Effect of heat treatment on strength and ductility of 52CrMoV4 spring steel.

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Abstract. In this study we examined the behaviour of the 52CrMoV4 spring steel at various tempering temperatures and soaking times. The hardening and quenching process was set up to achieve a minimum hardness of 800 HV by selecting an appropriate quenching medium. The microstructure was evaluated optically and with scanning electron microscopy (SEM) and the mechanical properties were characterised by hardness and tensile tests. An excellent combination of strength and ductility was achieved on conventional alloyed steel by adjusting heat treatment process parameters. The strength and ductility of the material was found to be comparable to that of advanced high strength steel (AHSS).

1 Introduction

The manufacturing of heavy duty springs from steel requires an exact understanding of the heat treatment process and material behaviour. Although the presence of alloying elements can improve the mechanical properties, they also escalate the cost of the steel [1]. Therefore, the selection of the steel and manufacturing process must be robust in such a way that the spring will exhibit excellent strength and ductility with minimal alloying elements. Furthermore, it is important to select a quenching media that will harden the steel without forming quench cracks or distortion. This is a function of the selected heat treatment process, the quenching media and the alloying elements in order to provide acceptable mechanical properties. The heat treatment process alters the microstructure and strength of material, which will directly influence fatigue life [2].

Spring manufacturing requires materials with good formidability as well as strength in order to improve performance [3]. The majority of automotive springs are made from medium carbon high strength steels [4]. To increase the strength of the steel is simple, however, it is difficult to get a combination of high strength and ductility. Generally, an increase in strength results in a loss of ductility [5]. This study will focus on the heat treatment process, microstructure and mechanical properties of spring steel. The manufacturing process of the springs entails high temperature coiling, hardening and tempering [6].

This study will investigate whether a heat treatment process can make a conventional 52CrMoV4 steel compete with advanced high strength steel (AHSS). The strength and hardenability of the 52CrMoV4 steel is improved by additions of elements such as chromium, molybdenum and vanadium. Molybdenum provides solution strengthening in steel during heat treatment, while chromium and vanadium forms carbides that improve the hardness of the material during tempering [7]. Molybdenum also forms fine carbides precipitates that increases the strain hardening effect [8]. On the other hand vanadium has been used as a micro-alloying element for high strength low alloy steels since the 1950s [9]. It improves the strength and hardness by formation of vanadium carbides and grain refinement [10]. With the effort to increase the strength, precaution is required to avoid temper embrittlement [11]. The strength is a critical factor in determining the fatigue life of a material.
2 Experimentation and material

A 52CrMoV4 steel rods were cut into 25 X 320 mm sections. The samples were placed in the furnace when it stabilised at 860 °C, thereafter the samples were soaked and austenitised at 860 °C temperature for an hour. The samples were quenched in oil with the quenching properties as shown in Table 1. Three tempering temperatures were used: 410, 450 and 470 °C; and two tempering times for each temperature, namely: 2 and 3 hours. The continuous cooling curve (CCT) of the steel were simulated using JmatPro software by inserting the chemical composition of the spring steel. The chemical composition was determined with a Bruker optical emission spectrometer. The oil quenching ability was analysed with a portable quenchant test system (IVF smart quench). The transverse section of the rod was cut, ground and polished to a 1 µm surface finish for metallographic examination. The polished surface was etched with a 3% Nital reagent. The microstructure was characterised with the optical microscope and SEM, while the penetrant test (PT) was used to determine the presence of quench related flaws. Micro hardness profile measurements were conducted across the transverse section of the steel rod from one edge to the other edge at a 1 mm interval using a 5 gf load for the micro Vickers hardness test. Rietveld analysis was used to quantify X-ray diffraction (XRD) results to characterise phases.

Table 1. Quenching oil properties

| Properties          | Oil  |
|---------------------|------|
| Appearance          | Liquid |
| Fire point (°C)     | 220  |
| Flash point (°C)    | 204  |
| Density (g/cm³)     | 0.854|
| Pour point (°C)     | -15  |
| Viscosity (mm²/s @ 40 °C) | 20   |

3 Results and discussion

3.1 Chemical Analysis

The chemical composition of the spring steel is presented in Table 1. The chemical analysis confirmed that the steel is a micro-alloyed 52CrMoV4 steel containing 0.19 wt% Mo and 0.11 wt % V. The addition of Mo and V alloying element improves the hardenability of the steel.

Table 2. Chemical composition of the steel in weight percentage

| Element | % C | % Si | % Mn | % P | % S | % Cr | % Ni | % Cu | % Mo | % V |
|---------|-----|-----|------|-----|-----|------|------|------|------|-----|
| Mass %  | 0.55| 0.28| 0.92 | 0.012| 0.007| 1.05 | 0.01 | 0.01 | 0.19 | 0.11|

3.2 Quench Test Analysis

The oil quench test results are shown in Figure 1. The oil showed complex cooling behaviour at various temperature stages. The harmonisation of the continuous cooling temperature (CCT) curve and the oil cooling rates observed in Figures 1 and 2, predicts full martensite transformation. The CCT curve revealed martensite start to be 265 °C, whilst the cooling rate of the quenching medium was approximately 6.7 °C/s.

3.3 Microstructural Examination

The microstructure of the as-quenched steel rods is presented in Figures 3 and 4. The general microstructure of the as quenched spring steel was martensitic. There was no evidence of cracks or quenching related flaws. The XRD analysis of the as quenched steel revealed the structure to be a mixture of martensite (79%), iron carbide (19.8) and ferrite (2%). The XRD spectrum is shown in Figure 5. The as tempered microstructures are presented in Figures 6 to 11. The general microstructure was tempered microstructure. Figures 6 to 11 revealed the decomposed unstable martensite to tempered martensite. The SEM analysis images are shown in Figures 12 to 17. Figure 12
showed rod shaped iron carbide (Fe₃C) layered around ferrite that retained the high-density dislocation of martensite. Figures 13 and 14 showed ferrites with low density of dislocation and the mixture of rod-shaped and spherical iron carbides (Fe₃C). Figures 15 to 17 presented a structure of tempered martensite which is predominately made up of spherical and rod-shaped carbides. There is a presence of needle like carbides as well. The observation on the samples tempered 2 hours was a microstructure with rod shaped carbides whilst the samples tested for 3 hours showed pronounced spherical carbides.

Figure 1. Quenching media cooling rate plot

Figure 2. Extrapolated CCT curve for 52CrMoV4

Figure 3. The as-quenched martensite

Figure 4. SEM image of the as-quenched martensite

Figure 5. XRD spectrum, showing -Martensite -Iron Carbide, -Ferrite
Figure 6. Microstructure tempered at 410°C for 2 hours

Figure 7. Microstructure tempered at 410°C for 3 hours

Figure 8. Microstructure tempered at 450°C for 2 hours

Figure 9. Microstructure tempered at 450°C for 3 hours

Figure 10. Microstructure tempered at 470°C for 2 hours

Figure 11. Microstructure tempered at 470°C for 3 hours

Figure 12. Microstructure tempered at 410°C for 2 hours

Figure 13. Microstructure tempered at 410°C for 3 hours
3.4 **Mechanical properties**

The as-quenched and tempered microhardness results are illustrated in Tables 3 and 4. The hardness generally decreased with the increase in tempering temperature, however the sample that were tempered for 3 hour showed evidence of secondary precipitation hardening when compared to the material tempered for 2 hours (see Figure 13). The secondary hardening was as a result of coalesce of Mo₃C and V₄C₃. On the other hand, the strength decreased, and ductility increased with the increase of tempering temperature. The tensile results are shown in Figure 14 and Table 5. The elastic region of the tensile test sample showed elastic behaviour or spring effect until yielding point.

**Table 3.** The as quenched hardness measurements

| Average | Standard Deviation | Standard Error |
|---------|--------------------|----------------|
| 804     | 15                 | 3.03           |

**Table 4.** The tempered hardness profile average

| Measurements | Average | Standard Deviation | Standard Error |
|--------------|---------|--------------------|----------------|
| 410°C 2hrs   | 521     | 12.4               | 2.6            |
| 410°C 3hrs   | 524     | 17.3               | 3.6            |
| 450°C 2hrs   | 475     | 12.8               | 2.7            |
| 450°C 3hrs   | 491     | 15.5               | 3.2            |
| 470°C 2hrs   | 482     | 14.6               | 2.9            |
| 470°C 3hrs   | 486     | 12.7               | 2.6            |
Figure 18. Hardness measurements for various tempering temperatures and times

![Hardness Measurements](image)

Figure 19. Tensile curves of quenched and tempered steel.

Table 5. Tensile strength and total strain of quenched and tempered steel.

| Tempering Parameters | Ultimate Strength (MPa) | Tensile Yield (MPa) | Strength | Strain (%) |
|----------------------|-------------------------|---------------------|----------|------------|
| 410°C 2h             | 1674                    | 1633                |          | 9          |
| 410°C 3h             | 1655                    | 1608                |          | 10         |
| 450°C 2h             | 1462                    | 1424                |          | 11         |
| 450°C 3h             | 1558                    | 1516                |          | 12         |
| 470°C 2h             | 1412                    | 1343                |          | 12         |
| 470°C 3h             | 1495                    | 1420                |          | 13         |

4 Conclusions

The presence of molybdenum and vanadium influenced the mechanical properties by forming fine carbides precipitates that introduced secondary precipitation hardening. The optimum strength and ductility of the spring steel was improved by subjecting the material to various tempering...
temperatures and soaking time. The study also showed that tempering time is an important variable in influencing precipitation hardening. The amount of Mo-rich and C-rich fine precipitates (carbides) varied at different tempering temperatures and soaking times. However, the amount carbides increased with increase in temperature. Tempering of 52CrMoV4 material at 470°C for 3 hour has provided high strength and excellent ductility. The findings of this scientific study will assist spring manufacturers optimise the mechanical properties of the spring steel.

5 Reference

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