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Strain-controlled fatigue testing of TRIP800 high-strength quenching and partitioning steel

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Abstract. In this paper, TRIP800 steel plates of thickness of 1.2 mm were subjected to the quenching and partitioning (Q&P) process and underwent strain-controlled fatigue tests. The respective experimental fatigue curves were plotted, and the influencing factors of fatigue resistance were identified and analysed, while the specimen fractographies were examined. The test results show that the existence of residual austenite inhibition of crack extension and strain induced the martensite phase transformation in the residual austenite. The residual compressive stresses improved the fatigue strength of Q&P steel plates under study. The fatigue fracture nucleation occurred in surface inclusions, the crack propagation zone exhibited the ductile fracture mode, while the transient area possessed the brittle fracture features.

1. Introduction

With the continuous expansion of production and marketing of automotive industry in China, the issues of energy saving, environmental protection, and safety become very topical. The efforts should also be focused on the formulation of relevant laws and regulations concerning the automobile material saving. High-strength steel application can ensure the light weight of automobiles, which is aimed by automobile and related industries [1-2].

In recent years, the researchers from Colorado University, US [3] developed a phase transformation-induced plasticity (TRIP) steel. After quenching and isothermal treatment above a certain temperature, the carbon and carbon became repeatedly included into martensite. The carbon by residual austenite to martensite distribution, thereby is gained by martensite and retained austenite consisting of two phases at room temperature of the high strength, plasticity and toughness. This process is called the quenching and partitioning process (Q&P) of martensite steel heat treatment [4-5]. Compared with the general high- and ultrahigh-strength steels, the proposed TRIP steel, which composition includes Fe, C, Mn, and Si, is cheap. Due to a lucrative combination of high strength and toughness achieved by the Q&P process, it draws the attention of international researchers, who seek to produce the Q&P steel at room temperature with low-carbon lath martensite and carbon-rich residual austenite.

However, the Q&P steel, as a lightweight substitute material for automobiles, must also have good fatigue properties, in order to have wider application prospects [6]. In this paper, through the Q&P processing of low-carbon and-low silicon TRIP800 steel plate, through the constant-strain fatigue test, the cyclic stress response of Q&P steel under the condition of constant-strain curve and strain fatigue life curve are established, and its fatigue resistance with the identification of influencing factors is analyzed. The macro- and microfracture of specimens are observed, the fatigue crack propagation and failure modes are discussed, and the basic data on fatigue design and reliability analysis of structural parts are provided.

2. Experimental

2.1. Test materials



The microstructure of TRIP steel is mainly composed of ferrite (F), superbainite (B + F), and residual austenite (γ), as shown in figure 1. Table 1 is the main component of TRIP800 steel plates for the test, while the main mechanical properties of steel plates are listed in table 2.

Table 1. Chemical composition of TRIP800 steel (wt %).

C	S	P	Mn	Si	Al
0.22	<0.005	0.021	1.87	1.54	0.050

Table 2. Mechanical properties of TRIP800 steel.

Tensile strength, MPa	Yield strength, MPa	Elongation, %
915.73	585.8	17.5

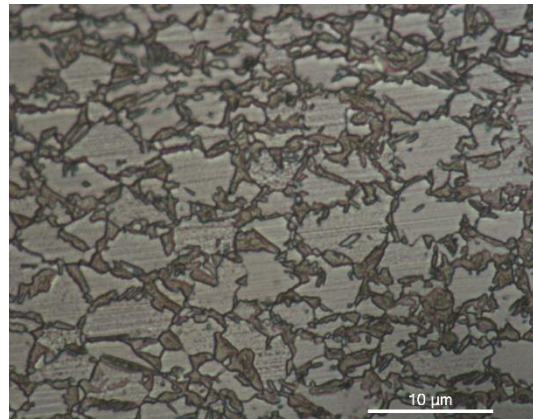


Figure 1. Microstructure of TRIP800.

2.2. TRIP800 steel plate Q&P processing

TRIP800 steel is in quenching after heating to 760 and 350°C, and then carbon distribution under the temperature of 400°C is to be heated for 1 min after cooling to the room temperature.

2.3. Test process

According to the national standard (GB -T 3075-2008) of China's metal axial fatigue test method, fatigue test is carried out on the electro - hydraulic servo fatigue test machine. The model of fatigue testing machine is the maximum test force of EHF-UM100k (SHIMADZU): dynamic plus or minus 100KN, static plus or minus 150KN, stress loading error plus or minus 0.5%, and strain measurement error plus or minus 0.5%. Load frequency is 0-50Hz, power is 380V. The microstructure of spot welding joint has been analyzed with the NiKonEPIPHOT300 optical microscope. The tensile fracture morphology has been observed by JSM-5600lv scanning electron microscope.

3 Results and Discussion

3.1. Cyclic stress response curve

The cyclic stress response curve of the maximum stress of the corresponding cyclic number is shown in figure 2.

It can be seen in figure 2 that the curve shows a rising trend in the early stage of Q&P steel constant-strain fatigue experiment, which indicates that the phenomenon of cyclic hysteresis is presented. In the process of cyclic loading, while the average stress is less than the yield strength, but it still exists within the local microstructure of individual single crystal weak zone. Recycling early will appear when the

slip. The slippage can cause the dislocation of the adjacent grain to be moved, and the dislocation will accumulate in the front of the obstacle, thus the deformation will be strengthened. When the dislocation reaches a certain critical value, the stress concentration reaches a certain critical value, and the dislocation will extend to other neighboring grains, because of the existence of the slip system, which is different from the production slip system. And, therefore, the strain-hardening occurs.

In the Q&P steel constant-strain fatigue test, the plastic deformation occurs in the maximum stress concentration zone. Because the existence of TRIP effect makes the residual austenite to martensite transformation, inhibition of the further plastic deformation occurs. If fatigue crack formation in the tip, the residual austenite to martensite transformation can produce significant work hardening, further set up the movement of the dislocation. Making the metal surface is not only difficult to form residues slip band, extrusion ridge of, or intrusion into a ditch, and delays the fatigue crack extension, but also possible strain aging, and can synthetically cause hardening phenomenon in this cycle until the number of cycles $N = 70000$ times or so is reached, the curve of a downward trend, stress gradually decreases with the cyclic time, and this stage for Q&P steel constant-strain fatigue test is of strain-softening stage. This stage is the initial boundary damage stage, which is accompanied by the formation of plastic deformation and a series of cavitation processes. Under the action of alternating load of reciprocating, the cyclic hardening reaches a turning point. Some fatigues reverse the process, such as dislocation reverses the movement caused by different number of dislocation interaction and offset, resulting in dislocation density decreased or cellular dislocation substructure change; or the interaction of dislocation can form micropores, which can be increased with the process development. In a region where the strain is aging, it dissolves and forms a weak zone with no aging. These processes are gradually playing an important role, which will lead to the strain-softening. The core of microcrack is formed when the microplastic deformation depletion and cavitation accumulation develop to a certain extent. The duration of this stage is the longest, and the evaluation of fatigue resistance of materials mainly considers the performance of this stage.

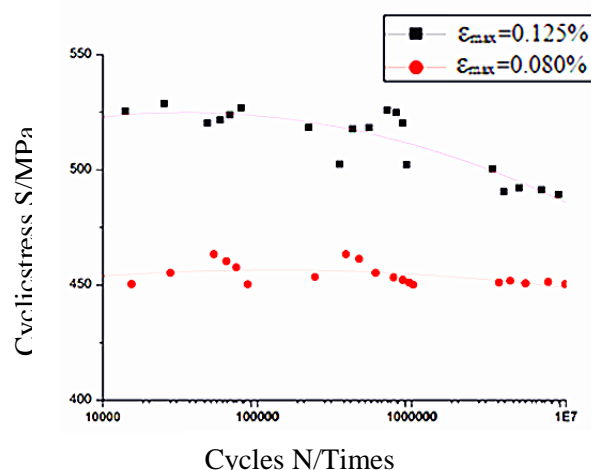


Figure 2. Cyclic stress response curve.

It can be clearly seen from both curves in figure 3 that the cyclic stress reduction trend corresponding to the two curves changes significantly during at $N=1 \times 10^5$. The strain level is $\epsilon_{\max}=0.125\%$ at the final phase of the strain-softening, and as the number of cycles continues to increase, the stress shows the change of accelerating decline. The macroscopic crack occurs during this period and is visible to the naked eye, and the corresponding plastic deformation is increased rapidly, then the crack is rapidly

expanded until the crack is broken. $\varepsilon_{\max}=0.080\%$ strain levels for the curve, at the end of the strain-softening stage, with the continue increase of cycle number, small variations in stress, is gradually stabilized. The specimen did not break. In general, the process of cyclic hysteresis and strain-softening is finally terminated.

3.2. Fatigue crack source and crack fracture mechanism

Figure 3 depicts of the fatigue fracture of the specimen, which can be seen in figures 1 and 2. Figures 1 and 2 depict two fatigue sources are produced in different plane. The crack location in figure 1 is herringbone stripe extended to the right, and the fan is scaled up. The crack location in figure 2 in the final crack extension plane. The cracks in three places are connected by the coalescence, and the final fracture occurs by tear. The crack expansion plane produced by crack sources in figure 2 is very rough on the right side, indicating cracks originating from the crack source in figure 2 have propagated and led to the final fracture in this point.

Figure 4 is a scanning electron microstructure of specimen fatigue crack source. The fatigue of Q&P steel plate can be seen from the plate surface or the surface inclusion. The crack source is in the tear of the plate and there are many inclusions. The plastic flow is blocked here, causing a large stress concentration. The first initiation of the crack is the source of the crack.

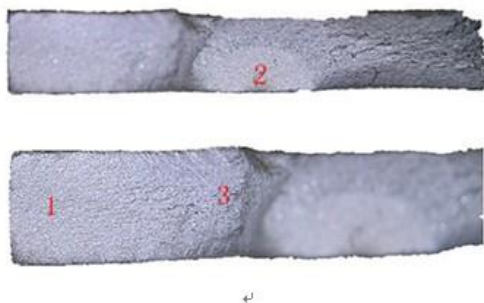


Figure 3. Fatigue fracture of specimen.

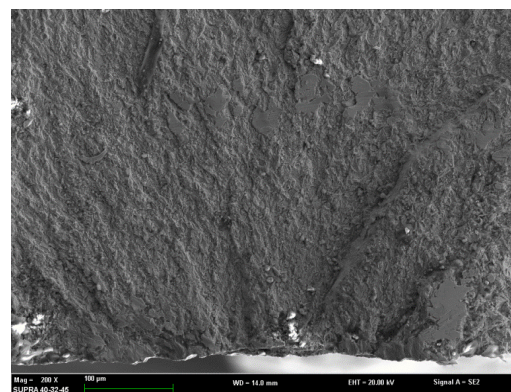


Figure 4. Scanning electron microstructure of specimen fatigue crack source.

Figures 5 and 6 are the SEM images of the fatigue crack propagation zone and the transient fracture zone. It is not difficult to see from figure 6 that there are two cracks in the crack propagation zone of the fatigue fracture. Because of the great stress at the tip of the crack, the Q&P steel can induce martensite around the crack propagation direction under the TRIP effect. The occurrence of martensite affects the stress field distribution at the crack tip, delays the crack propagation, and leads to the two cracks. Under the action of cyclic stress, the two cracks and the main crack expand at the same time. After a certain period of extension, the propagation rate of the main crack gradually slows down, and finally stops, while the new initiation of the two cracks replace the main crack and continues to expand. In the two cracks formation, a large amount of energy is absorbed. Therefore, the formation of the two cracks can well hinder the propagation of fatigue crack, which reflects the excellent strain fatigue property of fine grained structure of Q&P steel.

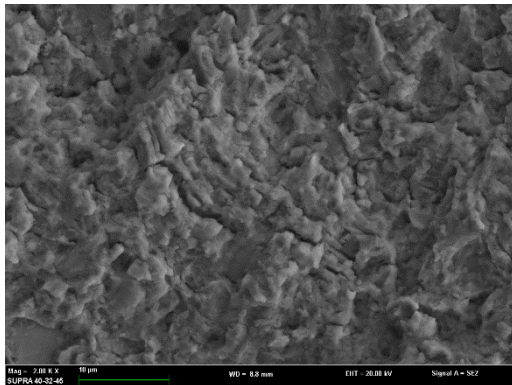


Figure 5. SEM of fatigue fracture crack propagation region.



Figure 6. SEM of fatigue crack in specimen.

As seen in figure 6, according to tearing edges and typical fracture, the plastic deformation occurred in the microregion with tearing edges. It is equivalent to the tensile fracture of plastic materials but here the necking zone, fracture zone fracture, and fatigue crack propagation area are more rough.

4. Conclusions

- ✓ The Q&P steel was subjected to strain-controlled cyclic tests with the loading frequency of 8Hz and zero strain ratio ($R=0$). The fatigue strain level corresponding to the base number of cycles (10^7) was $\varepsilon_f = \varepsilon_{10^7} = 0.080\%$.
- ✓ The existence of residual austenite inhibition of crack extension and strain induced the martensite phase transformation in the residual austenite. The respective residual compressive stress improved the fatigue strength of Q&P steel plate.
- ✓ The fatigue fracture nucleation in the Q&P steel occurred in surface inclusions, the crack propagation zone exhibited the ductile fracture mode, while the transient area possessed the brittle fracture features.

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