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Fatigue failure of SUP-9 spring steel

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Abstract

The SUP-9 is a widely used steel for the construction of springs due to its resistance to permanent deformation and quick vibration relief. Spring steels are subjected to heat treatment to improve their fatigue life. In this paper, the heat treatment procedure to improve the endurance limit of the SUP-9 is reported. The process of heat treatment was carried out to investigate its effect on Brinell and Rockwell hardness metrics. The endurance limits of steel before and after heat treatment were also measured. The heat treatment procedure reported in this paper resulted in an increased harness and endurance limit due to a change in the microstructure of the specimen. The test results showed that Brinell hardness and endurance limit increased by 50% and 20% respectively after heat treatment.

1. Introduction

Springs are made with a special class of steel known as spring steel. These steels contain iron, carbon, manganese, silicon, phosphorus, sulfur, and vanadium as major alloying elements. Various standardization organizations allot different codes to spring steels to identify them. One of the widely used spring steels is the Japanese Industrial Standards (JIS) SUP-9. The JIS-SUP-9 equivalent spring steels in other standardization schemes are European Standards (EN) 55Cr3, British Standards (BS) 525A58 & 525H60, Association Francaise de Normalisation (AFNOR) 55C3, American Society for Testing and Materials (ASTM) 5155, and Chinese Standards (GB) 55CrMnA. The SUP-9 is specially used to manufacture leaf springs for locomotives, wagons, and carriages [1, 2]. It is high carbon steel with a high melting point and specific heat capacity of 1450 °C and 470 J kg⁻¹·K, respectively [3].

Fatigue is one of the major causes of spring failure. Fatigue failure occurs due to repeated loading and unloading. It is important to increase the fatigue life of a component because fatigue failure shall not only be catastrophic but will cause great economic loss a well. Fatigue (or endurance) limit and fatigue strength are two metrics used to describe the fatigue life of the material. Fatigue limit is the highest fluctuating stress that a material can undergo infinitely [4]. Since it is not possible to test springs infinitely, fatigue strength is the metric used to indicate the fatigue property of a material. Fatigue strength is the greatest stress that material may undergo for a given number of cyclic loading without failure. To improve fatigue limit and strength, heat treatment may be employed. It may be defined as a procedure of controlled heating and cooling of metals and alloys to induce certain properties into them [5]. Heat treatment of material may be used to improve the mechanical properties of steel by altering the size and shape of its micro-constituents [6, 7]. By changing microstructure, heat treatment improves material hardness which, in turn, improves the fatigue strength of the material. Unlike fatigue strength measurement, hardness can be easily measured in a short time with low-cost equipment.

Various researches have been conducted related to leaf springs owing to their importance in vehicle dynamics. Y Harada et al. [8] have investigated to observe the effectiveness of micro shot peening on SUP-9 leaf spring fatigue life. They used compressed air-type micro shot peening and demonstrated sufficient deformation...
It was observed from the results that the process significantly improved the fatigue life of the spring steel. They also studied the effects of micro shot peening on the hardness of the spring steel which improved from 560 HV to 620 HV. The method was very effective especially in reducing surface defects. Authors of [9] performed finite element analysis on parabolic leaf spring to conventional leaf spring based on different materials. It was observed from the results that the composite material (Carbon- Epoxy) had better fatigue life than the conventional SUP-9 spring steel owing to the lightweight and low susceptibility to stress. P Dutt et al [10] have analyzed the design and strength of glass fiber reinforced plastic (GFRP) parabolic leaf spring. They showed that the GFRP parabolic leaf spring possessed better fatigue life than the steel leaf spring owing to its higher failure stress value of 78.3 N mm$^{-2}$. Moreover, the mass of the GFRP parabolic leaf spring was also lower than the normal leaf spring. In [11] authors report the impact of hot rolling and heat treatment on the SUP-9 and the AISI-1045 steels. The hot-rolled steels were subjected to subsequent heat treatment. The results showed a reduction in ductility and roughness with the decrease in thickness of the steels. The yield and tensile strengths improved due to heat treatment. The comparative analysis showed that SUP-9 demonstrated better mechanical properties than the AISI-1045 spring steel due to the higher quantity of martensite.

Compared to the aforementioned work, this research attempts to investigate a relationship between hardness and fatigue life of SUP-9 steel. The hardness may be defined as resistance to indentation [12]. Fatigue failure occurs due to repeated loading and unloading. Hardness and fatigue tests are carried out to investigate the relationship between hardness and fatigue strength. Metallography, the microstructural examination of metals under the microscope, is carried out to study the microstructural changes due to heat treatment. The fractography of the broken specimens was carried out to study the mode of failure.

The remainder of this paper is organized as follows. Section 2 describes the material used in this research, section 3 comprises of methods of different tests which are carried out, section 4 presents the results of the tests carried out, section 5 critically discusses the methods and results, and section 6 concludes the paper.

### 2. Material and methods

#### 2.1. Test specimen

JIS-G-4801 spring steels are available in different grades such as SUP-6, SUP-7, SUP-9, SUP-9A, SUP-10, SUP-11A, SUP-12, and SUP-13. The SUP-9 is a manganese chromium steel that is extensively used for the manufacture of laminated, coiled, and torsion springs. The SUP-9 used in this research has the chemical composition given in table 1 [13].

Silicon and Manganese enhance fatigue strength, toughness, and resilience. Some of the mechanical properties of SUP-9 are given in table 2 [13].

**Table 1. Chemical composition of SUP-9.**

| Element  | Value (Weighted Percentage) |
|----------|-----------------------------|
| Carbon (C) | 0.55%                      |
| Manganese (Mn) | 0.78%                     |
| Chromium | 0.76%                      |
| Phosphorous (P) | 0.22%                     |
| Silicon (Si) | 0.19%                      |
| Sulphur (S) | 0.12%                      |
| Copper (Cu) | 0.12%                      |
| Nickel (Ni) | 0.08%                      |

**Table 2. Mechanical properties of SUP-9.**

| Metric        | Value                           |
|---------------|---------------------------------|
| Elongation    | 9%                              |
| Reduction of Area | 20%                           |
| Yield strength | 100 kgf mm$^{-2}$ (0.2% off set) |
| Tensile strength | 125 kgf mm$^{-2}$               |
| Elastic modulus | 19400 kgf mm$^{-2}$            |
| Shear modulus | 7450 kgf mm$^{-2}$              |

in the workpiece. It was observed from the results that the process significantly improved the fatigue life of the spring steel. They also studied the effects of micro shot peening on the hardness of the spring steel which improved from 560 HV to 620 HV. The method was very effective especially in reducing surface defects. Authors of [9] performed finite element analysis on parabolic leaf spring to conventional leaf spring based on different materials. It was observed from the results that the composite material (Carbon- Epoxy) had better fatigue life than the conventional SUP-9 spring steel owing to the lightweight and low susceptibility to stress. P Dutt et al [10] have analyzed the design and strength of glass fiber reinforced plastic (GFRP) parabolic leaf spring. They showed that the GFRP parabolic leaf spring possessed better fatigue life than the steel leaf spring owing to its higher failure stress value of 78.3 N mm$^{-2}$. Moreover, the mass of the GFRP parabolic leaf spring was also lower than the normal leaf spring. In [11] authors report the impact of hot rolling and heat treatment on the SUP-9 and the AISI-1045 steels. The hot-rolled steels were subjected to subsequent heat treatment. The results showed a reduction in ductility and roughness with the decrease in thickness of the steels. The yield and tensile strengths improved due to heat treatment. The comparative analysis showed that SUP-9 demonstrated better mechanical properties than the AISI-1045 spring steel due to the higher quantity of martensite.

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2. Material and methods

2.1. Test specimen

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2.2. Hardness testing

Hardness is measured by resistance to permanent indentation under static load conditions. In this research, Brinell and Rockwell hardness tests are carried out. Brinell hardness testing machine comprises a ball mounted in a plunger and attached to a piston in the main cylinder. The ball is forced on the test surface resulting in an indent in the test piece. The diameter of the indent is measured using a microscope and Brinell hardness is calculated using the formula given in equation (1) [14].

\[
HB = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})}
\]

Where HB is Brinell hardness (kg/mm²), P is Load applied for indentation (kg), D is the diameter of steel ball (indenter) and d is the diameter of the indent. Tables 3 and 4 and record the indentation diameters of specimen before and after heat treatment. Tables 5 and 6 and record Rockwell hardness of the specimen before and after heat treatment.

Rockwell’s hardness test also calculates hardness by measuring the indentation of the sample. Compared with Brinell hardness testing, the loads and indenters are smaller resulting in shallower indentation. Moreover, it is faster than Brinell testing because it produces direct readings. The indenter for this machine comprises a steel ball of a specified diameter, and the load is applied using a diamond indenter.

| Table 3. Brinell hardness test data before heat treatment. |
|-----------------|----------------|
| Run | Indentation diameter (mm) |
| 1 | 3.4 |
| 2 | 3.5 |
| 3 | 3.4 |
| 4 | 3.5 |
| 5 | 3.5 |
| Mean | 3.46 |

| Table 4. Brinell hardness test data after heat treatment. |
|-----------------|----------------|
| Run | Indentation diameter (mm) |
| 1 | 2.8 |
| 2 | 2.8 |
| 3 | 2.9 |
| 4 | 2.8 |
| 5 | 2.9 |
| Mean | 2.84 |

| Table 5. Rockwell hardness test data before heat treatment. |
|-----------------|----------------|
| Run | Rockwell Hardness No. (HRC) |
| 1 | 23.5 |
| 2 | 22.5 |
| 3 | 22.6 |
| 4 | 22.0 |
| Mean | 22.5 HRC |

| Table 6. Rockwell hardness test data after heat treatment. |
|-----------------|----------------|
| Run | Rockwell hardness no. (HRC) |
| 1 | 39 |
| 2 | 37 |
| 3 | 41 |
| 4 | 39 |
| Mean | 39 HRC |
ball of several specified diameters and a diamond cone penetrator having an inclined angle of 120° with a spherical tip of a radius of 0.2 mm. Three different loads of 60 kg, 100 kg, and 150 kg were applied by a dead weight loading lever. The Rockwell number is read on the dial gauge of the machine. The Rockwell value is designated by a number and a prefix letter which indicates the loads applied and the size of the indenter. For instance, Rockwell B-scale uses a steel ball with a 100 kg load and Rockwell C-scale uses a diamond cone with a 150 kg load.

2.3. Fatigue testing

The rotary bending testing machine was used to perform fatigue tests. The test specimen, having dimensions shown in figure 1 was attached to the chucks of the testing machine. The test specimen was prepared on a Computer Numerical Control (CNC) lathe machine. A deadweight applied at the bottom of the machine developed a bending moment on the specimen as shown in figure 2. For cyclic loading and unloading of bending moment, the machine rotated the specimen axially at 2900 revolutions per minute. The digital counter on the machine displays the number of rotations.

Bending stress can be calculated using the following formula given in equation (2) [15].

\[ \sigma = \frac{Mc}{I} \]  \hspace{1cm} (2)

Where,
- \( M \) = bending moment (kg.cm),
- \( c \) = centre distance (cm),
- \( I \) = area moment of inertia (cm\(^4\)), and
- \( \sigma \) = stress in the specimen (kg cm\(^{-2}\)).

As seen in figure 2, distance \( L = S_1 - S_2 = S_3 - S_4 = 20 \) cm

Since, the specimen is simply supported beam, the bending moment can be calculated as given in equation (3):

\[ M = \frac{WL}{2} \]  \hspace{1cm} (3)

Where,
- \( W \) = dead weight (kg).
The center distance \( c \) may be calculated as given in equation (4):

\[
c = \frac{d}{2}
\]  

(4)

Where \( d \) is the diameter of the specimen (cm)

The area moment of inertia is calculated as given in equation (5):

\[
I = \frac{\pi d^4}{64}
\]  

(5)

Putting values of \( M, c \) and \( I \) from equations (3)–(5) respectively into equation (6):

\[
\sigma = \frac{16WL}{\pi d^3} \text{ kg cm}^{-2}
\]  

(6)

Since, \( L = 20 \text{ cm} \),

\[
\sigma = \frac{101.86W}{d^3} \text{ kg cm}^{-2}
\]  

(7)

Equation (7) gives bending stress in the specimen.

2.4. Heat treatment

Heat treatment of the specimen is carried out as follows:

1. Heating above the critical range (austenite condition) at a temperature of 850 °C.
2. Soaking (holding) at that temperature for 35 min [16].
3. Bringing to room temperature by oil quenching.
4. Tempering at a temperature of 490 °C in the furnace for 35 min
5. Cooling to room temperature in air.

These steps are shown in figure 3.

2.5. Metallography

The microstructural examination of the metal or alloy is referred to as metallography [17]. A flat, scratch-free, and mirror-like surface was prepared by mounting, grinding, and polishing specimen. To reveal microstructure, specimen etching was carried out. The following steps were carried out:

(i) The specimen was mounted in a synthetic plastic known as the Bakelite in mounting press at temperature and pressure of 160 °C and 30 kN, respectively.

Figure 3. Temperature curves during the heat treatment process.
(ii) The specimen was ground using a series of emery papers containing successively finer abrasive grit sizes 320, 500, 700, and 1200. These sizes correspond to 34, 18, 11, and 5 microns, respectively. The emery papers were mounted on rotating wheels and the specimen was held against it. Abraded particles were removed by a small stream of water on the center of the rotating wheel.

(iii) Intermediate polishing was carried out using diamond paste with abrasives in the 4–10 microns range. An oil-based extender was used to uniformly distribute diamond particles over the surface of the polishing cloth.

(iv) Final polishing was carried out using aluminum oxide on the polishing cloth. In this process, fine scratches remaining from previous processes were removed.

(v) The specimen was cleaned using a stream of water and dried under the blast of air.

(vi) Finally, etching was carried out to reveal the specimen crystalline structure. The Picral (4 g of Picric mixed with 100 ml of Methyl alcohol) etchant was used to dip the specimen for 5–10 s. The specimen was held by tongs and immersed with the polished face down into a small dish filled with the etchant. When the specimen showed sufficient etching, it was washed in warm water and dried in a blast of air.

(vii) The specimen was observed under an optical microscope at a magnification of 400. Photomicrographs were subsequently taken.

3. Results

3.1. Brinell hardness test

3.1.1. Received condition (Hot Rolled)

\[
HB = \frac{2 \times 2500}{3.1416 \times 10(10 - \sqrt{10^2 - 3.46^2})} \approx 5000
\]

\[
HB = \frac{2 \times 2500}{31.416(10 - 9.3823)} \approx 5000
\]

\[
HB = \frac{2 \times 2500}{19.406} \approx 257.65
\]

3.1.2. Heat treated condition

\[
HB = \frac{2 \times 2500}{3.1416 \times 10(10 - \sqrt{10^2 - 2.84^2})} \approx 5000
\]

\[
HB = \frac{2 \times 2500}{31.416(10 - 9.59)} \approx 12.93
\]

\[
HB = \frac{2 \times 2500}{19.406} \approx 386.7
\]

3.2. Rockwell hardness test

3.2.1. Received condition (Hot Rolled)

3.2.2. Heat treated condition

3.3. Fatigue test
3.3.1. Received condition (Hot Rolled)

Developed stress in table 7 was calculated using equation (3). For example, for sample number 1, calculations are given as under:

\[
\sigma = \frac{101.86(35)}{(1.015)^3} \text{ kg cm}^{-2}
\]
\[
\sigma = \frac{3565.1}{1.0457} \text{ kg cm}^{-2}
\]
\[
\sigma = 3409.3 \text{ kg cm}^{-2}
\]

A similar process was followed for other calculations given in tables 7 and 8.

3.3.2. Heat treated condition

3.4. Metallography microstructures

Figure 4 shows the microstructure of SUP-9 (as received) at room temperature. The structure shows the pearlite (black areas) and ferrite (white areas). The light black areas show the presence of alloys etched in Picral.

Figure 5 shows the microstructure of oil quenching and tempering (OQT) SUP-9. Metal was hardened at 850 °C, followed by oil quenching. Metal was then tempered at 490 °C, followed by air cooling. The soaking time for both operations was set to 35 min. The martensite formed after quenching takes the form of sorbite. Sorbite is minutely granular (not resolvable at this magnification). It is formed by a gradual breakdown of martensite resulting in a uniform distribution of minute particles of carbide in a ground mass of a ferrite. The precipitation of fine cementite particles decreases the time necessary to etch tempered martensite and tends to darken microstructure. Internal stresses are eliminated and metal’s toughness is improved.

Figure 6 shows the Scanning Electron Microscope (SEM) fractograph of the SUP-9 (as received) having fatigue strength 3400 kg cm\(^{-2}\) at 5030 cycles.

Figure 7 shows the fatigue strength of the SUP-9 after heat treatment that is 2370 kg cm\(^{-2}\) at 3000 cycles.

4. Discussion

The hardness and endurance limit of the SUP-9 spring steel before and after tempering and heat treatment was measured in this research. The microstructure was also examined before and after heat treatment. The SEM fractographs of the broken fatigue test specimens are also presented. The OQT resulted in increased hardness. The BHN of OQT SUP-9 registered an increase of 53%. Endurance limit showed improvement with increased
Figure 4. Microstructure of SUP-9 as received (X400).

Figure 5. Microstructure of OQT SUP-9. Etched in Picral. (X400).

Figure 6. SEM Fractograph of as received SUP-9 (X10).
hardness. Microphotographs showed that the structure became more refined after OQT. Oil quenching results in the formation of martensite, a hard needle-like constituent. On tempering, this martensite takes the form of troostite (medium temperature tempering) and sorbite (high-temperature tempering) for SUP-9. The development of sorbite resulted in increased hardness. It was observed that the uniform structure of sorbite resulted in a higher endurance limit. Both troostite and sorbite increased endurance limit. The results show a 20% fatigue strength and 50% BHN increase due to heat treatment. This indicates a positive correlation between hardness and fatigue strength. In [8], authors have used the micro shot peening process to improve the hardness and fatigue life of the SUP-9 spring steel. They reported an increase of approximately 10% Vicker’s Hardness (from 560 HV to 620 HV). They also reported some improvement in fatigue life. In the research reported in this paper, the authors found an increase of 50% in BHN. The fractography reveals the origin of cracks and their growth. The fractographs show the central ridges indicating brittle type failure. The improvement in hardness is due to oil quenching and subsequent tempering. The endurance limit due to this heat treatment increased by 20%. The comparative analysis shows that the methods reported in this paper produced better results in terms of an increase in hardness and endurance limit.

The results reported in this research indicate that oil quenching and tempering is an effective method of increasing the fatigue life of SUP-9 spring steel. The results also show that there exists a positive correlation between hardness and fatigue life. These inferences have great importance because there exist many methods of heat treatment and selecting the appropriate method is a major task to improve the fatigue life of the material. Moreover, hardness can be easily and quickly measured as compared to the measurement of fatigue strength which requires specialized testing equipment continuously running for many hours or even days.

The research has a limitation in that it is conducted using a testing machine rotating at a high speed. Hence, under actual low cycle loading and unloading fatigue strength may be different. Future work may include tweaking the optimum temperatures for heat treatment and using a combined bending-torsion fatigue testing machine.

5. Conclusions

The spring steel SUP-9 specimens underwent tests for Brinell hardness, Rockwell hardness, and endurance (fatigue) limit. The heat treatment consisting of oil quenching and subsequent tempering was carried out to improve the hardness and fatigue strength of the specimens. Microscopic tests were carried out before and after heat treatment to study the effect of heat treatment on the microstructure and fatigue strength of the material. The BHN of SUP-9 registered an increase of 50% after heat treatment. The corresponding improvement in endurance limit was measured to be 20%. The improvement of hardness and endurance limit is attributed to the development of refined microstructures known as sorbite and troostite. The results of hardness, fatigue, and

Figure 7. SEM Fractograph of OQT SUP-9 (X10).
metallographic tests presented in this article indicate the appropriateness of the selection of heat treatment methods for increasing the fatigue life of SUP-9 spring steel.

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