.7	77.3

3. Fatigue behavior of low carbon steel spot welded sheet

3.1. Fatigue test

3.1.1. Materials and specimen

The nominal chemical composition and nominal mechanical properties of cold rolled AISI 1020 mild steel sheet are shown in Table 3. The typical microstructure of AISI 1020 is mainly ferrite and some pearlite. Some of the specimens were post-heat treated to relieve residual stresses in the spot welded joint. During post-heat treatment, specimens were slowly heated to a temperature of 650 °C and soaked for 2 h, and then the specimens cooled down slowly within the furnace. Fig. 2 shows the microstructure of the spot welded joint (including base metal, heat affected zone and weld metal) under an optical microscope. No significant grain coarsening was found after post-heat treatment.

Specimens used for fatigue tests were of the tensile shear type, as shown in Fig. 3. The sheet thickness of the specimen was 1.0 mm, the length 180 mm and the width 30 mm. About 45 mm long tabs of the same thickness as the specimen were glued at each end of the specimen to reduce bending deformation at the joint. The average diameter of spot nugget was found to be 6.5 mm for all the samples.

Table 2
The effect of fatigue loading on residual stress in spot weld nugget [9]

Type of spot welded sample	Interrupted during high load fatigue test at 10,000 cycles (MPa)	
	At center	At edge
Single face	168.5 156.7 134.8 175.6	Not available
Average	158.9	
Double face	200.0 158.4 154.1	177.6 104.7
Average	170.8	141.2

Table 3
Nominal (A) chemical composition of mild steel AISI 1020 (wt %) and (B) mechanical properties of mild steel AISI 1020

(A) Chemical composition of mild steel AISI 1020	
C	0.18–0.23
Mn	0.30–0.60
P	0.04 (max)
S	0.05 (max)
(B) Mechanical properties of mild steel AISI 1020	
Tensile strength (MPa)	395
Yield strength (MPa)	295
Elongation (%)	37

3.1.2. Fatigue test procedure

An Instron universal testing machine was used to conduct load-controlled tension–tension fatigue tests. The specimens

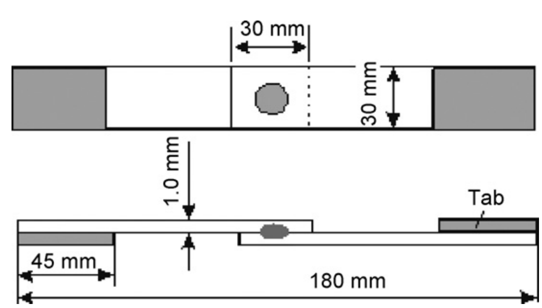

Fig. 3. Tensile shear type fatigue specimen.

Table 4
Quasi-static tension strength of spot welded AISI 1020 steel sheets

As welded (kN)	5.20
Post-heated (kN)	4.82

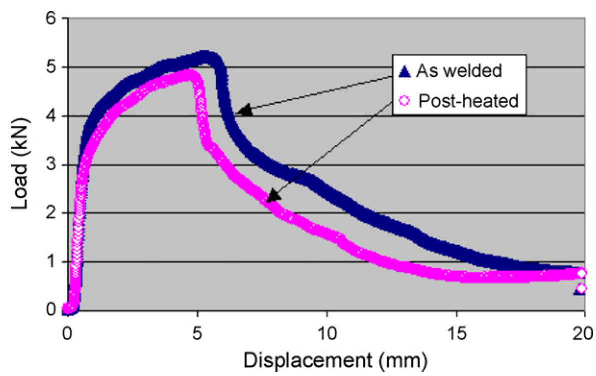

Fig. 4. Quasi-static tensile loading tests of spot welded AISI 1020 steel sheet.

were subjected to varying sinusoidal loading with a load ratio of $R=0.1$, at a frequency of 10 Hz. During the fatigue test, the maximum load, minimum load, maximum and minimum cross-head displacement, and the frequency were monitored by using the Instron Wave Maker Data Acquisition software and 8800 Plus digital controller.

3.1.3. Fatigue test results

Quasi-static tension tests were conducted to obtain the peak load in a spot welded AISI 1020 steel tensile shear specimen in an as welded condition and after post-heat residual stress relief condition, as listed in Table 4. The corresponding typical load versus displacement curves are shown in Fig. 4. It can be seen that after post-heat treatment, the tensile strength of spot welded sheet is decreased by about 8% and yield strength of the joint decreased about 20%.

Table 5 lists the fatigue tests conducted in this study. Since the objective of this study was to investigate the relationship among microstructure, residual stress and fatigue behavior of spot welded steel sheet, the tests were stopped at predetermined number of fatigue cycles. In Table 5 'AW' refers to 'as welded' and 'PH' to 'post-heated' conditions. In the fatigue tests, low loads (such as for specimens AW4, PH3 and PH5) and high loads (such as for specimens AW2, AW8 and PH8) were used to determine the fatigue life of as welded and post-heated specimens at high fatigue cycles and low fatigue cycles. Then, a series of fatigue specimens were stopped during the fatigue tests at the low (such as specimens AW7, AW10, PH9 and PH7), middle (such as specimens AW5), and final (such as specimens AW5, AW9, PH10 and PH6) periods of the fatigue lives under loads which were determined according to the above fatigue-to-failure tests. Those unfailed fatigue specimens were used for transmission electron microscopy (TEM) observations.

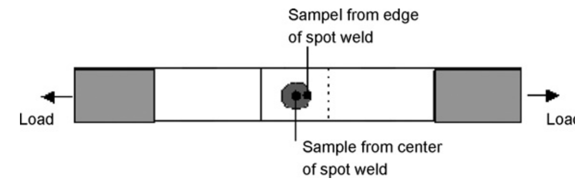

Fig. 5. TEM samples location from spot welded steel sheet.

3.2. Transmission electron microscope observations

3.2.1. Specimen preparation

Thin foil transmission electron microscope (TEM) samples were prepared with the material cut from the unfailed fatigue specimens using a low speed diamond saw. The normal direction of the thin foils was parallel to the specimen axis. Two locations (one is in spot nugget center, the other one is in the edge of spot nugget) in the spot welded sheets were taken to make TEM samples, which is shown in Fig. 5. It should be noted that the samples from the edge of the spot nuggets were under the highest tensile stress during the fatigue loading due to the stress concentration during tensile loading [12].

The thin foils were mechanically ground on both sides with fine sand papers down to a thickness of 100 μm. Discs

Table 5
Fatigue test of as received and after residual stress relief annealed spot welded AISI 1020 sheet

Specimen #	Amplitude (kN)	Maximum load (kN)	Minimum load (kN)	Cycles to failure	Cycles to stop the test
As welded					
AW4	0.68	1.5	0.15	586,235	
AW2	0.96	2.13	0.21	70,618	
AW8	1.49	3.30	0.33	13,214	
AW5	0.54	1.2	0.12		1,000,000
AW6	0.54	1.2	0.12		500,000
AW9	1.49	3.30	0.33		9,000
AW10	1.49	3.30	0.33		1,000
Post-heated					
PH8	1.49	3.30	0.33	20,469	
PH3	0.54	1.20	0.12	874,300	
PH5	0.54	1.20	0.12	789,067	
PH6	0.54	1.20	0.12		500,000
PH10	1.49	3.30	0.33		9,000