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A STUDY OF THE EFFECT OF ANNEALING HEAT TREATMENT ON THE FATIGUE PROPERTIES OF 0.17%C HSLA STEELS: A STATISTICAL APPROACH

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Abstract

The present study investigated the effect of annealing heat treatment on the fatigue properties of 0.17%C of HSLA steels using a statistical approach. The Carbon equivalent (CE) was first calculated to determine the ideal starting point for annealing which is 840°C from the Iron Carbon phase diagram. The steel samples were then exposed to multi-régimes of annealing temperatures namely; 840 °C, 870 °C, 900°C, 930°C, 960°C and 990°C at 30°C interval they were then soaked for 30 minutes. Some of the samples were thereafter machined into fatigue samples before being subjected to fatigue test. Quantitative metallography was also carried to examine its micro-structure; results showed that for the steel under study, higher annealing temperature improved the fatigue properties significantly. Highest number of cycles being recorded at 3.9 X 10^3 and 1.3 X 10^3 at 321.3 MPa and 1606.57 MPa stress levels for samples annealed at 990 °C, this is followed closely by samples annealed at 960 °C which had 3.5 X 10^3 and 0.8 X 10^3 number of cycles at the same stress levels before failure. The control had the least number of cycles of about 0.9 X 10^3 and 0.1 X 10^3 at the same stress levels, and, standard deviation of 5.960 and a mean of 26.881 which shows that annealing greatly improved the fatigue life of the steel. The implemented software (ANOVA) test confirmed the results at 95% confidence which further showed that there was significant difference amid the annealing parameters and, it shows promising results.

Key words: *Annealing, fatigue, statistical approach, high strength low alloy (HSLA) Steel*

1. introduction

The fatigue life of any engineering component is an important feature that is quantified in terms of the number of cycles it can undergo before failing due to fatigue occurrences. Fatigue is a factor that could influence all moving object [13]. Fatigue is a process wherein a metal fractures or breaks down as a result of cyclic applied stresses that can be axially, flexibly, or torsional. In the automotive industry, components that rotate become constantly subjected to loading that is static or dynamic that causes fatigue [5]. The fatigue phenomenon is typically observed as cracks developing at a specific location within the framework, with brittle fracture occurring irrespective of either or not the metal is brittle or ductile. Fatigue impairment happens whenever a stress significantly less than metal's strength of constant elasticity; it occurs when fluctuating stresses are applied that are well below the material's static elastic strength [13]. In general, fatigue failure is regarded as the most serious issue affecting components under dynamic loading conditions. Fatigue is responsible for nearly 90% of failure conditions in mechanical components [3]. As a result, having a metal with a long fatigue cycle becomes critical; the issue becomes critical due to major constraints such as reliability and strength [13].

New metals which provide exceptional mechanical integrity whereas minimizing volume and complexity, manufacturing costs are in high demand [15]. As a result, for the past few decades, an exceptional form of steel has been used (between 0.05 to 0.25% content of carbon). In addition, it blends with other alloys such as Chromium, Nickel, Molybdenum, Copper, Nitrogen, Vanadium, Niobium, Titanium, Tungsten, and Zirconium in low amounts as well as in various quantities, which have emerged and is commonly referred to as high strength low alloy steel (HSLA) steels [6]. According to Manricino, in his study on fatigue failure, identified high strength low alloy steels (HSLA) as steels made of micro-structures shaped by strong martensite grains that are dispersed in a matrix of ductile ferrite [9]. These categories of steel make an impact to the preference for rigidity and weight loss in the Auto parts manufacturing. That is due to its excellent attributes of ability to be formed. Such steel alloys are useful in the manufacture of vehicle Suspension mechanisms, support elements, horizontal beams, bending parts, and chassis are examples of such sections [9]. Pipelines for oil and gas, construction and agricultural machines, heavy-duty highway and off-road cars and trucks, industrial machinery reservoirs, quarry and railway road cars, vessels and dredges, pickup trucks, electric power towers, utility poles, mowers, likewise passenger car components all use HSLA steels. Therefore, having a thorough understanding of their fatigue behavior cannot be overstated.

Annealing is a heat treatment that changes the physical and often chemical properties of a material to improve its ductility and reduce its hardness, trying to make it far more usable; this entails heating a metal to a higher temperature than its austenite phase, holding that temperature and afterwards cool [13]. Annealing is used to increase ductility and toughness, decrease hardness, and remove carbides [1].

ANOVA is an empirical method that uses the Fishers F test and the student t test to determine the significance of a model and its parameters [2]. Using a p meaning criterion, the Student's ‘T’ test was used to evaluate the significance of the regression coefficient. Larger F values and lower p values, in general, suggest more important coefficient terms[2].This study is aimed atinvestigating the effect of annealing heat treatment on the on the fatigue properties of 0.17 %C of HSLA steels using a statistical approach.

Table 1: Specification table

Subject area	**Engineering and technology**
compound	0.17%C of HSLA steels rod, G-Clamp, hand gloves, natal, Silicon carbide papers of different grades (220,320,400, and 600), ranging from coarse to fine, selvt cloth, 0.5 m Silicon carbide solution, 2% NITAL
Data category	Design expert
Data acquisition format	Table, software
Data type	Filtered, raw, analyzed
procedure	It was then subjected to preliminary machining to remove its ribs, after which they were cut to desired sample specification according to the American Society for Testing and Materials (ASTM), 1990, and wire brushed before carrying out the heat treatment is carried out at 840^{o}C-990^{o}C with the as received not being heat treated. Thereafter subjected to fatigue testing.
Data accessibility	Manuscript

Table 2: Chemical constituents of the steel under consideration.

Elements	C	Si	Mn	S	P	Cr	Mo	Ni	Al
(wt. %)	0.1728	0.3016	1.2089	0.0352	0.0334	0.2559	<0.010	0.1218	<0.010
Elements	Cu	Ti	V	Nb	W	Co	B	Fe	
(wt. %)	0.2560	<0.0100	<0.0100	<0.0150	<0.050	<0.200	0.0047	97.3047	

2. Experimental procedure

2.1 Materials and Methods

The materials used for the work was a 20 mm diameter rod of 0.17 percent carbon. After machining, the samples were grouped for the different predetermined temperature and then normalizing was firstly done so as to remove internal stress induced during machining. Before the annealing was done the Carbon equivalent was calculated to choose the starting temperature from the Iron Carbon phase diagram.

$$CE= C +\frac{Cr+Mo+V}{5} +\frac{Mn+Si}{6} +\frac{Ni+Cu}{15} \qquad (1)$$

From the chemical composition in Table 1 above we have Cr = 0.2559, Mo = 0.0100, V = 0.0100, Mn = 1.2089, Si = 0.3016, Ni = 0.1218, Cu = 0.2560 and C=0.17.

Substituting these figures in equation 1 above, we have

$$CE= 0.17 + \frac{0.2559+0.0100+0.0100}{5} + \frac{1.2089+0.3016}{6} + \frac{0.1218+0.2560}{15}$$

CE = 0.17 + 0.05518 + 0.25175 + 0.02513 = 0.50206, hence CE is 0.5. Hence, from the Iron Carbon phase diagram, the ideal starting point for annealing is 840^{o}C. Following the ascertainment of the temperature for which the annealing operation was carried out, the samples were subjected to different annealing temperatures starting from 840°C to 990°C at 30°C interval and then soaked for 30 minutes to allow the heat get to the core of the samples. Mechanical testing (hardness and impact) was carried out and thereafter, the micro-structural analysis was carried out.

3.0 Results and Discussion

The combined graph result for the effect of annealing temperature on fatigue strength of steel samples with control at 30 minutes soaking time is shown in Figure 1. It shows the test results of fatigue analysis obtained from the annealed steel samples at different temperatures (840 °C, 870 °C, 900 °C, 930 °C, 960 °C and 990 °C) using 30 minutes soaking time with the control for comparison. The graph reveals that at the same stress level and at 30 minutes soaking time, the control was able to withstand the least number of cycles at 900 cycles before failure while 990 °C annealing temperature was able to withstand the highest number of cycles at 3000 before failure.

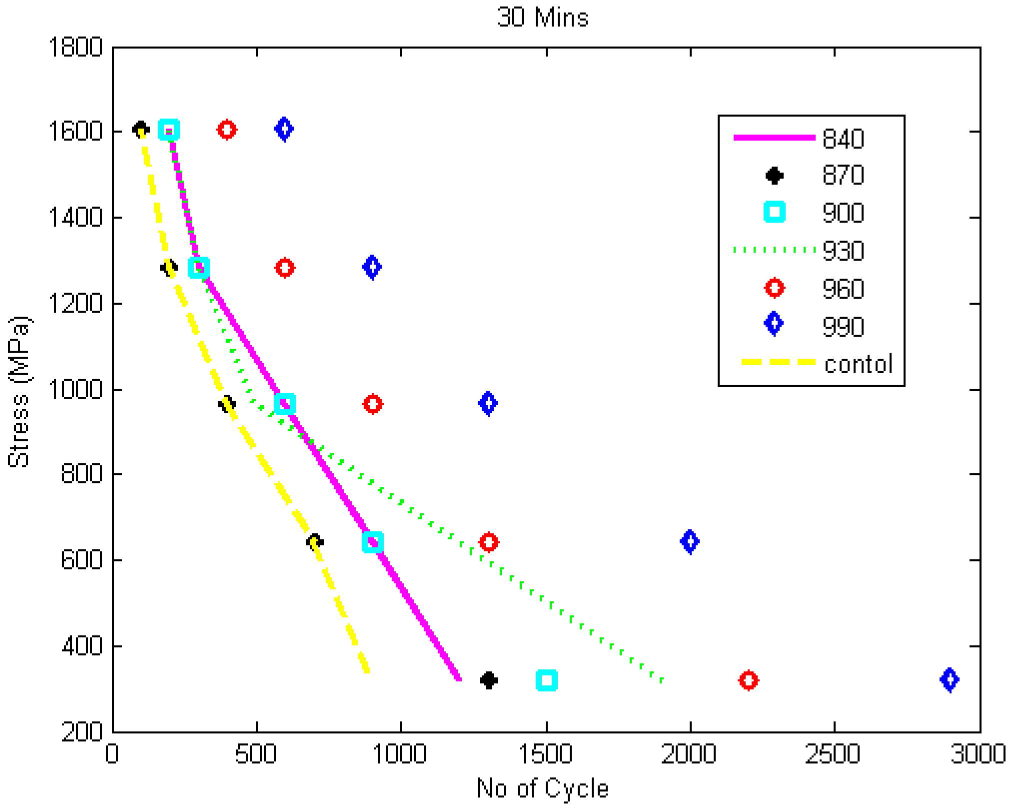

Figure 1 Figure 1: Stress (MPa) against number of cycles (10^3) for the steel at various annealing temperatures for 30 minutes

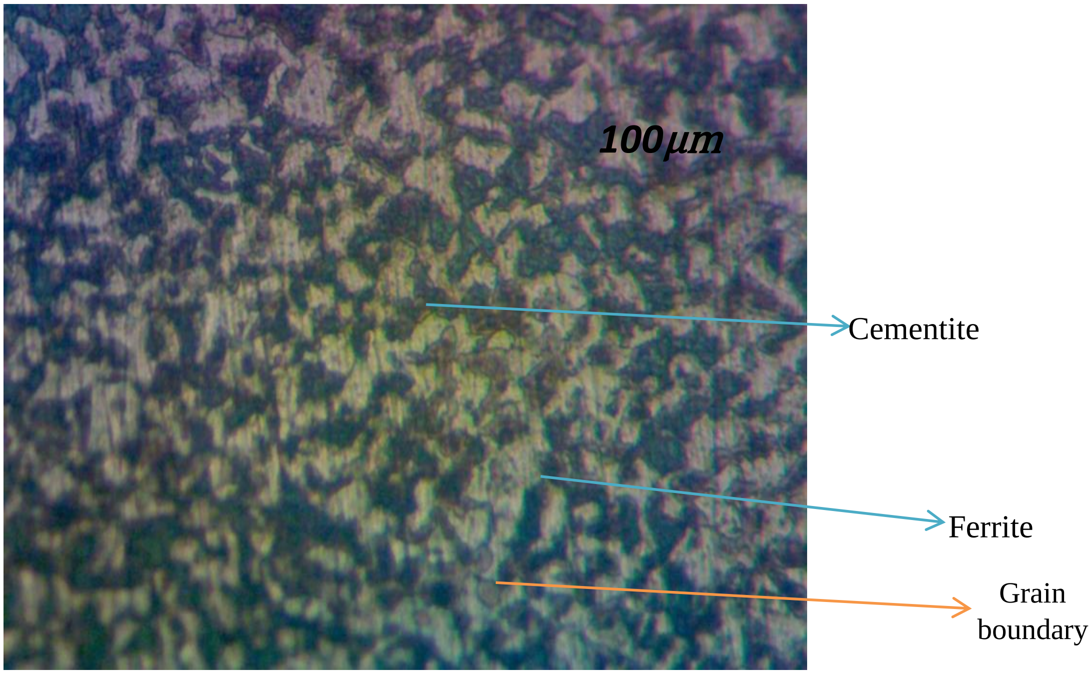

Plate1: Micro structure of specimen held at 840^{0}C for 30 minutes

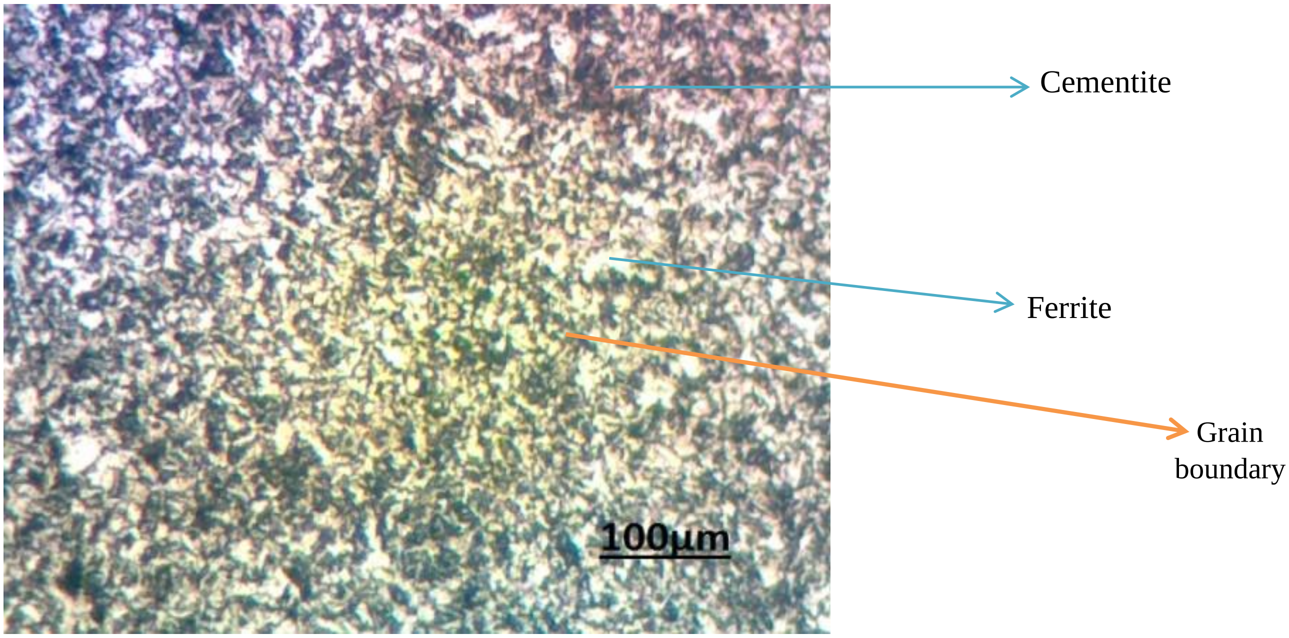

Plate 2 As-Received

Plate 1 depicts the micro-structure of a heat-treated (annealed) sample obtained after 30 minutes of keeping time at 840^{o}C annealing temperature. The micro-graph reveals uniform distribution of ferrite. From the point count calculations, the ratio percentage of ferrite to cementite is 44:56.

Plate 2 depicts the micro-structure of the as-received sample; cementite increased and dominated the micro-structure, while the grains were less coarse, resulting in more grains and grain boundaries; ferrite was found to be distributed unevenly in the microstructure. In the micro-graph, the grain boundaries are not clear. The calculation of point counts shows that the ferrite to cementite ratio in the micro-structure is equally distributed, suggesting a 50:50 ratio.

3.2 Statistical analysis of the fatigue life of HSLA steel using ANOVA

Mathematical Model of the heat treatment (annealing) on the fatigue properties of 0.17 %C of HSLA steels as a function of the considered factors are expressed in the final equation in relation to both the coded and actual factors as shown: for the final equation in terms of coded factor, Fatigue value equals the followings:

$$\text{No of cycles} = +1.10+0.22*A+0.39*-1.19*C+ O.078*AB -0.027*AC-0.22*BC+0.43+A^2 + 0.043*B^2 +0.18*C^2 -0.024*ABC- 0.10*A^2B - 0.036*A^2C-0.027*AB^2 +0.21*AC^2 + 0.15*B^2C-0.067*BC^2 +0.21*A^3 +0.14*B^3 +0.14*C^3$$

In terms of the coded variables, the model predicted the response for each factor at different level considered. The coded model showed the relative importance of the variables while the equation in the terms of actual factors, can be used to make predictions about the response for given levels at each factor. From the analysis of variance, ANOVA, The three models have a sufficient precision of greater than 4, indicating an adequate signal. The models are useful for navigating the design space.

Fatigue life model F-value of 183.89 clearly shows that the model is important and can be applied in predicting the fatigue life. An F-value this large could happen as a result of noise as low as 0.01 percent of the time. Prob>F values less than 0.0500 mean that model terms are important. Temperature, time, and moment are all essential factors influencing fatigue life in this model. For any value greater than 0.1000 indicate that the words are insignificant. The summary of the ANOVA results for the Fatigue life response are shown in Table 3. It includes the R^2, updated R^2, and projected R^2 adequacy metrics. All of the adequacy tests agree logically and display substantial relationships. The tables also provide a statistical overview for each model generated by Design Expert 10. While having lower R^2 and adjusted-R^2 (Adj-R^2) values than the cubic model, a quadratic model was proposed. This is due to the aliasing of the cubic model; this implies that the effects of each variable that causes different signals become interchangeable.

The determinant coefficient, R^2 is a degree of fit measure defined as the ratio of variation explained to total variation. A good model fit, will have an R^2 of at least 0.8 [8]

The signal-to-noise ratio is determined fairly precisely. It is preferable to have a ratio greater than four. The three models have a sufficient precision of greater than 4, indicating an adequate signal. The models are useful for navigating the design space.

Fatigue Life Model F-value of 183.89 clearly shows that the model important. The “Pred R-Squared” of 0.9561 is reasonably close to the “Adj R-Squared” of 0.9669, with a gap of less than 0.2. It is preferable to have an adequate precision ratio that is greater than 4. The precision ratio of 60.280 for this design shows that the proposed model is usable to traverse the design environment. A mathematical model was created to predict fatigue life based on a fixed target of maximized. The built model has a high level of statistical accuracy.

Table 3 Summary of the ANOVA results for the fatigue life response

Model Summary Statistics

Source	**Std. Dev.**	**R-Squared**	**Adjusted R-Squared**	**Predicted R-Squared**	**PRESS**	
Linear	0.33	0.8750	0.8718	0.8651	13.23	
2FI	0.27	0.9139	0.9093	0.9018	9.64	
Quadratic	0.19	0.9584	0.9550	0.9494	4.96	
Cubic	0.17	0.9722	0.9669	0.9561	4.30	Suggested
Quadratic	0.15	0.9791	0.9711	0.9500	4.90	Aliased

Comparative analysis between the actual and the predicted fatigue life

The comparison between the calculated (actual and experimental) Vs predicted plot is shown in Figure 2. The plot shows that points clustering along the straight line suggest a good fit for the model.

The percentage error is calculated as:

$$\text{Percentage error} = \frac{Actual\ value - predicted\ value}{Actual\ value} \times 100$$

A percentage very close to zero means we are approaching the targeted value which is good.

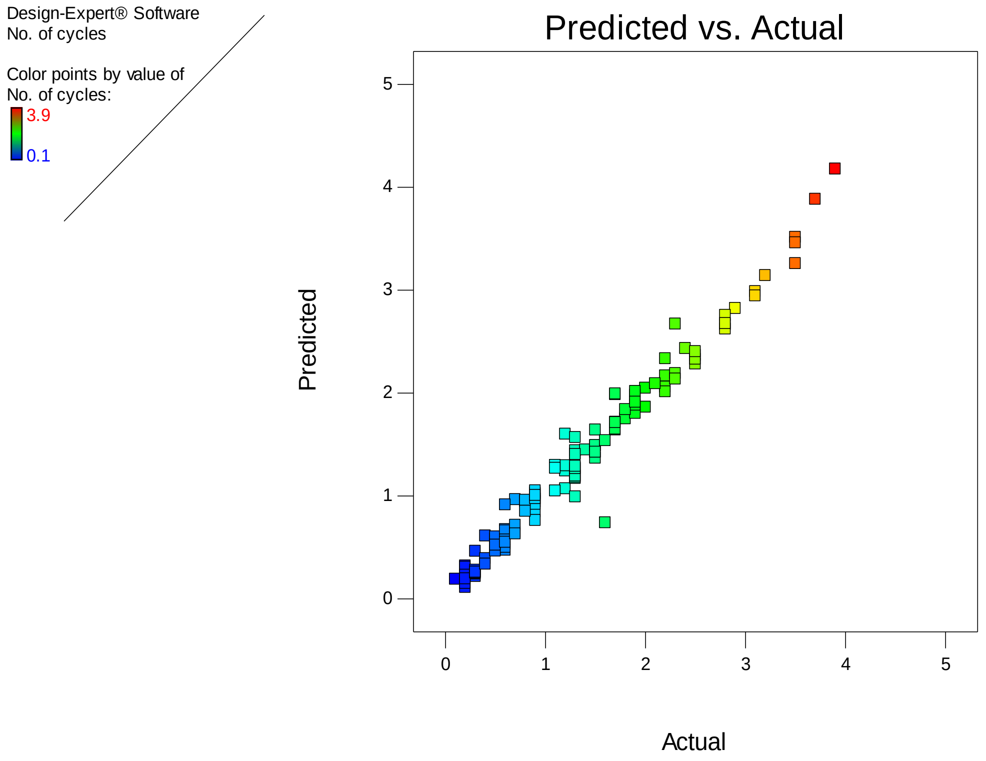

Figure 2: Predicted vs actual plot

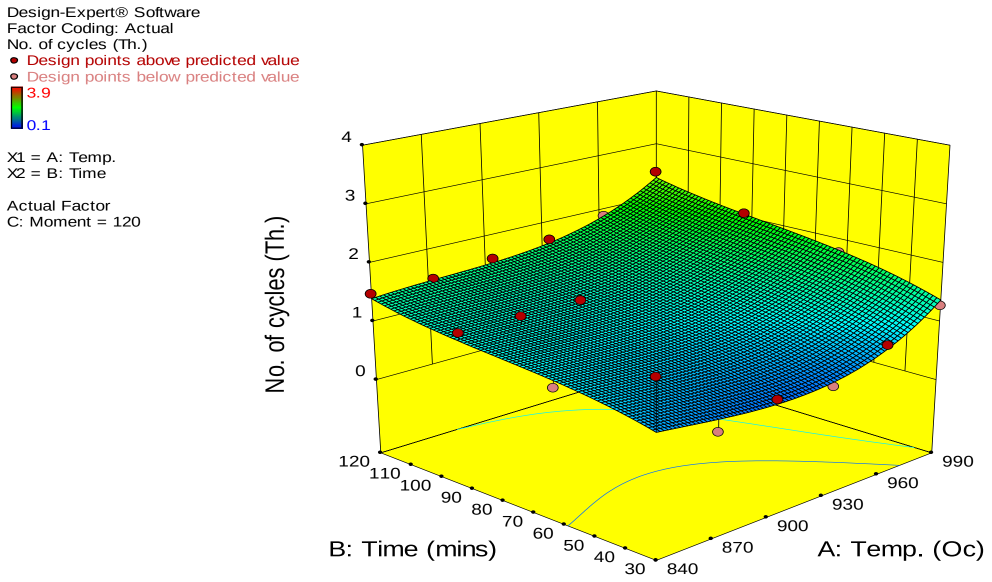

Figure 3: Contour plots of time and temperature on fatigue life

Table 4: Optimization criteria used in this study

Factor and Response	Limits		Criterion	Goal
	Lower	Upper		
Temperature	840	990	In range	In range
Time	30	120	In range	In range
Moment	40	200	In range	In range
No. of cycles			In range	Maximize

Design Expert's optimal solution based on the criteria and target on the number of cycles

Table 5: Validation of results

Exp.no	**Temperature**	**Time**	**Moment**		**No. of cycles**
1	989.694	111.268	40.017	Actual	4.1220
				Predicted	4.0755
				Error %	1.123
`2	989.807	108.776	41.262	Actual	3.9201
				Predicted	4.0252
				Error	0.1051

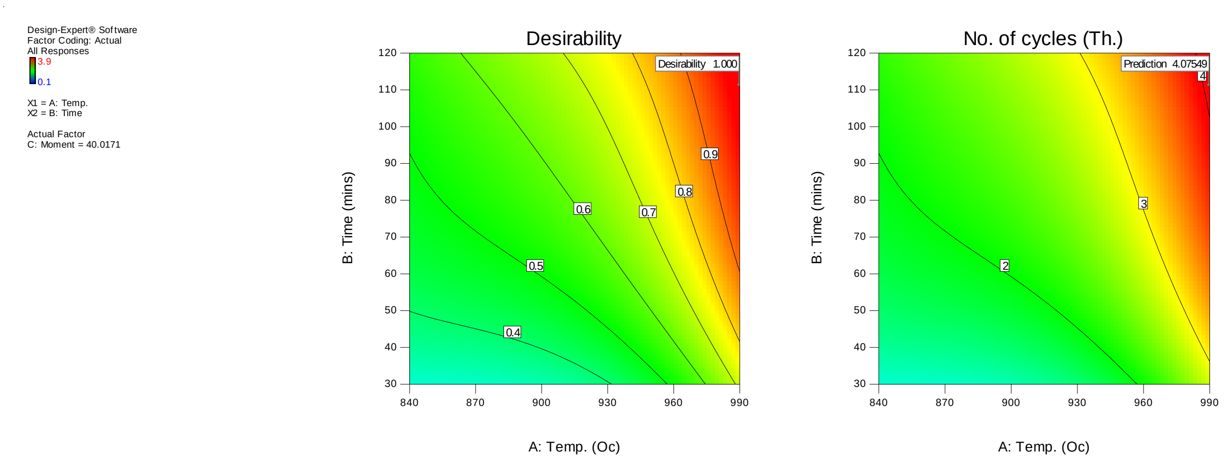

Figure 4: 2-Dimensional plot for desirability and optimized result plot for output 1

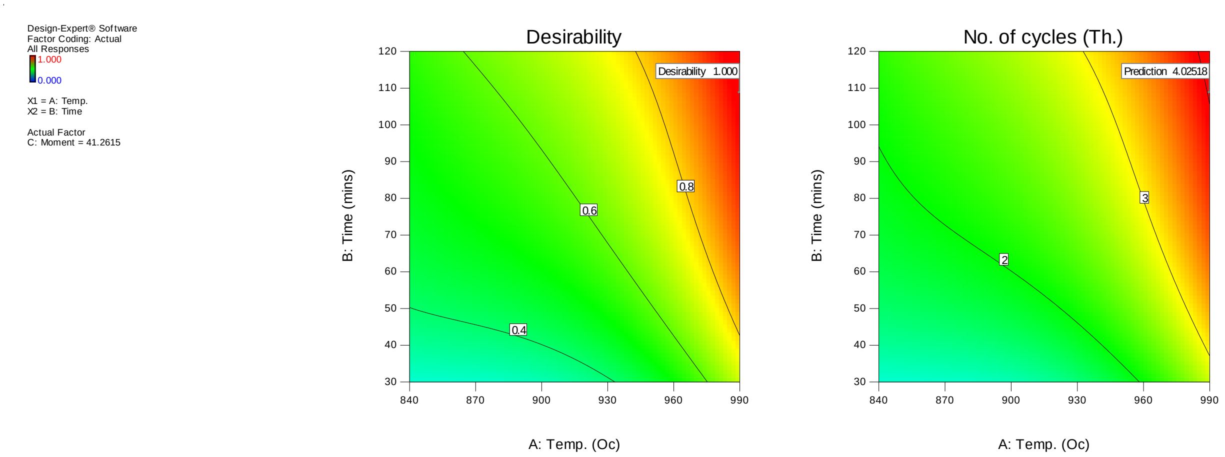

Figure 5: 2-Dimensional plot for desirability and optimized result plot for output 2

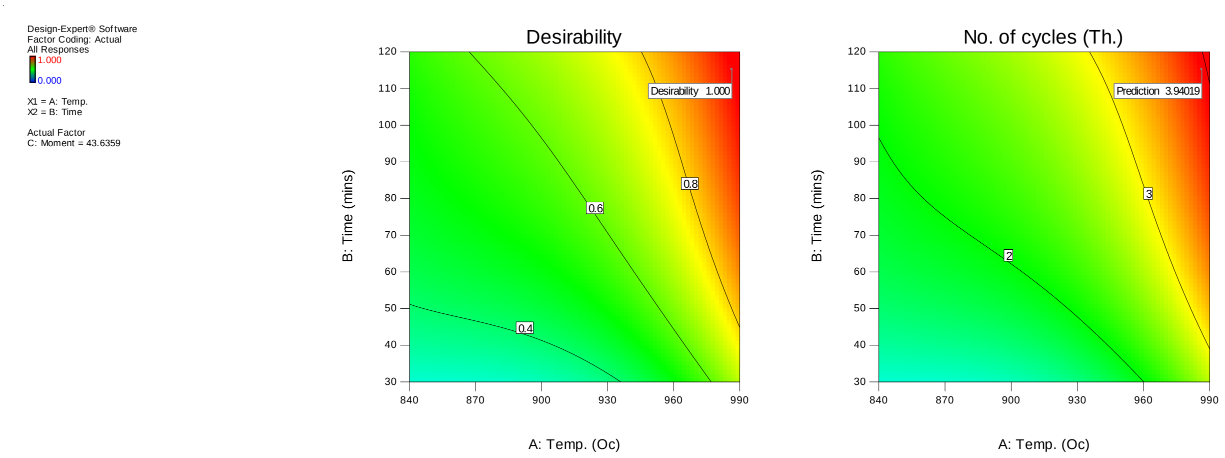

Figure 6: 2-Dimensional plot for desirability and optimized result plot for output 3

Fatigue life of the steel increases as temperature and cooling time rises. Moment rise, on the other hand, reduces the fatigue life of the steel. The predicted vs. actual plots are shown in Figure 2 The plot shows that points clustering along the straight line suggest a good fit for the model.

Figures 4 - 6 represent the relationships between fatigue life and the three variables under consideration. Each plot depicts the impact of two variables within their study ranges, with the other variables held constant at the middle. The response surfaces depict the proclivity of each factor to affect fatigue life more clearly. An elliptical contour plot indicates a major interaction, while a circular contour plot indicates a minor impact.

Plotting responses requires keeping certain variables constant while varying one of interest. A steep slope indicates a sensitive response, while a flat line indicates insensitivity of relating factors.

4.0 Conclusion

In this study, different annealing temperatures were used on the steel under investigation to ascertain the effect of temperature on the fatigue properties. It was observed that annealing generally improved the fatigue properties of the steel under investigation with a better microstructure at 990° C. Thus, optimum fatigue properties was attained at an annealing temperature of 990 ^{0}C and soaking time of 30 minutes. Also, a change in grain size of the steel which resulted in an improved fatigue properties of the steel was observed. Results obtained from the Analysis of Variance (ANOVA) showed that all of the adequacy tests agree logically and display substantial relationships implying that the developed mathematical model can used to predict the fatigue life (fatigue properties) of the steel within the limit of the indicated operating conditions.

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