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Effect of heat treatment on hardness of modified spring steel material

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Abstract. Spring steel materials are mainly used for semi-static loading applications. In addition, they provide a proper suspension of engineering structures in order to maintain their structural integrity. In order to meet properties required for engineering service, spring should be able to deform elastically during loading and return to its original shape upon unloading, without any plastic deformation or fracture. A plastic deformation alters the structural integrity, resulting in a loss of spring functionality. Since hardness is one of required primary properties of spring steel, this study conducted several heat treatment designs to optimize hardness of altered spring steel material. Microstructures were acquired and analysed using an optical microscope. A suggested approach for heat treatment design is recommended for engineering applications.

1 Introduction

A global challenge of transitioning to green energy plummets majority of engineering fields such as power generations and transportations [1]. Current engineering technologies are heavily reliant on electricity that has a base-load generated from thermal coal power generation, which is the major green-house gas (GHG) emitter [2]. Majority of future technologies, including artificial intelligence (AI), are designed to operate on electrical energy supply, hence electricity remains a primary requirement to unleash such technologies. A spring steel is an engineering component, with different design shapes, possessing a potential energy that can be harnessed in engineering applications, e.g. kinetic energy or rotational energy [3], see Figure 1 below. It has been reported that to generate electricity of alternating current (AC) type, using a generator that has one pair of poles, a rotational speed of 3000 rpm (revolutions per minute) is good enough to achieve a frequency of 50Hz, which is a standard frequency of transmitting electricity in South Africa power grid [4].

Most steel-based springs are primarily used for semi-static loading applications. Although other applications are for inducing or absorbing impact loading. For example, in structural engineering applications, a dynamic suspensions are achieved by the use of a helical compression springs, holding the structure onto desired functional position while absorbing shocks or impact loading when structure is in motion, especially in bogie structure of trains.

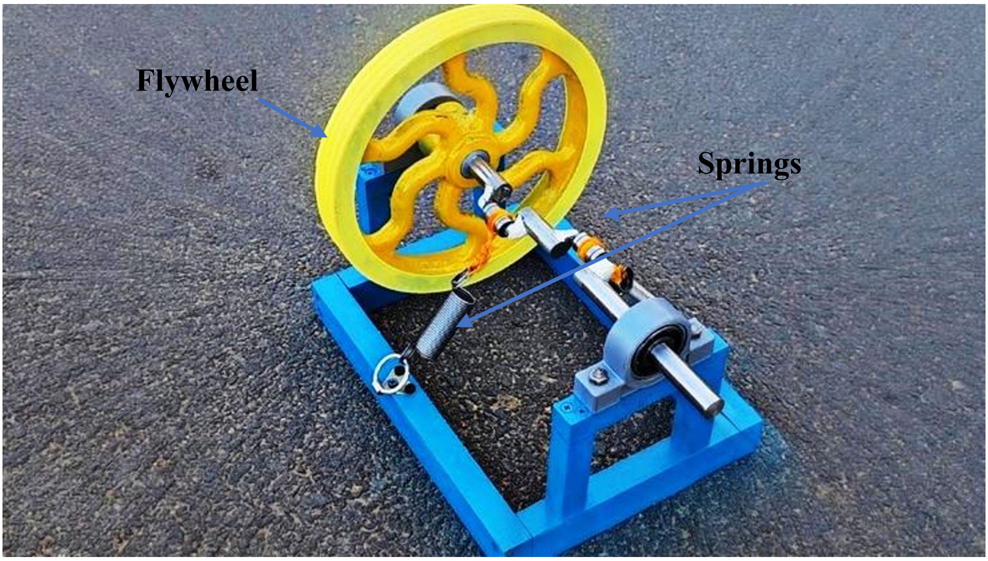


Fig. 1. A Flywheel-Spring Machine operates on flywheel and spring steel energies [3].

For a spring to perform efficiently and optimally, it needs to be able to elastically deform during loading and resume its original shape when a load is released, without any plastic deformation. If it undergoes plastic deformation, its integrity is altered or compromised, resulting in loss of its functionality. Some of the key properties required from springs for their successful engineering applications include resilience, stiffness, fatigue strength, impact toughness and hardness. These mechanical properties can used to determine at what load a spring will undergo plastic deformation. As a result, these properties determine the maximum load of operation, surface wear resistance and fatigue a spring can withstand without plastic deformation or fracture.

In this study, an effect of four different heat treatment cycles on hardness properties of modified spring steel material were investigated. The microstructures were acquired using an optical microscope. The obtained hardness values from applying different cooling rates on a modified spring steel material are reported and the microstructures that govern obtained hardness values are revealed.

2 Materials and experimental procedure

2.1 Material elemental composition

A modified spring steel alloy was prepared by mixing different metal powders to make 100 gram alloy powder using elemental weight percentage given in Table 1 below.

Table 1. Elemental composition of modified Spring Steel alloy (wt. %).

C	Si	Mn	Cr	Ni	Cu	Al	Nb	V	Mo	B	Fe
0.289	0.346	0.650	1.230	0.040	0.043	0.026	0.020	0.125	0.015	0.044	96.8

The 100 gram powder was thoroughly mixed using Planetary Ball Mill PM 100 without ball charge, to ensure a homogenous mixture of the powder. A mixed powder was then reserved for die compaction, then followed by arc melting to produce a metal rod using AmazeMet rePowder Electric Arc Melting machine, see Figure 2 (a) below.

2.2 Experimental procedure

A thoroughly mixed powder alloy of modified spring steel alloy was compacted into two rods of equal size and mass using a steel die. A universal Zwick-Roell Z250 model uniaxial tensile machine, a maximum compression load of 70 kN was used to compact the powder into rods. The produced two rods, weighing 50 grams each, were then melted under controlled inert argon atmosphere to form a single metal rod using AmazeMet rePowder Electric Arc Melting machine, see Figure 2 below of AmazeMet rePowder machine and a produced cast rod.

(a) (b)

Fig. 2. (a) AmazeMet rePowder Electric Arc Melting Machine and (b) metal rod produced by melting compacted powder rods using AmazeMet rePowder machine.

A rod of a diameter 14.15 mm and a length of 102.62 mm was obtained, see Figure 2 (b) above. A heat treatment samples were withdrawn from metal rod, four samples were cut into equal sizes, where the length was 25 mm and diameter was 14.15 mm. The heat treatment was scheduled as follows, three samples were placed in muffle furnace, allowed to heating up to 960°C at a heating rate of 60°C/hr, allow samples to soak at 960°C for an hour. After an hour elapsed, one sample was water quenched, second sample was air cooled and the last third sample was left in furnace to cool with the furnace down to room temperature. Thereafter all three samples and as-cast were reserved for microstructures and hardness measurement.

2.3 Metallographic examination

The sample preparation was done by using ASTM E 3-02 standard [5]. All samples were mounted in a resin, see Figure 3 below. The mounts were plane and fine ground, thereafter polished to mirror surface finish according to the following steps, SiC papers #120, #240, for plane grind and #400, # 600, #1200 for a fine grind, then polishing using diamond lubricants of 9 um, 6 um, 3 um and 1 um on magnetic discs Mol and Nap (MD-Mol and MD-Nap) polishing cloths to mirror surface finish.

(a) (b)

Fig. 3. (a) A modified spring steel samples after heat treatment, where 1: as-cast, 2: water quenched, 3: air cool, 4: furnace cool and (b) polished and 2% nital etched samples.

The mounts were etched using a 2% nital solution to reveal microstructures. The etched samples were then examined and photographed under an optical light microscope, i.e. Olympus DSX50. The micrographs were acquired at 277X magnification using bright field mode and microstructures were reported under results and discussion section.

2.4 Vickers hardness measurement

A Vickers Hardness test method was adopted on Emco-Test DuraVision machine to measure hardness values of as cast and three heat treated samples, see Figure 4 below.

(a) (b)

Fig. 4. (a) An Emco-Test DuraVision hardness machine, and (b) screen showing how indents were measured.

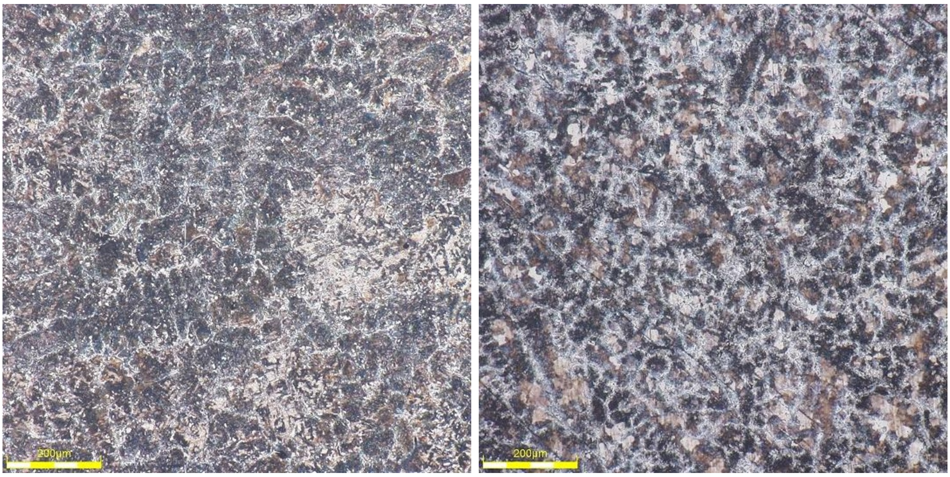
A test load of 30 kg with indenting dwelling time of 30 seconds were used. A standard block EP9715985 with a hardness value of 532.0 of HV30, was used to standardize the machine, three indents were taken on standard block and readings were recorded in Table 2. Thereafter, hardness measurement was carried out on four different samples, three indents were measured from each samples and results were presented in Table 2 below under results and discussion section.

3 Results and discussion

Microstructures and hardness of modified spring steel samples after exposed to different heat treatments were reported in subsequence section 3.1 and 3.2, respectively.

3.1 Microstructures from a modified spring steel from various heat treatments

An as-cast sample revealed the microstructures with pro-eutectoid ferrite or upper bainite phase (white colour) appears as a thin, continuous network at prior austenite grain boundary, finer pearlite phase (light brown colour) and martensite phase (dark colour), as seen in Figure 5 (a). Figure 5 (b) a water quenched revealed the same phases observed from as cast samples, but the upper bainite phase (white colour) prevail thicker continuous network at prior austenite grain boundary and an increase volume fraction of martensite phases, with few patches of retained austenite phase (spherical white phase).

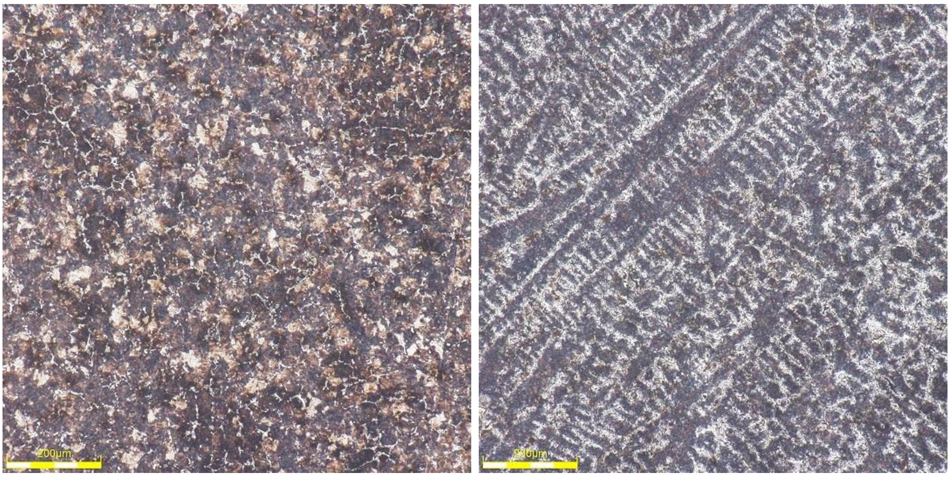


(a) (b)

Fig. 5. (a) A modified spring steel sample at different heat treatment conditions (a) as-cast and (b) water quenched (WQ) condition from 950°C temperature and soaked for a 1 hour.

The increase of upper bainite and martensite phases could be attributed to the fast cooling rate, which promote austenite to transforms of these phases. An increase in cooling rates lowers the transformation temperature that permits bainite and martensite phases to form [6].

During air cooling, a very thin, continuous network of pro-eutectoid ferrite phase at prior austenite grain boundary (white phase) and ferrite phase (spherical white phase) were formed with domination of pearlite phase (dark brown phase) as shown in Figure 6 (a). However, pearlite phase appeared dominating the microstructures than the ferrite phase. This could be attributed to the slow cooling rates which permit eutectoid transformation temperature to exit for prolonged time for eutectoid reaction to occur, which is austenite phase completely decomposed into ferrite and pearlite phases.



(a) (b)

Fig. 6. A modified spring steel sample at different heat treatment conditions (a) air cooled (AC) and (b) furnace cooled (FC) conditions from 950°C temperature and soaked for a 1 hour.

It was found that the thick, continuous network morphology of pro-eutectoid ferrite phase dominated and surrounded the patches of pearlite phase (dark phase) during furnace cooling, as see in Figure 6 (b) above. It is observed that the decreasing continuous cooling rate promotes pro-eutectoid ferrite phase and pearlite phase of modified spring steel. These results show that different heat treatment or continuous cooling rates resulted into different morphology of phases with different volume fractions of the phases.

3.2 Vickers hardness values of a modified spring steel from various heat treatments

A modified spring steel samples that were exposed to different heat treatments reveal various hardness values. A water quenched (WQ) sample recorded highest hardness value than the rest of the samples, which is in average of 731±0 HV30, as seen in Table 2 below.

Table 2. Vickers HV30 hardness values of modified spring steel from various heat treatments.

Sample ID	**Std Block**	**As-Cast**	**WQ**	**AC**	**FC**
1	531	357	731	293	201
2	534	359	731	295	200
3	535	361	731	289	200
Average	533	359	731	292	200
Std Deviation	±2	±2	±0	±3	±1
Abbreviation	Std block = Standard block. **Heat Treatment**: As-Cast = As Casting, WQ = Water Quench, AC = Air Cool and FC = Furnace Cool				

While as-cast sample revealed hardness average value of 359±2, then followed by air cooled (AC) and furnace cooled (FC), in average hardness value of 292±3 and 200±1 respectively. The higher hardness value noticed on the water quenched (WQ) sample could be credited to the large amount of martensite and upper bainite phases that formed matrix phase of material, as seen in Figure 5 (b), which is not a desired phases due to its detrimental effect in toughness [7]. A further heat treatment such as tempering will remedy the brittleness and restore toughness, which is good for spring impact loadings.

The furnace cooled (FC) sample revealed lower hardness values, due to high volume fraction of pro-eutectoid ferrite phase and pearlite phase, which are considered soft phases in steel [8]. It was observed that different heat treatments have significant influence on hardness of spring steel material. However, water quenched hardness is quite higher which will renders material with brittleness and lower toughness for spring applications

4 Conclusions

The following conclusions were made:

- The powder alloy was successful melted and cast into solid metal rod using AmazeMet re-Powder Electric Arc machine.
- Different heat treatments or cooling rates yield various microstructure morphologies
- Water quenched heat treatment produce microstructures dominated with upper bainite and martensite phases, with small fraction of pearlite phase
- While slow cooling rates, i.e. air cool and furnace cool produce microstructures that have ferrite and pearlite phase domination.
- As-cast microstructure revealed domination of ferrite-martensite phase mixture.
- Water quenched revealed highest hardness of average 731±0 HV30
- But as cast sample recorded second highest average hardness 359±2 HV30
- The air cooled and furnace cooled revealed lower average hardness values of 292±3 and 200±1, respectively,

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References

1. L. Van Dyk. The philosophy -tool continuum, SAJIE, vol. **12(1)**, pp 1-14, (2001)
2. H. A Ibrahim *et al.* Sustainability of power generation for developing economics: A systematic review of power source mix. Energy Strategy Reviews 47 (2023) 101085.
3. https://www.tiktok.com/@d.i.y.generator/video/7377022314367683886 (2024)
4. Generation communication, Eskom Fact Sheet, The roles of voltage and frequency in the transmission of electricity, TD 0004 Revision **9 (August 2021)**.
5. ASTM Designation E 3-01 Standard Guide for Preparation of Metallographic Specimen (2001).
6. D. R. Askedland, The Science and Engineering of Materials, Chapman and Hall, London, pp. 329. (1996)
7. I. Madariage, I. Gutierreza, A. C. Garcia-De and C. Capdevila, Scripta Mater., Vol **41**, pp 229, (1999)
8. S. Gunduz, and A. Capar, J Mater Sci., Vol **41**, pp 561-564, (2005)