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Using Heat Treatment in Design Optimization of High Carbon Spring Steel

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***Abstract* - A heat treatment procedure for improving the mechanical properties and fatigue life of JIS-SUP3 high carbon spring steel was reported in this study, and the use of computer aided engineering softwares (CAE) was also demonstrated to benefit from the improvements of the heat-treated steel to optimize the design of springs and reduce the material costs. Hardness, tensile, fatigue and simulation tests were carried out on the heat-treated specimens to investigate the material properties and determine the optimal heat treatment procedure and it was found that the hardened and tempered at 400^0 specimen possessed the best combination of tensile and fatigue test values. A 3D model and simulation were also done to optimize the design of the support spring in the spinning machine of the textile factory which led to a noticeable reduction in part weight without compromising the factory standards of the service life of the part.**

Keywords; Springs, Heat Treatment, SUP3, Fatigue, Simulation.

I. INTRODUCTION

Spring steel is a class of steel that has appropriate properties for making springs, specifically a high tensile strength and a yield strength that helps the springs to exert high stresses without deforming permanently or breaking. Spring steel can be low alloyed steel such as the high carbon spring steel JIS SUP3 steel (or 1095) or high alloyed steel such as JIS SUP9 steel or stainless steel. The SUP3 steel is used widely in manufacturing springs [1] due to its low cost and the high tensile strength that can be achieved using heat treatments, while other types of spring steel are used when creep and other special detrimental factors play a role.

Fatigue is the major failure the springs encounter in their service because of the role the springs do in any mechanical system which is the repeated tension and compression, thus it's of utmost importance that the fatigue characteristics of springs are studied and evaluated so the design criteria is achieved. Researchers have found that the main idea in improving spring steel fatigue properties is by adjusting the microstructure using heat treatments [2] or using surface treatments such as shot-peening [3].

The effects of heat treatment parameters are constantly studied for different types of spring steel, Daudpoto et al [4] experimented with SUP9 steel and reported an increase in endurance limit by 50% using heat treatments, while Fragoudakis et al [5] also studied the effect of heat treatment on the fatigue behavior of 56SiCr7 spring steel and have found a positive effect on its fatigue life when transforming the microstructure into tempered martensite. Other researches experimented with different types of steels and heat treatments and all have concluded that using heat treatments is an important process that improves spring steel mechanical properties and fatigue life [6] [7].

Computer aided engineering (CAE) is the use of computer softwares to design and simulate the performance of products to make improvements in designs and help solving the engineering problems, researchers are keen to use such softwares to improve the designs and cut down the testing costs. Çetinkaya et al [8] used Ansys to analyse multiple parabolic leaf springs systems. Ceyhanli et al [9] also did a numerical analysis for the static strength and fatigue life of leaf springs in heavy commercial trucks and backed the analysis with experimental results, and Perichiyappan et al [10] modeled and simulated the primary suspension springs used in railways to obtain deformation values and compared the results for different materials using the simulation software.

Improving fatigue resistance of spring steel is the main goal for the automotive industry because of the possible decrease in parts weight, which leads to less material costs and less fuel consumption, the same can be said about any type of machinery that uses springs as a main component. The spinning machine in the textile industry does the processing of cotton roving into workable threads and uses a lot of springs, small sized and large sized coil springs, and leaf springs. The support springs shown in (Figure 1) are located under the bobbins table and are responsible for supporting the table and balancing it and damping the vibrations. These springs are loaded constantly as the machine is working, when the table ascends, the springs are compressed, and when the table descends the springs are extended, this cyclic loading results in fatigue failure of springs which causes the production to stop frequently.

Figure 1. Support spring in spinning machine in the textile factory.

Compared to the aforementioned work, this research aims to use heat treatments in developing a heat treatment process that improves the fatigue resistance of the carbon spring steel SUP3, and then using CAE softwares to optimize the design for the support springs in the spinning machine and make changes in dimensions that cut down the material costs and ensure a working criterion is achieved based on the data sheet the factory provides. Different heat treatments were applied and hardness, tensile and fatigue tests are carried out on a number of specimens to investigate the difference in heat treatment results, the CAE work was done using ANSYS and SOLIDWORKS and the weight reduction was calculated in the end.

II. MATERIALS AND METHODS

A. Test Specimen

JIS-SUP3 steel is a high carbon low alloy spring steel that is used widely in manufacturing springs, the SUP3 steel that was used in this research has a chemical composition as shown in (Table 1).

Table 1- Chemical Composition of the studied spring steel

Fe	C	Si	Mn	Cr	S
98%	0.90%	0.208%	0.391%	0.129%	<0.003%

B. Modeling and Simulation

The support springs are reverse engineered and modeled using SOLIDWORKS, the working conditions of the springs are dependent on the parameters set in the machine such as the table stroke which contributes to the extension and compression of the springs. The table stroke in the studied case is set to 100 [mm], this corresponds to cyclic loading on the springs which develops stresses and ANSYS simulation package was used to determine the stress values. Fatigue simulation was also used to optimize the design. (Figure 2) shows the dimensions of the support spring.

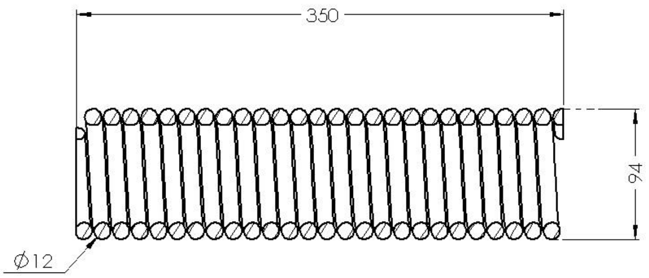

Figure 2. Dimensions of the support springs in spinning machine [mm]

C. Heat Treatments

Proposed heat treatments for the specimens were as followed:

I. Hardening and tempering at relatively low temperature:

1. Austenization: heating above the critical temperature at 810^0.
2. Holding at that temperature for 30 minutes.
3. Quenching using oil at room temperature.
4. Tempering at 250^0 for 1 hour.
5. Air cooling to room temperature

II. Hardening and tempering at relatively high temperature:

1. Austenization: heating above the critical temperature at 810^0.
2. Holding at that temperature for 30 minutes.
3. Quenching using oil at room temperature.
4. Tempering at 400^0 for 1 hour.
5. Air cooling to room temperature

III. Austempering:

1. Austenization: heating above the critical temperature at 810^0.
2. Holding at that temperature for 30 minutes.
3. Isothermal quenching at 400^0 for 1 hour.
4. Air cooling to room temperature

D. Hardness Test

Hardness is determined by the material resistance to indentation, in this research, Rockwell hardness tests were carried out using Metrology RHT-9000ED hardness tester.

E. Tensile Testing

Tensile tests were carried out using IBERTEST-IBMU4, and the specimens were prepared according to ASTM E8.

Figure 3. Tensile testing machine IBERTEST-IBMU4.

F. Fatgiue Testing

Fatigue testing in this research was divided into two stages, the first stage was for comparing the results of different heat treatments at a certain stress level that mimic the actual working conditions of the spring, and the second stage was for obtaining the S-N curve for the heat treatment that possessed the best results in the first stage.

The fatigue testing machine used is TecQuipment-SM1090, and fatigue specimens were prepared as shown in (Figure 4).

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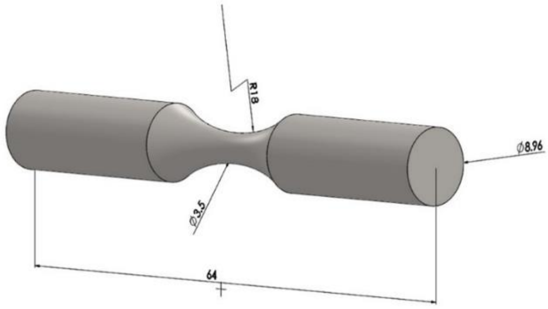

Figure 4. Fatigue specimen according to ASTM E606 (dimensions in mm).

III. Results

A. *Modeling and Simulation*

(Figure 5) shows the 3D model in loading condition and (Figure 6) shows the stress results in the support spring after a 100 [mm] displacement in different points.

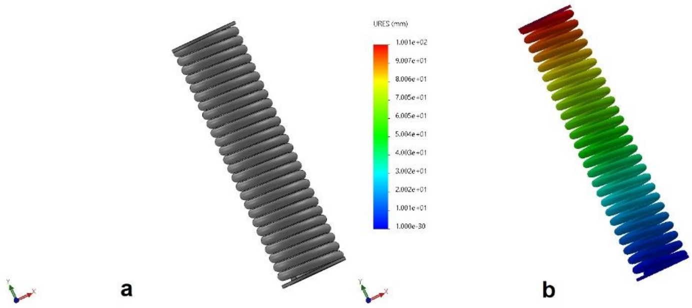

Figure 5. Spring model (a) relaxed state (b) full extension at 100 [mm].

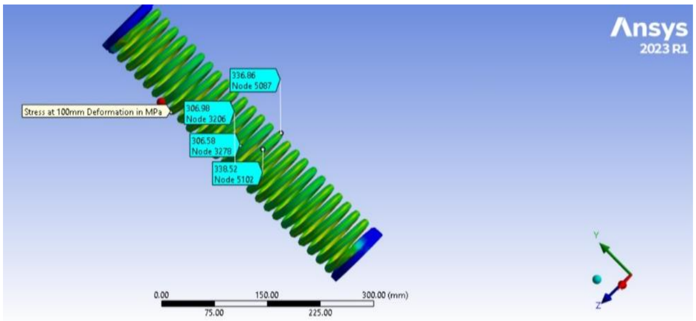

Figure 6. Stress at 100 [mm] displacement.

B. *Hardness Test*

Table 2. Rockwell hardness test results

Specimen	Hardness [HRC]
Hardening and tempering at 250^0	54
Hardening and tempering at 400^0	52.5
Austempering at 400^0	32

C. *Tensile Test*

Table 3. Tensile test results

Specimen	R_m [MPa]	$R_{p.02}$ [MPa]	Elongation [%]
Hardening and tempering at 250^0	1840	1530	1.265
Hardening and tempering at 400^0	1827	1511	2.06
Austempering at 400^0	1073	890	2.214

D. *Fatigue Test*

1. Initial Fatigue Testing:

Table 4. Fatigue test data for different heat treatments

Specimen	Neck diameter [mm]	Maximum bending stress [MPa]	Cycles to failure [N]
Hardening and tempering at 250^0	3.35	308	92,815
Hardening and tempering at 400^0	3.40	309	155,014
Austempering at 400^0	3.30	307	41,549
Not Heat Treated	3.40	309	10,885

2. Fatigue testing for the hardened and tempered at 400^0 specimen:

Table 5. Fatigue test data for hardened and tempered at 400^0 specimen.

Maximum bending stress [MPa]	Cycles to failure [N]
1000	890
414	47,182
309	155,014
250	347,600
200	714,215
180	1,000,000* (no fracture)

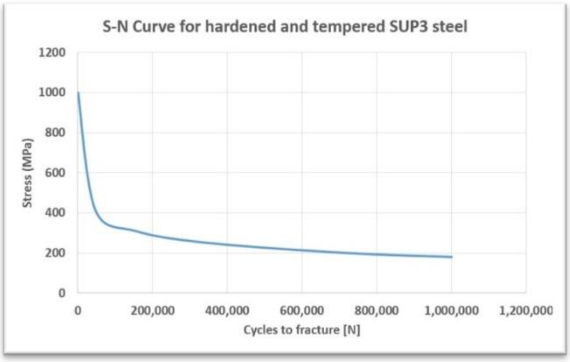

Figure 7. S-N Curve for the hardened and tempered at 400^0 specimen.

E. *Design Optimization of the support spring*

ANSYS 23 simulation package was used alongside the actual heat-treated material properties that were obtained from the mechanical tests to optimize the design of the support springs and reduce it costs, the main goal of the simulation was reducing the wire diameter to achieve a decrease in part weight while maintaining a good service life of the spring.

(Figure 8) shows the fatigue simulation results after inputting the material properties and fatigue test data for the spring steel, and (Table 6) shows the fatigue simulation results after reducing the wire diameter.

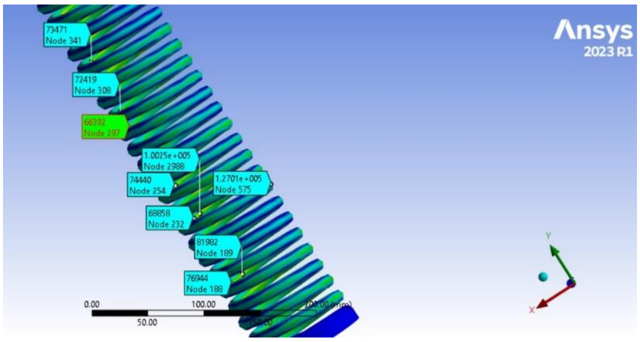

Figure 8. Fatigue simulation results for the heat-treated spring, the expected number of cycles to fatigue failure is shown for different points.

Table 6. Design optimization and reduction of parts weight.

	Oil hardening and tempering at 400^0			**Not Heat Treated**
Wire Diameter [mm]	Ө12	Ө11.5	Ө11	Ө12
Spring Weight [gram]	5898.53	5450.97	5018.21	5898.53
minimum expected number of cycles to fatigue failure [cycle]	66392	34677	16056	10602
Weight difference from original spring dimensions [gram]	0	447.56	880.32	0

IV. DISCUSSION

Different heat treatments procedures had different material properties and it was found that the oil hardening and tempering of SUP3 steel led to a very high tensile strength of 1840 and 1827 MPa, while using the isothermal tempering only gave a tensile strength of 1073 MPa, and the fatigue tests showed that although the first specimen had the highest tensile strength it didn't have the best fatigue life, and taken the nature of fatigue failure into consideration which is the nucleation and propagation of micro fractures, the decrease in fatigue life could be caused from the more brittle structure which is the result of the low temperature temper compared to a higher temperature temper which helps decompose the martensite into ferrite and stable carbide (Figure 9) and that would eventually give a more ductile structure that dissipates the fatigue crack propagation, this means that the less brittle the structure is the more the specimen could withstand the propagation of the micro fractures.

The use of CAE softwares opens the doors for a very effective and practical method in testing and optimizing designs without the need of damaging a lot of parts which costs a lot of money, and with the help of the experimental results from heat treatment procedures it's of great importance to combine the advantages of the two methods to improve the designs and reduce their weight and make them cost less and this has a major impact on the industry. The use of both heat treatment and CAE softwares made it possible to reduce the weight of the spring and change its dimensions while still getting a better fatigue life than the As bought material.

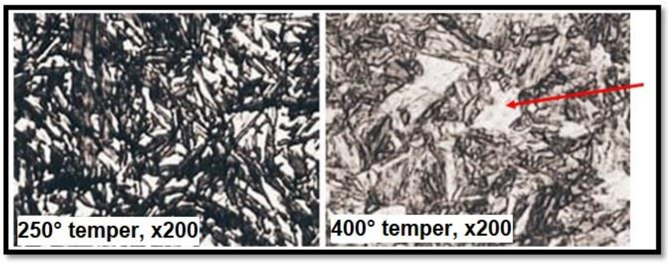

Figure 9. Comparing the microstructure images of the low temper (250^0) and high temper (400^0) specimens, the white areas are tempered martensite which led to a more ductile structure that dissipated the fatigue crack propagation through the higher number of plastic deformation happening compared with the more brittle structure on the left.

V. CONCLUSIONS

Heat treatment procedures for SUP3 spring steel were tested and evaluated through hardness, tensile, fatigue and simulation tests to improve the steel overall mechanical and fatigue resistance properties, it was found that the hardening and tempering at 400^0 of the mentioned steel possessed the optimal results. The use of CAE softwares was also demonstrated in fatigue simulation to possibly benefit from the improvements of heat-treated steel in reducing the support spring weight in the spinning machine of the textile factory. The proposed heat treatment procedure in this research made the optimization of the design of the spring possible which led to a decreased part weight while maintaining a good service life for the part.

REFERENCES

[1] Y. Yamada and T. Kuwabara, *Materials for Springs*. Springer, 2007.
[2] W. Hu, J. Li, K. Li, T. Zhang, and X. Ren, "Improving the cycle fatigue life of spring steel by a novel thermal cycling process," *Mater. Res. Express*, vol. 8, no. 5, 2021, doi: 10.1088/2053-1591/ac006c.
[3] B. Xia *et al.*, "Improving the high-cycle fatigue life of a high-strength spring steel for automobiles by suitable shot peening and heat treatment," *Int. J. Fatigue*, vol. 161, 2022.
[4] J. Daudpoto, D. K. Soother, S. A. Shaikh, T. Hussain, and Z. A. Memon, "Fatigue failure of SUP-9 spring steel," *Mater. Res. Express*, vol. 8, no. 6, p. 066509, 2021, doi: 10.1088/2053-1591/ac0773.
[5] R. Fragoudakis, S. Karditsas, G. Savaidis, and N. Michailidis, "The effect of heat and surface treatment on the fatigue behaviour of 56SiCr7 spring steel," *Procedia Eng.*, vol. 74, pp. 309–312, 2014, doi: 10.1016/j.proeng.2014.06.268.
[6] C. Liu, Y. Chen, C. Zhang, D. Chen, and G. Cui, "Enhanced strength and plasticity in a novel 55Si2MnMoV spring steel via austempering," *Mater. Sci. Eng. A*, vol. 825, no. March, p. 141887, 2021, doi: 10.1016/j.msea.2021.141887.
[7] V. J. Matjeke, G. Mukwevho, A. M. Maleka, and J. W. Van Der Merwe, "Effect of heat treatment on strength and ductility of 52CrMoV4 spring steel.," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 430, no. 1, 2018, doi:

10.1088/1757-899X/430/1/012044.

[8] M. B. Çetinkaya and M. İşci, "ANSYS based analysis of multi-level parabolic leaf spring systems," *Alexandria Eng. J.*, vol. 73, 2023, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1110016823003241

[9] U. T. Ceyhanli and M. Bozca, "Experimental and numerical analysis of the static strength and fatigue life reliability of parabolic leaf springs in heavy commercial trucks," *Adv. Mech. Eng.*, vol. 12, no. 7, pp. 1–17, 2020, doi: 10.1177/1687814020941956.

[10] S. Perichiyappan and T. Jagadeesha, "Modelling and simulation of primary suspension springs used in Indian railways," *Mater. Today Proc.*, vol. 46, no. xxxx, pp. 8450–8454, 2021, doi: 10.1016/j.matpr.2021.03.478.