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# FATIGUE BEHAVIOUR OF TEMPERED AND ISOTHERMAL HEAT TREATED AISI 5160 LEAF SPRING STEEL

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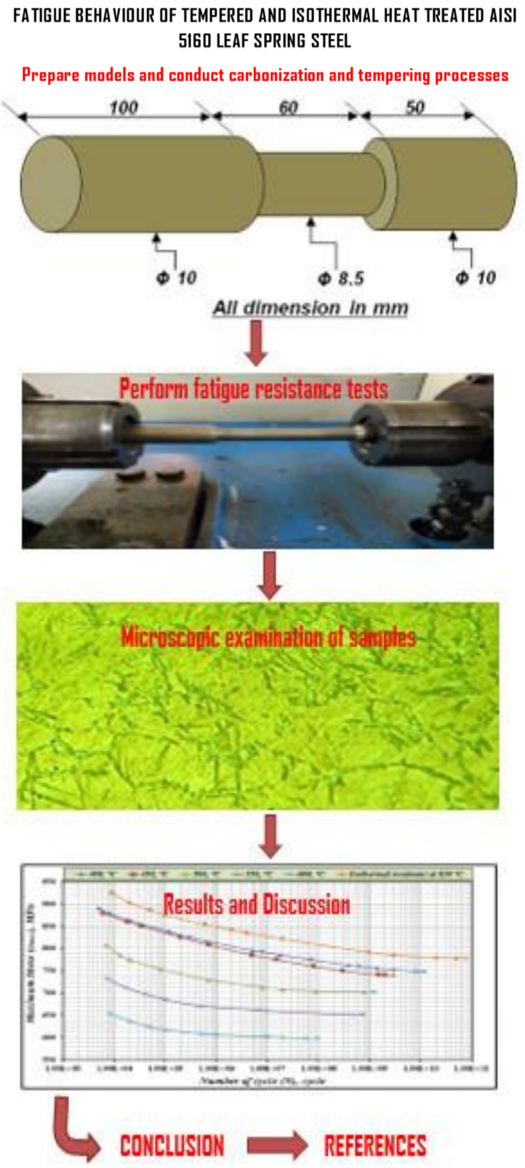
## Graphical abstract




## Abstract

The oil quench and temper technique have a lot of benefits for heavy duty spring manufacture since it may expose the best balance of toughness and ductility, as well as increase fatigue life. The current study looked at the fatigue behavior of tempered AISI 5160 leaf spring steel samples at tempering temperatures of 400, 450, 500, 550, and 600 °C, as well as isothermally heat- treated steel samples at 830 °C. All leaf spring steel samples that had undergone thermal tempering and isothermal heat treatment were then tested up to fracture utilizing rotational fatigue test equipment under the effect of various stress levels. All steel samples subjected to tempering heat treatments of 400°C to 600°C showed a decrease in hardness ratings. The Rockwell hardness ratings of the steel samples that treated to isothermal heat treatment increased significantly. Experimental fatigue testing revealed that the values of fatigue resistance for steel samples tempered at (400 and 450) °C temperatures dropped by a small amount. The fatigue resistance values for steel specimens tempered at 500 °C to 600 °C temperatures decreased more than the values for steel samples tempered at 500 to 600 °C temperatures. A fatigue resistance of steel samples that were treated to isothermal heat treatments, on the other hand, increased. Steel samples that were isothermally heat-treated at 830 °C and then chilled in a salt brine solution, on the other hand, showed an increase in fatigue resistance.

*Keywords:* Fatigue, tempering heat treatment, Isothermal heat treatments, Oil quenching, Bainite, Retained austenite

## 1.0 INTRODUCTION

With outstanding mechanical features such as hardness, yield strength, and fatigue resistance, AISI 5160 Leaf spring steel is one of the most extensively used materials in vehicle suspension systems. These are the primary criteria for transporting heavy loads, and the suspension system's leaf spring is subjected to cyclic pressures as a result of road undulations [2]. Heavy-duty leaf springs in automobile suspension systems are commonly made of AISI 5155 steel that has been oil quenched and tempered. Only a few technical applications call for quenched steel. Temperatures may be adjusted to gradually reduce hardness while increasing ductility and impact strength [1]. Temper treatment considerably influences the mechanical characteristics of a selected alloy. Hardness and ultimate tensile strength were steadily reduced while ductility was enhanced by increasing the tempering time and temperature [2]. Under high cycle settings, the fatigue fracture behaviors of 60Si2MnA spring steel tempered at 400 °C were examined. The temperature at which it is tempered has a significant effect on its fatigue properties. That instance, when tempered at 440 °C, the S-N curve shows a continuous decrease, but when tempered at 400 °C, the S-N curve shows a continuous increase, and fatigue failure is predominantly caused by massive oxide inclusions. Despite the fact that specimens tempered at 400 °C have greater fatigue strength than specimens tempered at 440 °C [3]. The effect of Pb % in SAE5160 steel was measured after introducing the temper temperature and employing the cooling oil at 66 Co. Charpy experiments revealed that the presence of phosphorus causes embrittlement even at low levels of phosphorus and causes intergranular fracture. While taking nucleation life into consideration, embrittlement has no influence on the specimen's nucleation fatigue life [4]. 5160 steel specimens containing 0.001 and 0.034 in mass phosphorus were austenitized at temperatures ranging from 830 to 1100 °C before being quenched to produce martensite. The specimens were subsequently tempered at temperatures ranging from 10 to 500 °C. Scanning electron microscopy pictures revealed the production of carbides as well as fracture surfaces on the boundaries of austenite grains. The low phosphorus steel was subsequently improved by austenizing at 1100°C and then quenching [5]. The influence of immersion rate on distortion and residual strains induced after heat treatment was investigated using Deform-3D software (hardening of SAE5160 steel used in leap springs). Certain ranges of immersion rates were discovered to be effective in reducing distortion and residual strains [6]. The impact of heat treatment on AISI 5160 steel sheets was discussed. Hardening was followed by water quenching, and the steel sheets were then tempered and quenched by water. It was discovered that the steel hardness rose from 40 HRC to 62 HRC after tempering, and that the hardness value slightly reduced while the percentage elongation and ultimate tensile strength increased [7]. It was addressed how a succession of heat treatments affected the fatigue strength of hot work steel H13. It was discovered that these heat treatments improved fatigue strength. The results also demonstrated that twofold tempering heat treatment leads in the best value of steel fatigue strength [8]. To meet the leaf spring specifications, the steel leaf springs were replaced with lighter ones made of fiber reinforced composite materials. Carbon fiber composites were discovered to save roughly 80 % of material while providing stronger endurance strength than steel [9]. The fatigue life of leaf springs was investigated using two materials, SAE5160 and SAE51B60H, with constant amplitude loading. In this investigation, the fatigue life of the leaf springs was estimated using the finite element method to the relation curve S-N. It was discovered that SAE51B60H has a longer fatigue life than SAE5160 [10]. The static and fatigue properties of steel and glass fiber reinforced polymer leaf springs were studied. Static analysis of 2-D and 3-D is done using ANSYS 7.1 and the results are compared to the experiment results. It was discovered that the fiber glass spring had 67.35 percent less stress, 64.75 % greater stiffness, and 126.89 percent higher natural frequency weight reduction than steel. Furthermore, the fatigue life of fiber glass is greater than that of steel leaf springs [11]. Steel rod specimens to produce a multi-phase matrix, lower bainite transformation occurred at the 561°K, 589 °K, and 566 °K isothermal temperatures for 5160 steels, according to hardness data. The thermodynamic and kinetic models were used to characterize the genesis of the bainitic phase in SAE 5160 of the steel [12]. The influence of the quenching media on cooling time and the resulting microstructures of AISI5160 leaf spring steel were studied. Ten different media were employed, as well as an AISI5160 steel heat-slag to 850Co for 30 minutes. After quenching in oil, the resulting microstructure was approximately 78.4 percent martensite, with the highest martensite percent found to be 94.4 percent after quenching in water plus urea 25g [13]. The influence of a cleaner and more uniform microstructure obtained via electro-slag remitting on the mechanical and dynamic characteristics of spring steel was studied. The resulting microstructures improved scattering while having a detrimental influence on the fatigue characteristics of spring steel [14]. The fatigue of leaf springs was elucidated by increasing the % of ferrite in the leaf spring structure, which occurred by decarburization on heat treated leaf spring. To achieve minimal decarburization in the manufacture of leaf springs, thermographic surrey was utilized in heat treatment furnaces [15]. The effect of decarburization on a compressing residual stress field (CRSF) for shot peening conditions on SAE5160 steel was studied. The decarburization depth was shown to be altered by CRSF [16]. The influence of several temperature cycles on the decarburization process was studied using the thermo-mechanical simulator Gleeble 1500. The duration between furnace reheating and hot rolling, the temperature of hot rolling, the temperature in concluding the rolling process, and the temperature of lying are the parameters used. While the temperature ranges of phase change are covered in detail [17]. Articles [18-

20] show that stress behavior in PHS is subject to surface irregularities, such as crack defects in the coating and shear edge defects, which act as the sites of initiation and growth of fatigue cracks. These effects can be reduced by conducting lead-piercing or sandblasting operations that smooth the surface and eliminate internal stresses, as noted in articles [21-23] that of uncoated PHS and AHSS. However, the stress resistance of PHS may also depend on the microstructure of both the coating [24-27] and the bulk material [28], which is strongly dependent on the heat treatment conditions during the pressure hardening process [29-36].

In this manuscript, the effect of tempering temperature at different degrees 400, 450, 500, 550, 600 °C, and isothermal heat treatment temperature 830 °C will be studied on the fatigue strength behavior of the specimens of steel type AISI 5160, which is used in the manufacture of leaf springs for composites.

## 2.0 METHODOLOGY

### 2.1 Materials

The test material was AISI 5160 leaf spring specimen of steel. Chemical compositions of the specimen steel utilized in this experiment were determined using a spectrometer, and the amount of the standard range chemical composition material Table 1.

**Table 1** The chemical composition for AISI 5160 leaf spring specimen of steel used with slandered range composition

| Wt., % | C | Si | Mn | P | S | Cr | Fe |
|---|---|---|---|---|---|---|---|
| Standard value [100] | 0.56 - 0.64 | 0.15 - 0.3 | 0.75 - 1 | ≤0.035 | ≤0.04 | 0.7 - 0.9 | 97.08 - 97.84 |
| Actual value | 0.61 | 0.17 | 0.77 | 0.028 | 0.03 | 0.81 | 97.582 |

### 2-2. Fatigue Samples Preparations and Heat Treatments

The dimensions displayed in Figure 1 were used to machine fatigue test samples from a single bar. To meet the needed sample dimensions for the rotating bending rig depicted in figure 1, the grasping ends were turned and polished to a final length of 50 and 100 mm and 10 mm in diameter, while the necked areas were machined and polished to a final length of 60 mm and 8.5 mm in diameter. Each sample had an average surface roughness of 0.12 m C.L.A. After that, all test samples were heat treated as shown in the next section and then tested at a stress ratio of (R = -1).

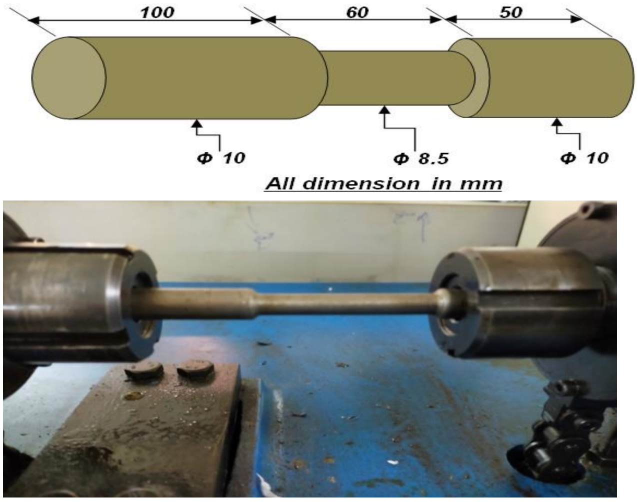



**Figure 1** Dimension of the standard fatigue sample and rotating bending fatigue testing

Two sets of fatigue samples were prepared for heat treatment processes: the first was heated to 830 °C and then quenched in water to room temperature. After water quenching, the microstructure of those samples is obviously martensite with residual austenite microstructure, as shown in Figure 2.

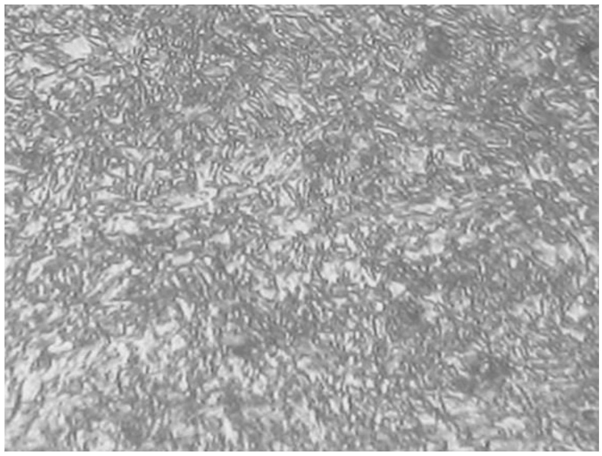
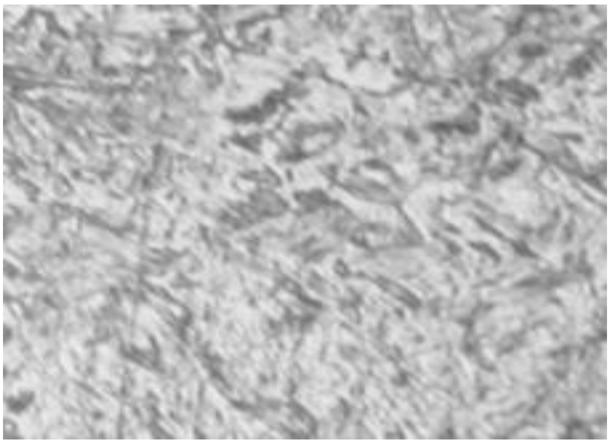


**Figure 2** The microstructure of water quenched AISI 5160 spring steel from 830 °C temperature: Microstructure: martensite and retained austenite. Magnification: X600

After that, each of the sample groups was created and divided into five subgroups. The temperature of each sample of those five gropes was then raised to 400, 450, 500, 550, and 600 °C.

The microstructure of each group is shown in Figure 3, which clearly demonstrates a mixed structure of martensite and bainite or Martensite with bainite and pearlite.



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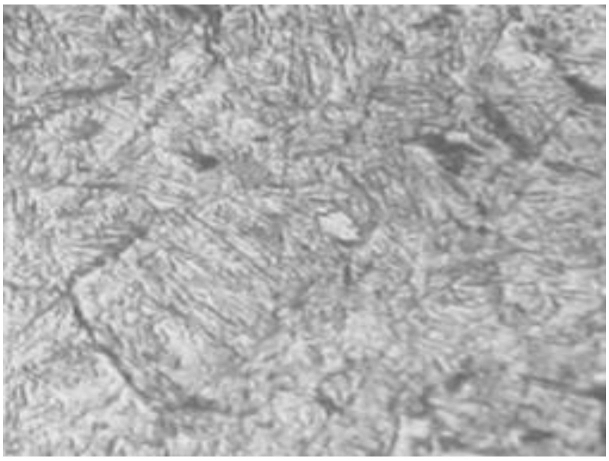
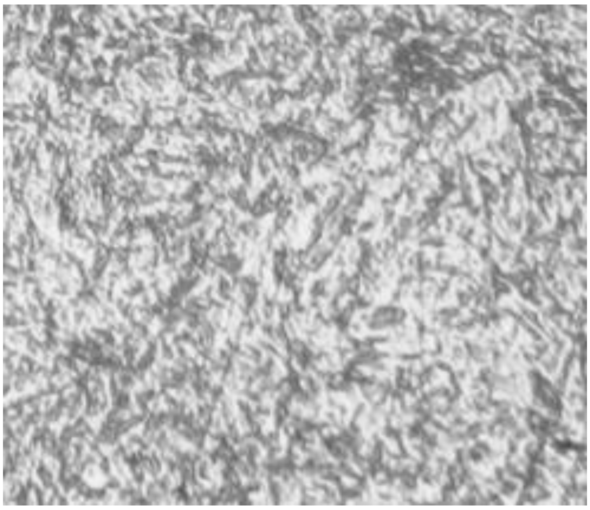


b.



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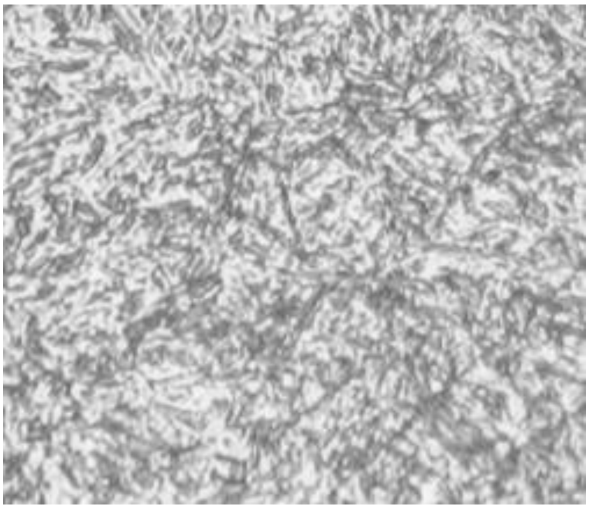

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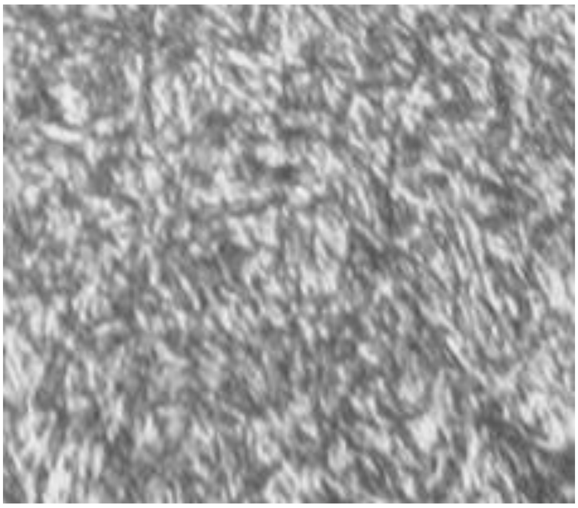

e.

**Figure 3** The microstructure of AISI 5160 spring steel. Water quenched from 830 °C temperature and then tempered to: a - 400, b - 450, c - 500, d - 550 and e - 600 °C temperature. Mixed structure of martensite and bainite or martensite with bainite and pearlite. Magnification: X600

Other fatigue sample groups were then given isothermal heat treatments, which involved heating them to 830 °C for 20 minutes and then cooling them in a salt bath at 300 °C for 60 minutes to get a reduced bainitic structure, as shown in Figure 4.

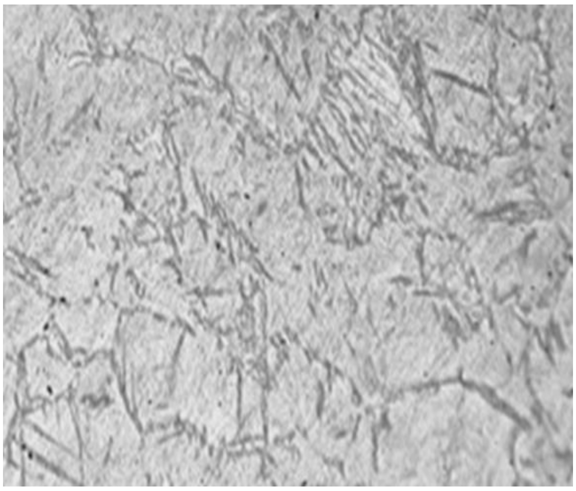

**Figure 4** The microstructure of isothermally heat treated AISI 5160 spring steel. Bainite microstructure. Magnification: X600

## 3.0 RESULTS AND DISCUSSION

### 3.1 Relation between Hardness and Tempering Temperature

Figure 5 shows the relationship between AISI 5160 leaf spring steel hardness and heat treatment temperatures. The figure shows a decline in steel hardness from 62 to 51 HRC when tempering temperature rises from 400 to 600 °C. At 830 °C, an isothermal heat treatment of AISI 5160 leaf spring steel results in a hardness increase of up to 65 HRC. An earlier study on the heat treatment effects of different tempering temperatures 400 °C, 450 °C, 500 °C, and 550 °C on the mechanical properties of spring steel revealed a large decrease in the Rockwell hardness values with an increase in tempering temperatures from 400 to 550 °C, which was attributed to the martensite and retained austenite microstructure obtained after tempering

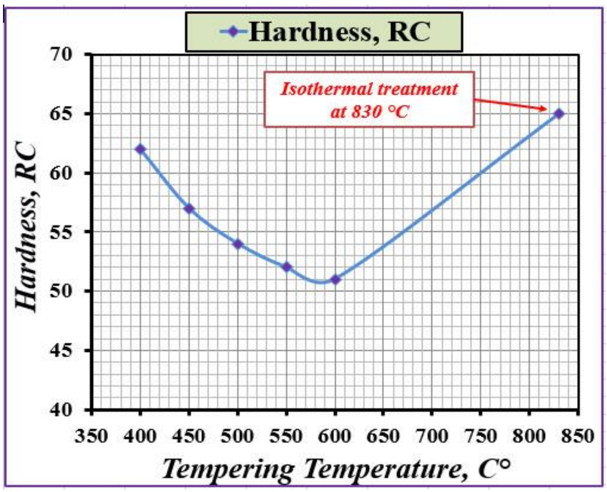


**Figure 5** The relation between hardness vs. tempering temperature

### 3.2 Schemes the Relation between Maximum Stress and Number of Cycles

Figure 6 depicts the fatigue tests findings, which show a relationship between maximum stress and the fatigue life, namely, the number of cycles at fracture (Wohler). The results show that as the tempering temperature increased from 400 to 450 °C, the number of cycles to failure was reduced from 8 x $10^9$ cycles to $1x10^9$ cycle and the fatigue strength limit was decreased from 749 MPa to 740 MPa which clearly reveals a decrease in the fatigue resistance by roughly 0.987 %. When tempering temperatures increased from 500 °C to 600 °C, the number of cycles to failure was also reduced from $8x10^8$ cycles to $6x10^7$ cycle and the fatigue strength limit was decreased from 702 MPa to 599 MPa which clearly reveals a decrease in the fatigue resistance by roughly 0.853 %. The loss in fatigue resistance was caused by a drop in steel hardness, as illustrated in Figure 6, which shows a significant fall in steel hardness as tempering temperatures were increased from 400 to 600 °C. For isothermally heat-treated steel samples at 830 °C temperature the number of cycles to failure increased up to $5x10^{10}$ and the fatigue strength limit was increased to 778 MPa which clearly reveals an increase in the fatigue resistance of steel samples that were isothermally treated up to 830 °C increased by roughly 1.038 % as compared with samples tempered at 400∘C temperature. The high hardness of bainitic microstructure formation, as demonstrated in Figure 5 and the hardness values plotted in Figure 6, was responsible for the increase in fatigue resistance.

An earlier investigation using $17Cr_2Ni_2MoVNb$ gear steel samples tempered at 180 °C, 400 °C, and 620 °C temperatures found that fatigue life rose as cycle stress reduced and decreased as tempering temperatures climbed from 180 °C to 600 °C, which is consistent with the current findings. [18]. It should be emphasized that the dislocation had a role in determining fatigue strength limitations, and high-density dislocations helped to improve fatigue strength.

The stacking of dislocations coalesces as the tempering temperature rises, resulting in a decrease in dislocation density. As a result, the samples that were tempered at 400 °C had the highest fatigue strength limits when compared to other tempered samples, in addition to the decrease in the hardness values from 62 HRC to 57 HRC. The Isothermal heat-treated samples at 830 ∘C temperature revealed a highest fatigue strength limit as compared to all other tempered samples.

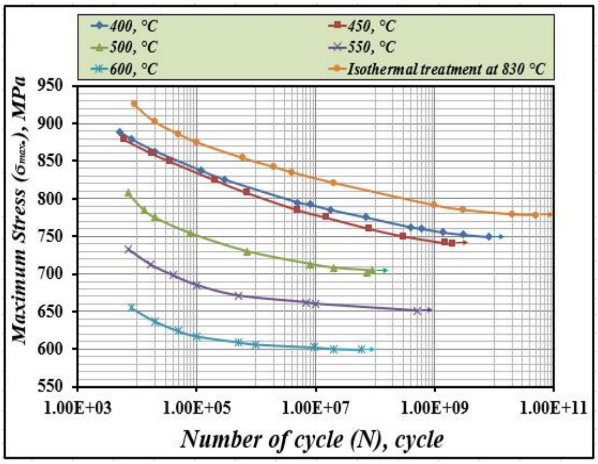


**Figure 6** Relation between numbers of cycle vs maximum stress

### 3.3 Schemes the Relation between Tempering Temperature and Stress Failure

Figure 7 shows the relationship between sample tempering temperature and stress to failure. The stress values to failure were somewhat reduced from 745 to 740 Mpa as the tempering temperatures of spring steel samples increased from 400 °C to 450 °C, which clearly revealed a decrease in the amount of stress to failure by about 0.993 %.

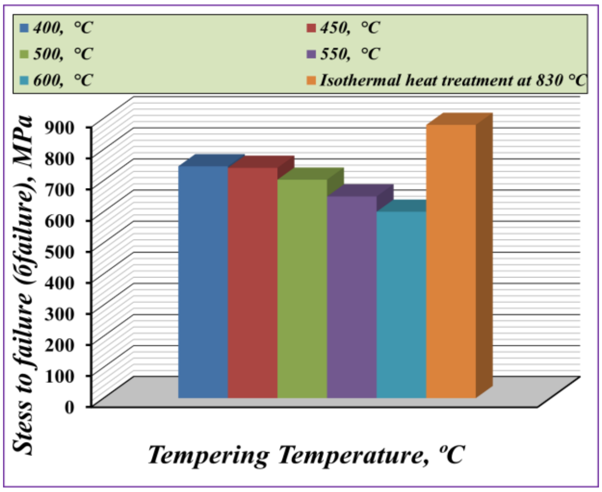


**Figure 7** Relation between tempering temperature vs stress failure

As previously shown in Figure 6, the decline was owing to a modest decrease in the hardness values from 62 HRC to 57 HRC. Spring steel samples had a more substantial decrease in stress to failure from 740 MPa to 599 MPa as tempering temperatures were increased from 450 to 600 °C, which was about 0.809 % reduction in the stress to failure, and this decrease in stress to failure was also attributable to a decrease in spring steel hardness from 57 HRC to 51 HRC as well as due to the dislocations coalesces at high tempering temperatures [3]. The stress to failure of spring steel samples that were isothermally heat-treated at 830 °C increased by 878 MPa, which is a considerable increase. That increase in stress to failure was due to the high hardness 65 HRC of the bianitic microstructure illustrated in Figure 5 and the high hardness values 65 HRC given in Figure 6. The stacking of dislocations coalesces at high isothermal heat treatment temperatures, resulting in a reduction in dislocation density. A previous study discovered that increasing the tempering temperature of spring steel from 400 to 550 °C dramatically diminishes the material's endurance limit [37].

### 3-4 Schemes the Relation between Tempering Temperature and Number of Cycles to Failure

The association between the number of cycles to failure and the tempering temperatures of the spring steel samples is shown in Figure 8. The figure clearly illustrates that as the spring steel samples' tempering temperatures were increased from 400 to 600 °C, the number of fatigue cycles to failure dropped from 8x109 to $6x10^7$. As previously depicted in Figure (6), the decrease in the number of fatigue cycles to failure was ascribed to a decrease in the spring steel samples. The greater hardness 65 HRC bainitic microstructure depicted in Figure 5 and displayed in Figure 8 resulted in a considerable increase in the number of fatigue cycles to failure $5x10^{10}$ cycles in spring steel samples that were isothermally heat treated at 830 °C temperatures.

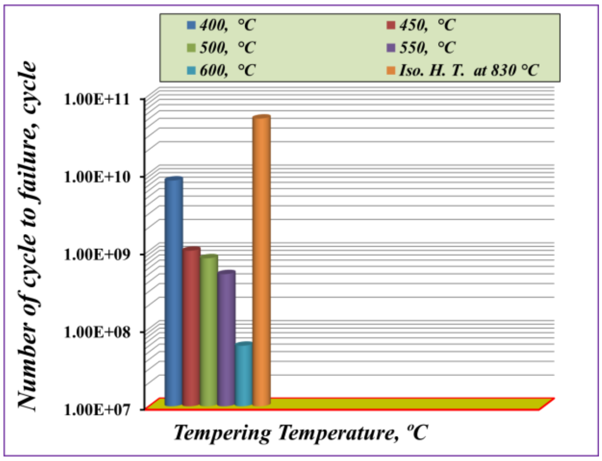


**Figure 8** Relation between tempering temperature vs number of cycle to failure

### 3.5 Schemes the Relation between Tempering Temperature and Crack Growth Rate

Figure 9 shows the relationship between spring steel sample crack growth rates and tempering temperatures. As the tempering temperatures of the spring steel samples were increased from 400 to 600 °C, the fracture growth rate values increased from $1.122x10^{-9}$ mm/cycle to $2.02x10^{-7}$ mm/cycle. The crack growth rate of spring steel samples that were isothermally heat treated at 830 °C temperatures was reduced to $5.3x10^{-10}$ mm/cycle. There are previous studies that focused on studying the behavior of all steel's fracture resistance under the influence of high cycles, and this steel is tempered with temperatures 400 & 450 °C revealed that tempering temperature has a significant impact on spring steel fatigue properties, with lower strength levels obtained when tempered at higher temperature 450 °C and higher strength levels obtained when tempered at lower temperature 400 °C [38].

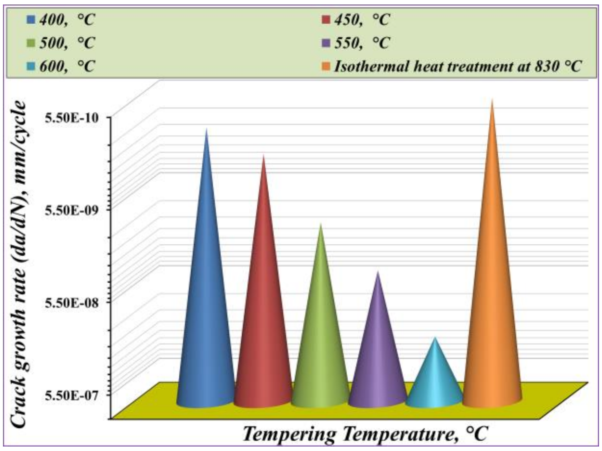


**Figure 9** Relation between tempering temperature vs crack growth rate

### 3.6 Schemes of the Number of Cycles with Crack Length

Figure 10 depicts the crack length vs. cycle number relationship of spring steel samples at varied tempering temperatures and isothermal treatment. The fracture length increased as the number of cycles increased for all of the heat-treated leaf spring steel samples.

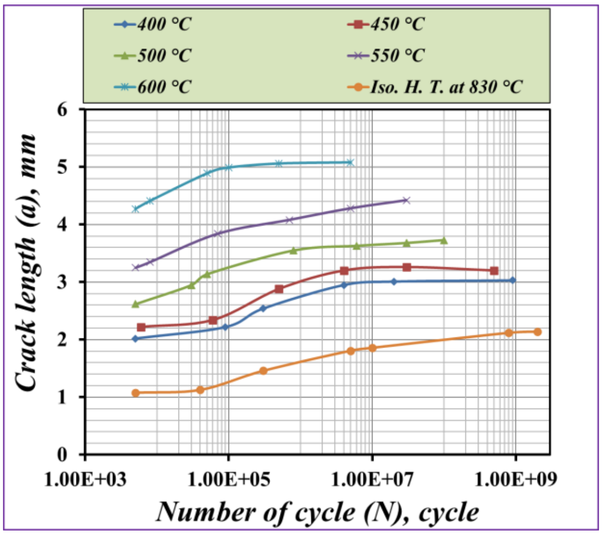


**Figure 10** Comparison of the group - A stress crack growth curves with the original specimen

The results also show that as tempering temperatures increased from 400 to 450 °C, a slight increase in crack lengths developed in the fatigue regions of the leaf spring steel samples, and a significantly large increase in crack lengths has been observed for steel samples tempered beyond 400 °C up to 600 °C. When compared to temper steel samples, isothermally heat-treated steel samples had shorter crack lengths. It was revealed in a prior study of the overall crack growth behavior of thermomechanical control process steel EH36 in which the higher the number of cycles, the faster and faster the crack length expanded. The crack propagation curves were generally exponential between the crack length and the number of cycles, indicating an increased crack growth rate.

### 3.7 Conclusion of Fatigue Crack Growth Rate Charts

A fatigue crack growth rate values were obtained by entering all values obtained from different tests for fatigue crack progression growth with a special program using finite difference (front Newton difference, central finite difference and Newton's method for posterior ended difference). Figures 11 show the results of deducing those curves and the relationship between slit length and average slit length for all models tested. The results showed as in the Figure 11 that the fatigue crack growth rate at tempering temperature 400 °C was the highest value for the fatigue crack growth rate 0.0022 mm/cycle when the crack length was 2.02 mm, then the fatigue crack growth rate became almost constant with the increase in the crack length, and if we compare the fatigue crack growth rate at tempering temperature 400 °C with more tempering temperatures, we note the following: The fatigue crack growth rate at tempering temperature 450 °C increased by 24.14 % when the crack length was 2.2 mm, and then the fatigue crack growth rate stabilized with the increase in crack length , the fatigue crack growth rate was more with increasing the crack length at tempering temperature 500 °C by 50 % when the crack length was 3.16 mm, then the fatigue crack growth rate stabilized with the increase in the crack length, the increase in the fatigue crack growth rate was more at the tempering temperature 550 °C, where the ratio 62.1% was when the crack length was 3.28 mm and then the fatigue crack growth rate was stable with the increase in the slit length, and the highest increase was 72.5 % at the tempering temperature 600 °C and the crack length it was 4.4 mm, but the growth rate of the fatigue crack was significantly lower at the temperature of isothermal heat treatment 830 °C by 50 % than the growth rate of the fatigue crack at the degree of tempering 400 °C, when the crack length 1.1 mm and then the crack growth rate of the fatigue stabilized when the crack length increased.

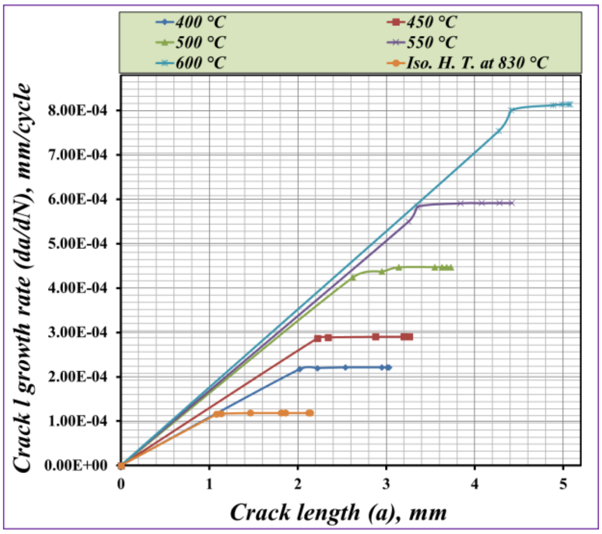


**Figure 11** Shown the relation between fatigue crack length vs crack growth rate

### 3.8 Relation Between Failure Stress and Crack Growth Rate

Figure 12 displays the crack growth rate vs maximum stress relationship for tempered and isothermally heat-treated steel samples. The figure clearly shows that crack growth rates *da/dN* of leaf spring steel samples tempered at 400°C were significantly lower than those of other tempered steel samples, and crack growth rates slightly increased for steel samples tempered at 450°C, but a significant increase in crack growth rates was found for specimens tempered at 500°C, 550°C, and 600°C. Isothermally heat-treated steel samples demonstrated a lower crack growth rate when subjected to maximum stress. Figure 13 further demonstrates that crack growth rates for steel samples tempered at 400 C and 450 C were marginally reduced while maximum stresses were raised, but crack growth rates for steel samples tempered at 500, 550, and 600 °C temperatures were decreased as maximum stressors were increased.

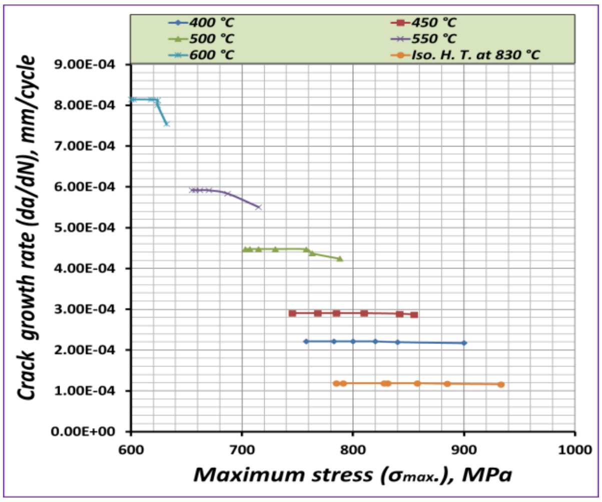


**Figure 12** Shown the relation between stress failure vs crack length rate

## 4.0 CONCLUSION

AISI 5160 leaf spring steel samples tempered at temperatures of 400, 450, 500, 550, and 600 °C, as well as isothermally heat- treated steel samples at 830 °C were tested by rotating bending fatigue apparatus to examine the effect of tempering heat treatment temperatures as well as the influence of isothermal heat treatment temperature on the behavior of fatigue properties of AISI 5160 leaf spring steel led to the following conclusions.

For all leaf steel samples tempered at 400 to 600 °C temperatures, the Rockwell hardness values of AISI 5160 steel samples reduced from 62 HRC to 51 HRC. For isothermally treated steel samples at 830 °C, the Rockwell hardness values of AISI 5160 leaf spring steel samples enhanced to 65 HRC. The fatigue resistance of leaf spring steel samples that tempered at 400 to 450°C temperatures exhibited a modest drop. The fatigue resistance of leaf spring steel samples tempered at temperatures ranging from 500°C to 600 °C drastically reduced. The fatigue resistance of isothermally heat-treated leaf spring steel samples was much higher than that of steel samples tempered at 400, 450, 500, 550, and 600 °C.

For samples tempered at 400 to 450 °C temperatures, the crack growth rates da/dN marginally reduced from 1.12 $x10^{-9}$ to 2. $x10^{-9}$. For samples treated at temperatures ranging from 500 to 600 °C, crack growth rates *da/dN* rose significantly from 1.18 $x10^{-8}$ to 2.02 $x10^{-7}$. At a temperature of 830 °C, isothermally heat-treated samples showed a significant reduction in crack growth rates of $5.3x10^{-10}$. For both tempered and isothermally heat-treated samples, the crack length increased as the number of cycles to failure increased. For steel specimens tempered at temperatures ranging from 400 to 450 °C, crack lengths rose marginally, but crack growth rates increased dramatically for samples tempered at 500°C, 550°C, and 600°C temperatures. Steel samples that were isothermally heat treated at 830 °C had shorter crack lengths than steel samples that were tempered at 400, 450, 500, and 600 °C temperatures.

The results of analyzing and calculating the fatigue crack growth rate with the crack length showed an increase in the crack growth rate of the whole when the revision temperature was increased more than 400 °C, but it decreased significantly at the isothermal heat treatment temperature 830 °C. For steel samples treated at temperatures ranging from 500 to 600 °C, the crack growth rates *da/dN* rose somewhat with maximum stress. With an increase in steel sample tempering temperatures from 500 °C to 600 °C, a substantial big rise in crack growth rates *da/dN* with maximum stress was found. Maximal stress, isothermally heat-treated steel samples at 830 °C showed decreased crack growth rates *da/dN*.

## Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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