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Fractographic Study on the Fatigue Failure Surfaces of Heat-Treated and Shot Peened EN- 8 Steel (080M40/AISI 1040)

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The microstructure study has been carried out on the fatigue fractured surface of heat-treated and shot peened EN-8 (080M40/AISI 1040) steel. This microstructure study has revealed the characteristic appearance and physical arrangement of a metal as observed with a microscope. In order to realize the initiation and progression of fatigue failure, the fractured surfaces have been analyzed with the Scanning Electron Microscope (SEM). In this present work, the different categories of heat-treated and shot-peened fatigue fractured samples such as WT, Q&T, SP, and combined Q&T and SP have been taken for fractographic investigation. For probing the fractured surface, SEM images have been taken with different magnifications for each category of samples fractured under 293.45MPa bending stress. The combined Q&T and SP sample has fractured at the interface of a granular region and beach marks have been spread over the fractured surface. The results of Q&T and SP sample fractured surface analysis have concluded that the brittle fracture with inter-granular cracks has been formed due to the relieving of residual stresses at the surface of the samples obtained from combined treatments.

Keywords: Fractography, Fatigue, Microstructure, Quenching & Tempering (Q&T), Shot Peening (SP), Without Treated (WT)

1 Introduction

The metal fatigue phenomenon has been focused on the failure of bridge structures and the rotary parts of various machineries. This fatigue failure has different characteristics and effects than other kinds of failures. It occurs without any obvious warning and without gross deformation at the fracture. Henceforth, enhancing fatigue strength to yield better performance in these applications has become mandatory. In general, heat treatment and peening processes have yielded good results in enhancing fatigue strength in medium carbon steels. The combined Q&T and SP process has improved fatigue strength (2.31x 10^6 cycles for 293.45 MPa) in EN-8 (080M40/ANSI1040) steel compared to the WT, Q&T, and SP processes. This combined treatment has resulted in a 75% improvement in fatigue life compared to WT samples. The shot peening process has extended the life of fatigue and crack propagation. For hard materials, shot peening has developed hard surfaces on the topside due to induced plastic deformation, while homogeneous deformation arises in soft materials to restrict crack nucleation. However, high-intensity shot peening processes have failed to enhance fatigue strength due to greater surface damage. The Q&T and SP processes on 51CrV4 steel have provided an 86.3% improvement in fatigue life compared to non-treated samples[1-3].

The combined nitriding and induction hardening process has increased fatigue strength in EN-8 steel compared to individual nitriding and induction hardening processes. The grain size, non-metallic inclusions, porosity, and texture are key microstructural features in fatigue crack initiation and also affect the trend line of the stress-life curves. Specimens possessing a martensitic structure have a higher tendency to develop surface crack initiation than bainitic structured specimens under polished and rough surface conditions[4-6].

The reduction in grain size and elongation of unalloyed medium carbon (EN8) steel has increased the tensile strength as well as the hardness of the material. Tempering done after normalizing in EN-8 steel has provided a reasonable hardness value and fine grains with a pearlite microstructure. The yield strength, ultimate tensile strength, and elongation at the failure region have various influences on the stress flow and formability of the material, all of which are controlled by the structural parameters. Samples possessing induction hardening and cryogenic

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treatment have a martensitic structure when tempered in the low-temperature range[7-10].

2 Materials and Methods

2.1 Methodology

Figure 1 displayed the complete methodology that was followed in this present work, presented in a sequential order.

2.2 Material and Properties

The EN-8(080M40/AISI1040) medium carbon steel was selected for a fractographic study on its fatigue fractured surface. It was received in the form of a round bar with a diameter of 14mm and in a normalized condition. The mechanical and chemical properties of the metal were shown in Table 1 & 2, respectively.

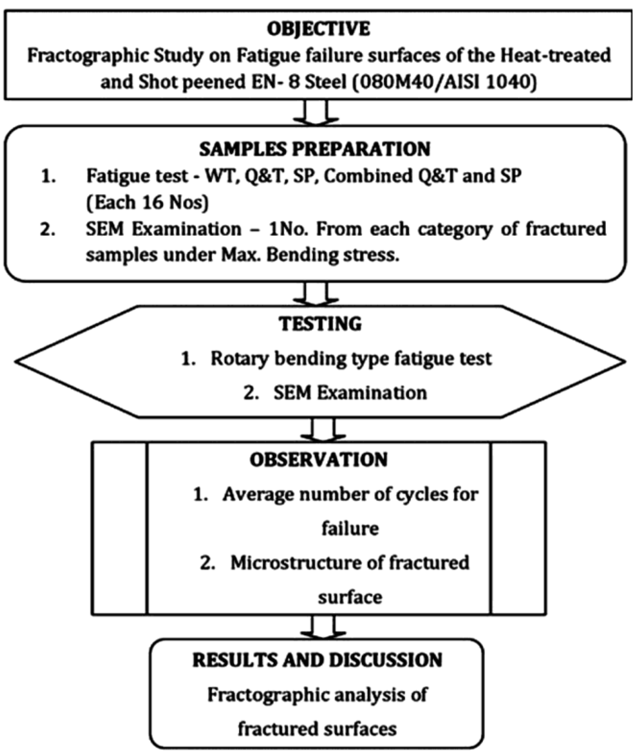

Fig. 1 — Methodology.

2.3 Sample Selection

The sample selection had an inevitable role in the experimental design. The number of samples that were taken for the study reflected in the accuracy of the experimental results. Generally, testing more samples resulted in better accuracy compared to the minimum. For this proposed work, 16 samples were selected for the fatigue test, and one sample (fractured under maximum bending stress) was chosen for SEM examination from each category sample.

2.4 Processing Techniques and Procedure

2.4.1 Quenching and Tempering

In this process, quenching and tempering were achieved in two stages. Initially, the samples were heated to a temperature of 870° C for 60 minutes and then suddenly cooled by oil. Subsequently, they were heated to 220° C and allowed to cool in atmospheric air for a period of 120 minutes. This process resulted in improved mechanical properties and reduced internal stresses and brittleness of the metal[1].

The Fig. 2 illustrated the time and temperature relationship for quenching and tempering. It showed that the above-mentioned process had been completed below the GSK-line temperature regions, except for austenitizing. The quenching process was done by reducing the temperature with a lesser time interval, while tempering was completed with a controlled temperature for a fixed time. It was clear that the temperature range for strengthening was higher than that of tempering.

2.4.2 Shot Peening

In this process, the samples were shot peened on the peripheral surface with high carbon steel shots of diameter 0.1mm under a striking pressure of 0.6MPa for 100 seconds. As a result of this process, a compressive residual stress layer could be created on the outer surface of the samples, leading to a significant enhancement in the fatigue life of the metal[1]. The Fig. 3 showed the internal details of the peening nozzle used in the peening process.

Table 1 — Mechanical property - Manufacturer / Suppliers Data – (Bentech Steels (P) Ltd, Coimbatore)

Property	Hardness (HRC)	Tensile Strength (MPa)	Yield Strength (0.2% offset (MPa)	%of Elongation (Total) (%)	Density (g/cc)	Modulus of Elasticity (GPa)	Poisson's Ratio
Value	16	550	280	16	7.845	200-210	0.26 -0.30

Table 2 — Chemical properties (Observed) - Optical Emission Spectroscope (Omega Inspection and Analytical laboratory, Chennai)

Element	C	Mn	Si	P	S	Cr	Ni	Fe
Content Range in Wt %	0.44	0.82	0.26	0.16	0.03	0.01	0.01	Remaining

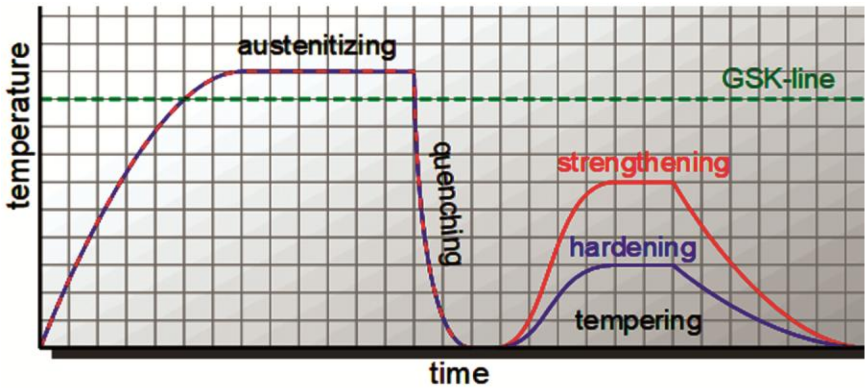

Fig. 2 — Quenching and Tempering (Source: Tec-science.com/material-science).

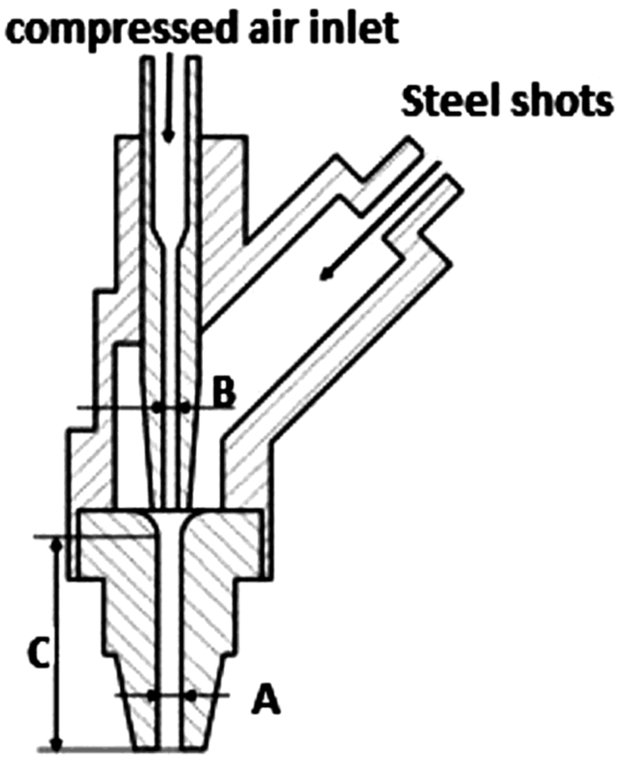

Fig. 3 — Cross sectional view of peening Nozzle.

2.4.3 Combined Q&T and SP Process

The Combined Q&T and SP process was proposed to achieve the united outcomes of both processes and enhance the fatigue strength of the material. In this process, the Q&T process preceded SP in the sequential order. This was because the effect of the Q&T process influenced up to the center core of the sample, while SP only affected the surface[1].

2.5 Testing Methods

2.5.1 Fatigue Test

For the conduct of the fatigue test, 16 samples were taken from each category and 4 samples were tested per stress value. The samples were prepared in a CNC turning centre following the testing standards of (IS: 5075-1969). The entire test was completed in an MFT-8-D rotary bending type machine at a speed of 4,500 rpm, maintaining the bending stress range above 290MPa under room temperature[1].

2.5.2 SEM Examination

In this examination, only one sample was taken in each category, which failed under ultimate bending stress and had a higher average number of cycles. Firstly, the fractured surfaces of the samples were sized to 10x10 pellets using a cutting process, and the surfaces were cleaned from dust and moisture. Afterwards, the polished sample pellet was positioned inside the vacuum chamber and images were taken at different magnifications (16X, 100X, 249X, and 500X). The VEGA3 TESCAN type Scanning Electron Microscope was employed in this work, and its constructional features were shown in Fig. 4. This machine consisted of a LaB6 filament with paramount resolutions of 2 nm and 2.5 nm at 30 kV in high-vacuum mode and low-vacuum mode, respectively. The fractured surface of each category of samples, such as Combined Quenching & Tempering and Shot Peening, Quenching & Tempering, Shot Peening, and Without-Treated, were shown in Fig. 5, (a,b,c, & d) respectively.

3 Results and Discussions

3.1 Fatigue analysis

It was observed that, with the consideration of fatigue life, the Q&T and SP samples had a greater average number of cycles than the WT samples. However, the individual comparison between Q&T and SP samples revealed that Q&T had superior quality compared to SP. The fatigue test results

Fig. 4 — Scanning Electron Microscope (VEGA3 TESCAN) – Research Lab – GCE, Salem.

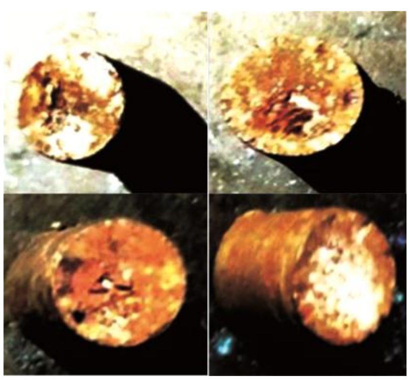

Fig. 5 — Different category samples for SEM examination (a) combined quenching & tempering, (b) shot peening, quenching (c) shot peening, & (d) without-treated.

confirmed that the combined Q&T and SP samples had a greater average number of cycles than the other category samples. It was evident from the analysis that the fatigue strength increased with the decreased bending stress[1].

3.2 SEM analysis

The fractured samples of the fatigue test were used to identify the fracture mode and causes of failure and to carry out a micro-structural study of the fatigue region. Mostly, fractography required examination at a better-quality scale, which was normally provided by SEM, which had higher resolution than the optical microscope.

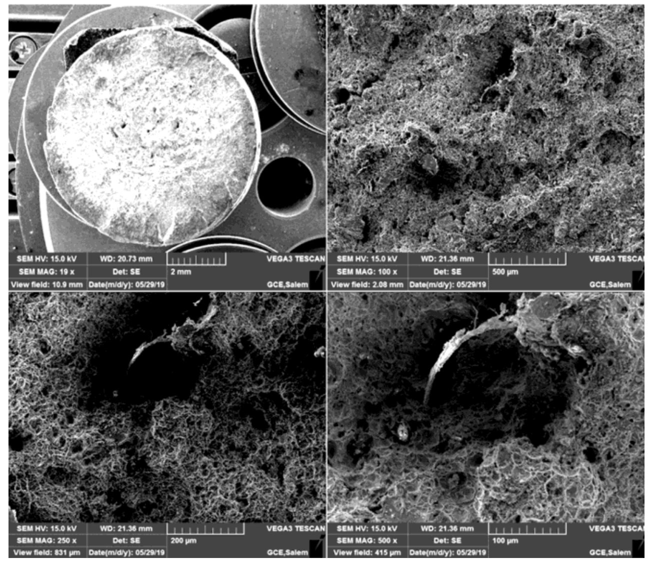

Fig. 6 — SEM Images of Fractured Without-Treated sample (WT) of AISI 1040 Steel.

3.2.1 Fractography study on Without-Treated sample (WT)

The Fig. 6 showed the SEM images of the fractured surface of Without-Treated (WT) AISI 1040 steels tested under 293.45MPa of bending stress and fractured after 1.32 X 10^6 cycles with different magnifications. It was observed from the images that the cracks were initiated at the outer layer and proliferated to the center core of the sample. It was identified that the sample failed under the transgranular fracture mode by observing the crack propagation paths.

3.2.2 SEM Fracture Study of Quenching and Tempering Samples (Q&T)

The Fig. 7 showed the fractured surface of Quenching and Tempering Samples (Q&T) of AISI 1040 Steel tested at 293.45MPa and failed after 1.85 X 10^6 cycles. From the magnified images, it was observed that the fractured surface had more burnished region than the WT sample. This increased burnishing region indicated a delay in crack propagation and resulted in better fatigue strength against the same bending stress compared to the WT sample.

3.2.3 SEM Fracture Study of Shot Peening Samples (SP)

Figure 8 illustrated the crack nucleation, crack growth, and fracture region. From the SEM images, it

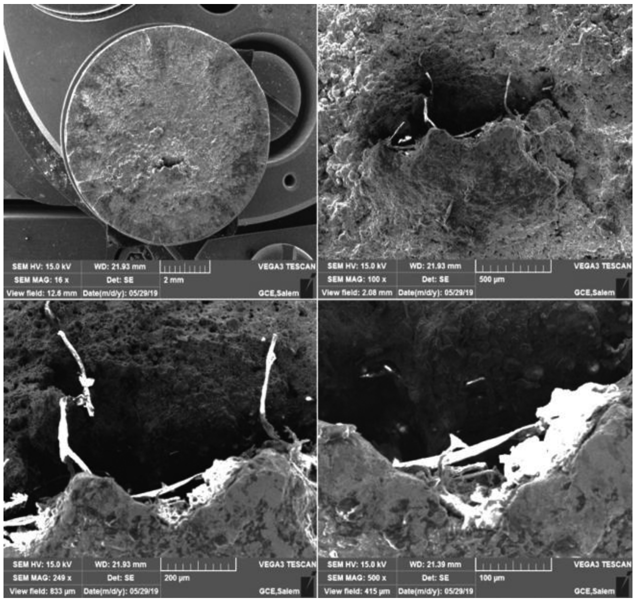

Fig. 7 — SEM Images of Fractured Quenching and Tempering Samples (Q&T) of AISI 1040 Steel.

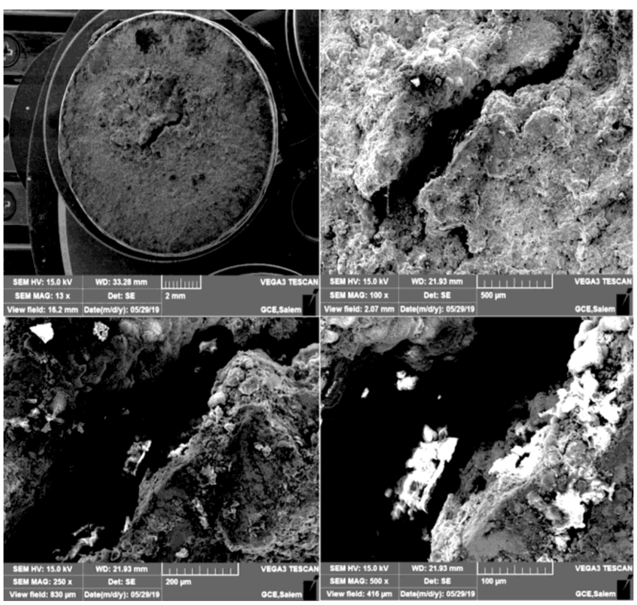

Fig. 8 — SEM Images of Fractured Shot Peening Samples (SP) of AISI 1040 Steel.

was noticed that the cracks originated from the outer surface of the sample and slowly moved towards the center. The crack growth rate was considerably low in the burnished region, and the SP samples had more granular regions than Q&T samples. Generally, the crack growth rate was significantly increased in the granular region due to less resistance in crack propagation. Hence, the quickness in crack propagation decreased the fatigue strength of the SP samples compared to Q&T. These SEM images were

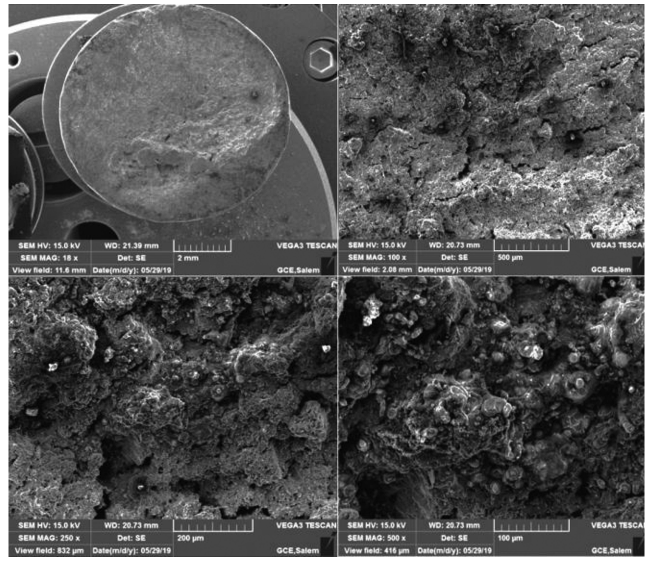

Fig. 9 — SEM Images of Fractured Quenching & Tempering and Shot Peening Samples (Q&T and SP) of AISI 1040 Steel.

taken from the SP fatigue tested samples under 293.45MPa and fractured at 1.58 X 10^6 cycles.

3.2.4 SEM Fracture Study of Combined Quenching &Tempering and Shot Peening Samples (Q&T and SP)

Figure 9 showed the fractured surface images of the combined Quenching & Tempering and Shot Peening (Q&T and SP) samples of AISI 1040 Steel tested at 293.45MPa and fractured at 2.31X 10^6 cycles. By investigating the images, it was confirmed that the failure of the sample occurred at the junction of the granular region and beach marks which spread over the fractured surface. This combined treatment released the residual stresses on the outer layer of the sample and led to brittle fracture with inter-granular cracks. These inter-granular cracks had a lower propagation speed than the granular and burnished region cracks. Hence, the fatigue strength of the combined Q&T and SP samples was significantly higher than the other category samples.

4 Conclusion

Based on the fractography investigation on the fractured surface of WT, Q&T, SP, and combined Q&T and SP samples tested under the same bending stress value of 293.45MPa, a few conclusions have been obtained as follows.

- According to the WT sample, the cracks have been initiated at the outer layer and have proliferated to the center core of the sample. By visualizing the crack propagation paths, it has been observed that the failure has occurred under transgranular fracture.

- In the Q&T sample, the fractography analysis of the fractured surface has shown a greater burnished area which has been formed due to the rubbing of metal particles compared to the WT sample. This increased burnishing region has reduced the crack propagation velocity and has resulted in better fatigue strength (40.15%) in the Q&T sample compared to WT.
- The SEM images of the SP sample have confirmed that the crack development in the granular region has been considerably more than the burnished area. The microstructure has indicated that the increased granular region has resulted in a significant loss of fatigue strength (20.12%) compared to Q&T.
- By analyzing the microstructure of the combined Q&T and SP sample, it has been found that the failure has occurred at the junction of the granular region and beach marks due to brittle fracture with inter-granular cracks caused by the liberation of residual stresses. Due to the reduction in the propagation velocity of inter-granular cracks, the fatigue strength of the combined Q&T and SP sample has shown a significant improvement (75%) compared to WT.

Hence, the study has proven that the combined Q&T and SP process is most suitable for EN-8 (080M40/AISI1040) steel.

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