International Journal of Fatigue 66 (2014) 20–28

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Investigation on fatigue fracture behaviors of spot welded Q&P980 steel

B. Wang [a,b], Q.Q. Duan [a], G. Yao [a], J.C. Pang [a], X.W. Li [b,c], L. Wang [d], Z.F. Zhang [a,*]

[a] *Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, China*
[b] *Key Laboratory for Anisotropy and Texture of Materials, Ministry of Education, Northeastern University, Shenyang 110819, China*
[c] *Institute of Materials Physics and Chemistry, College of Sciences, Northeastern University, Shenyang 110819, China*
[d] *Baoshan Iron & Steel Co., Ltd., Shanghai 201900, China*

ARTICLE INFO

Article history:
Received 17 November 2013
Received in revised form 24 February 2014
Accepted 6 March 2014
Available online 14 March 2014

Keywords:
Resistance spot weld
Q&P980 steel
Failure mode
Fatigue properties

ABSTRACT

Microstructural characterization, micro-hardness tests, tensile and fatigue tests of spot welded Q&P980 steel were performed using tensile-shear and cross-tension specimens. The hardness values of nugget and base material were measured to be 497 HV and 334 HV, respectively. It is found that the fatigue cracks in heat affected zone (HAZ) initiate at the interface between two sheets. The fatigue failure modes consist of the fracture along the circumference or along the direction of width for tensile-shear specimens and pullout or fracture along the direction of width for cross-tension specimens. It is also found that the fatigue properties of spot welded Q&P980 and DP780 specimens are approximately the same in the case of tensile-shear and cross-tension specimens.

1. Introduction

In order to satisfy the weight reducing, energy saving and security principles of new generation cars, the advanced high-strength steels (AHSS) have been widely used in automobile industry. Sheet steels for automotive application have been defined as the “First Generation” of AHSS and the “Second Generation” of AHSS. The dual phase (DP) steels, transformation induced plasticity (TRIP) steels, complex phase (CP) steels and martensitic (MART) steels are considered as the first generation AHSS [1]. Second generation AHSS includes twinning induced plasticity (TWIP) steels, Al-added lightweight steels with induced plasticity (L-IP®), and shear band strengthened steels (SIP steels) [1]. Recently, there have been increased interests in the development of the “Third Generation” of AHSS, namely, steels with strength-ductility combination significantly better than that of the first generation AHSS but significantly cheaper than the second generation AHSS [1]. In 2003, Speer et al. [2] defined a new heat treatment process that can make steel microstructures which have residual austenite and controlled amounts of martensite, and the process was referred to as “quenching and partitioning (Q&P)”. In this process, austenite was quenched below martensite start temperature (Ms) to contain martensite–austenite, and then heat treated at partitioning temperature which can either be equal to or greater than quench temperature. At partitioning temperature, carbon diffused from martensite to residual austenite to enhance the austenite stability [1,3]. Currently, the Q&P steel becomes the third generation advanced high-strength steel [1]. More recently, Paravicini Bagliani et al. [4] compared the properties of a low alloy medium carbon steel (0.28C wt%) obtained after Q&P and quenching and tempering (Q&T) treatments, and it was found that the strength–toughness combination of specimens treated by the Q&P process was better than that of the Q&T process; Sun and Yu [5] also found that the mechanical properties of low-carbon steels (0.2C wt%) treated by the Q&P process exhibited better combination of strength and ductility than that of the Q&T process. Besides, Černý et al. [6] reported that the fatigue endurance of the Q&P treated material was excellent, followed by classically heat treated and as received conditions in sequence; and Wang et al. [7] found that Q&P exhibited much higher formability than other same grade high-strength steels. Therefore, the Q&P steel has potential application in automobile industry due to its good combination of high strength and good ductility, as well as the excellent fatigue performance and formability. Q&P steels are well suited for cross members, longitudinal beams, B-pillar reinforcements, sills and bumper reinforcements [7].

On the other hand, the materials used in auto manufacturing can be joined by a variety of methods, such as resistance spot welding, fiber laser welding and weld bonding [8]. But the resistance spot welding remains the primary method in automobile manufacturing. For example, a typical vehicle could contain more than 3000 spot welds [9]. Wang et al. [7] reported that when resistance spot welded, Q&P980CR steels required less current and

---

[*] Corresponding author. Tel.: +86 24 23971043.
E-mail address: zhfzhang@imr.ac.cn (Z.F. Zhang).

http://dx.doi.org/10.1016/j.ijfatigue.2014.03.004
0142-1123/© 2014 Elsevier Ltd. All rights reserved.

higher electrode force than conventional steels, and the 1.6 mm Q&P980CR showed good spot weld strength performance. In general, the spot weld undergoes fatigue damage during the service period. Thus, it is of significant importance to investigate the fatigue performance of spot welds for achieving a safe and reliable design. There are many reports about the fatigue behavior of steels after resistance spot welding. For example, Rathbun et al. [10] found that the fatigue performance of spot welded high-strength steels was mainly determined by the geometric factor rather than the material and microstructure. As well as, Vural and Akkus [11] found that the fatigue life increased as the nugget diameter increased; and Shariati and Maghrebi [12] found the longer fatigue life in thicker tensile-shear specimens. Xu et al. [13] concluded that for thin spot welded sheet its microstructure played an important role in the fatigue strength, when sheet thickness increased the fatigue strengths of spot welds of different materials were almost the same. The fatigue strengths of spot welded DP600 GI (1.53 mm), TRIP600 (1.64 mm) and HSLA340YGI (1.78 mm) specimens were approximately the same in the case of tensile shear tests and coach peel type specimens for both low- and high-cycle fatigue lives [9]. In addition, Nakayama et al. [14] confirmed that the fatigue limit of spot welded 270 MPa-grade steel and 590 MPa-grade steel was determined by the fatigue limit of heat affected zone (HAZ) and the residual stress. However, there were no reports about the fatigue behaviors of spot welded Q&P steel.

Based on the investigations above, the purpose of the current study is to further investigate the fatigue behavior of Q&P980 steel after spot welding for both tensile-shear and cross-tension specimens. Firstly, the microstructure change, micro-hardness distribution and tensile properties of spot welded steel were examined. Then, the fatigue failure modes were studied and the crack initiation and propagation mechanisms were discussed. Finally, the fatigue properties of spot welded Q&P980 steel were compared with those of spot welded DP780 steel.

2. Experimental material and procedure

The material used in this study was Q&P980 steel, the chemical composition and mechanical properties of which are shown in Tables 1 and 2, respectively. The dimensions of fatigue specimens are shown in Fig. 1, and the sheet thickness was 1.6 mm. The tensile-shear specimens had length of 125 mm and width of 40 mm. The cross-tension specimens had length of 150 mm and width of 50 mm, respectively.

The metallographic samples were cut along the center of the spot welding steel in the direction of the width of specimens, polished, and etched by 4% Nital (4 mL HNO_3 and 96 mL alcohol). The size of nugget and spot weld were measured by Keyence VHX-1000E Digital Microscope. The nugget diameter and spot weld diameter of fatigue specimens were equal to 6.62 ± 0.04 mm and 7.93 ± 0.04 mm, respectively; as shown in Fig. 2. The microstructure was observed by LEO SUPER35 scanning electron microscope (SEM) and confirmed by the D/max 2400 diffraction instrument. Micro-hardness was carried out at intervals of 0.2 mm using LECO AMH-43 Micro-Hardness Tester at 200 g load for holding 13 s, and the sample and paths are shown in Fig. 4.

The tensile tests of spot weld were carried out according to GB 2651-89, and the tensile experiments of spot weld were carried out on INSTRON 5982 (Fig. 3(a)) testing machine with a strain rate of 1 mm/min. The fatigue tests of spot weld were performed according to GB/T 15111-94, and three specimens were required for each load level. The fatigue experiments of tensile-shear and cross-tension specimens were performed on INSTRON 8801 (Fig. 3(b)) and INSTRON 8871 (Fig. 3(c)) testing machine, respectively. The specimens were under sinusoidal load with a load-ratio $R = 0.1$, in the frequency range from 10 to 50 Hz. In order to prevent a bending moment applied at the spot weld, shims with the same thickness as the sheet were glued at both ends of the tensile-shear specimens. As the specimens ruptured or the length of cracks was equal to the diameter of spot weld, the failure was considered to take place, and specimens that survived 10^7 cycles were called as running out. As the three specimens performing under the same load level all survived 10^7 cycles, the corresponding fatigue load was considered as the conditional fatigue limit load (10^7 cycles). Finally, LEO SUPER35 (SEM) was used to identify the fatigue crack initiation site, crack propagation route and to observe the characteristics of fracture surface.

Table 1
Chemical composition of Q&P980 steel (wt%).

C	Si	Mn	P	S	Al
0.23	1.55	1.92	0.010	0.002	0.040

3. Results and discussion

3.1. Micro-hardness distribution and microstructure change

The micro-hardness distribution is shown in Fig. 4. It could be seen that the hardness of nugget and base material (BM) were 497 HV and 334 HV, respectively; and the hardness of nugget was nearly 1.5 times higher than the base material. The SEM and X-ray diffraction (XRD) examination indicated that the microstructure of nugget was predominantly martensite (Figs. 5(a) and 6(a)), and the microstructures of BM were ferrite, martensite and residual austenite (Figs. 5(d) and 6(b)). The microstructure in the nugget depended on heat input and cooling rate during resistance spot welding progress. It was reported that the cooling rates ranged from over 10^5 °C/s for sheet thickness less than 0.5 mm, to nearly 2000 °C/s for 2 mm thick sheet [15]. Thus, the cooling curve missed to touch the nose of the continuous cooling transformation (CCT) curves, resulting in only martensitic transformation [16]. Also Xu et al. [13] and Ma et al. [17] reported that the nugget was full of martensite. There was a hardness peak between the nugget and heat affected zone (HAZ) (see Fig. 4). The reason for the occurrence of hardness peak could be that the thermal history of this region results in smaller grain size compared with that of nugget [13]. Besides, Ma et al. [17] found that there was a transition zone between nugget and HAZ, and that the microstructure comprising of martensite in the transition region was finer than that of the nugget; however, such a transition zone was not found in this study. The microstructure of HAZ was mainly composed of martensite and carbide (Figs. 5(b) and 6(b)), but the martensite in the HAZ was smaller and its weight fraction (~84.3%) was lower than that in the nugget. In the HAZ, the hardness value varies, i.e., the region near the nugget had a higher hardness value than the region far away from nugget, similar results were also found in fiber laser welded DP980 [16] and DP600 [18]. In addition, there was a region with a lower hardness value (~300 HV) even than the BM (334 HV) between the base material and HAZ, which was called the soft zone as indicated in Fig. 4. The similar soft zone was also found in spot welded DP600 [19] and M190 [20] steels. Fig. 5(c) showed that the soft zone of Q&P980 steel after spot welding contained ferrite and tempered martensite. The softening degree depends on material chemistry and welding heat input [21].

3.2. Tensile properties of spot weld

The ultimate tensile loads of spot welded Q&P980 tensile-shear and cross-tension specimens were 23.7 ± 0.6 kN and 10.8 ± 0.5 kN,