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Experimental Modeling and Optimization of Fatigue Life and Hardness of Carbon Steel CK35 under Dynamic Buckling

Ahmed Naif Al-Khazraji

Department of Mechanical Engineering / University of Technology

E-mail: Dr_ahmed53@yahoo.com

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Abstract

The aim of this paper is to model and optimize the fatigue life and hardness of medium carbon steel CK35 subjected to dynamic buckling. Different ranges of shot peening time (STP) and critical points of slenderness ratio which is between the long and intermediate columns, as input factors, were used to obtain their influences on the fatigue life and hardness, as main responses. Experimental measurements of shot peening time and buckling were taken and analyzed using (DESIGN EXPERT 8) experimental design software which was used for modeling and optimization purposes. Mathematical models of responses were obtained and analyzed by ANOVA variance to verify the adequacy of the models. The resultant quadratic models were obtained. A good agreement was found between the results of these models and optimization with the experimental ones with confidence level of 95 %.

Keywords: *Buckling; Fatigue Life, Hardness, Shot Peening, Modeling, Optimization.*

1. Introduction

The yielding is a phenomenon of failure of a material under different statical and dynamic loads, this is a fact for short members or bars. But if a bar is long (strut), the failure become a buckling phenomenon or elastic instability. The strut (column) buckled at a certain critical load (Pcr.) and then collapsed suddenly [1]. Thus, a column fails by buckling at load lower than the yield load. The objective of column analysis methods is to estimate the load or stress at, which a column would become unstable and buckle [1].

Surface treatments of shot peening on steel have been extensively used in the automotive, aerospace and petro-chemical fields. Shot peening is an effective way of surface treatment in engineering components widely used creation compressive residual stresses and improving the strength to buckling failure, corrosion, fatigue and fatigue-creep interaction [3,4].

This paper investigates the effect of different shot peening time (SPT) under the variant combined loads to get mathematical models of optimum fatigue life and hardness based on experimental results. Different soft computing techniques are widely used to improve the predicting and optimization capability [5], and various statistical tools have been applied for the modeling and optimization purposes [6], such as using the Design of Experiment (DOE) with the Response Surface Methodology (RSM).

The objective of the DOE is to optimize a response (output variable) which is influenced by several independent variables (input variables). An experiment consists of a series of tests, called runs, in which changes are made in the input variables in order to identify the reason for changes in the output response. RSM has been extensively used in various engineering applications and fields. It is a collection of mathematical and statistical techniques that are used for empirical models building and analysis of problems, in which a response of interest is influenced by several variables, the objective is to optimize this response [7].

Due to the little work carried out to model and optimize the fatigue life and hardness of medium carbon steel CK35 under dynamic buckling by using DOE to determine the effect of the input parameters (shot peening time and critical slenderness ratio) on the behavior of these responses, therefore this paper aims to investigate the influence of using different shot peening times (SPT) and critical slenderness ratios under constant combined stresses (compression and bending) which was (222MPa) to get mathematical models of optimum fatigue life and hardness based on experimental results by using the Design Expert version 8 software with RSM technique and ANOVA variance for statistical analysis, prediction, optimization and comparison purposes.

2. Experimental Work

The material used in this work was a medium carbon steel CK35. This alloy is widely used in many manufacturing and engineering applications; some typical examples are in the manufacture of connecting rods and railway couplings. During preparation the experimental specimens, carful control was performed to produce a good surface finish to minimize the tensile residual stresses at the surface. The received CK35 was a rod of (3 m length and 12 mm diameter). Table 1 and Table 2 show the chemical composition and mechanical properties of CK35, respectively which were experimented at room temperature.

The specimens were prepared for buckling test with different slenderness ratios (S.R = Le/r). It was designed to use these different slenderness ratios (S.R) to classify the intermediate and long buckling columns behavior subjected to variant loading. The values of fatigue life for the buckled specimens (columns) were determined by buckling test using the buckling testing machine type (Wekop-TAIIE), while the values of hardness were obtained for different shot peening times using the hardness testing machine.

The input parameters used in the whole experimentation procedure were selected according to the practical experience and the limitations of the experimental measurements taken in the present work. These factors are given in Table 3 with two levels. The experimental design was the response surface methodology using a central composite rotatable design for 2^2 factors, with 5 central points and $\alpha = \pm 2$. 13 runs were performed according to the experimental design matrix (5 center points). The runs were performed at random using the order listed in Table 4. Each parameter was used a different code levels of -2, -1, 0, +1, +2, whereby each level used conformed to an actual value equivalent to the coded value.

Thus, the input parameters studied are shot peening time and slenderness ratio. The experimental design matrix used for input parameters in terms of actual factors with the experimental values of fatigue life and hardness is given in Table 5. The software DESIGN EXPERT 8 was used to develop the model. Results of test runs are reported as well as the prediction model produced within a 95% confidence interval.

3. Results and Discussion

3.1. Modeling of Fatigue Life

The obtained average response for fatigue life was used in calculating the model of the response surface using the least-squares method. For fatigue life, a quadratic model in coded terms was analyzed with drawbacks elimination of insignificant coefficients at an exit threshold of alpha = 0.1. Some coefficients were removed from model in order to obtain a formula with actual factors rather than coded ones. The terms removed were A^2B and AB^2, while the terms A, B, AB, A^2 and B^2 had significant effect on fatigue life.

Table 6 shows the statistical analysis of variance produced by the software for the remaining terms. The model is significant at 95% confidence. It is noted that the shot peening time A),critical slenderness ratio (B), their interaction (AB) and their squares (A^2 and B^2) are all significant terms. The lack of fit test indicates a good model. This models illustrates that only five terms (A, B, AB, A^2 and B^2) have the highest impact on fatigue strength. The final equation in terms of coded factors is:

$$Fatigue\ life = +297.00 + 24.42 * +1.75 * B + 3.75 * A * B - 9.69 * A^2 + 3.44 * B^2 \quad \ldots(1)$$

Final Equation in Terms of Actual Factors:

$$Fatigue\ life = +15374.77778 - 22.52222 * Shot\ peening\ time - 304.94444 * Slenderness\ Factor + 0.33333 * Shot\ peening\ time * Slenderness\ factor - 0.17222 * Shot\ peening\ time^2 + 1.52778 * Slenderness\ factor^2 \quad \ldots(2)$$

To check the adequacy of the model, the following diagnostic plots have to be inspected. Looking at the normal probability plot (Fig. 1) or the fatigue life data, the residuals generally that falling on a straight line implying errors, are normally distributed. Also, according to Fig. 2 that depicts the residuals versus predicted responses for fatigue life data, it is seen that no obvious patterns or unusual structure, implying models accurate.

Figure 3 reveals that the contour graph of fatigue life as a response, and only the two factor interaction is shown. It is seen that the increase in both shot peening time and slenderness ratio leads to increase the fatigue life. This is most likely due to increasing the compressive residual stresses on the surface. But, at lower values of these parameters, this effect will be less influential. Figure 4 manifests the predicted fatigue life data versus the actual ones for comparison purpose. While Fig. 5 shows the 3D graph of fatigue life as a function of shot peening time and slenderness ratio. It can be noted that the increase of shot peening time results in an increase in the fatigue life value, while the increase in the slenderness ratio has no effect. Therefore, it can be concluded the shot peening time has the highest impact on the fatigue life values at lower and higher slenderness ratios, whereas the slenderness ratio has no significant influence at lower and higher shot peening times.

3.2. Modeling of Hardness

For hardness measurements, a reduced quadratic model in coded terms was analyzed with backwards elimination of insignificant coefficients at the exit threshold of alpha = 0.1. The terms removed were AB, B^2, A^2B and AB^2, the term B^2 was reinserted to the hierarchy of the model. This means that the interaction of shot peening time and slenderness ratio had no significant effect on hardness. Therefore, only shot peening time (A), slenderness ratio (B) and the squared shot peening time (A^2) are significant model terms, and this model indicates that these three terms have a great impact on hardness, as shown in Table 7 for the statistical analysis of variance (ANOVA) produced by the software for the remaining terms. The model is significant at 95% confidence. The lack of fit test indicates a good model. The final equation in terms of coded factors is:

$$Hardness = +24.28 + 1.33 * A - 0.50 * B - 1.17 * A^2 - 0.30 * B^2 \quad \ldots(3)$$

And, the final equation in terms of coded factors is:

$$Hardness = -1215.22989 + 1.00996 * Shot\ peening\ time + 25.38697 * Slenderness\ factor - 0.020805 * Shot\ peening\ time^2 - 0.13123 * Slenderness\ factor^2 \quad \ldots(4)$$

Figure 6 exhibits the normal probability plot of residuals for hardness data, and it can be seen that the residuals (errors) fall generally on a straight line, and they are normally distributed. And, Fig. 7 illustrates that no obvious patterns or unusual structure, implying models are accurate.

Referring to Fig. 8 for the contour graph the interaction of shot peening time and slenderness ratio, it can be noticed that the hardness increases with increasing the shot peening time and decreasing the slenderness ratio. This is attributed to increasing the compressive residual stresses and intermediate columns. Figure 9 depicts the predicted versus actual hardness data. Whereas, Fig. 10 reveals the 3D graph of hardness as a function of shot peening time and slenderness ratio. It can be noted that the increase of shot peening time resulted in a higher increase in the hardness value, while the increase in the slenderness ratio has generally a very little effect about 3 % on the hardness at higher shot peening times, since the hardness value decreased slightly with the increase of slenderness ratio. In other words, the shot peening time is more significant than the slenderness ratio in the hardness model. Therefore, it can be concluded that the shot peening time has the highest impact on the hardness values at lower and higher slenderness ratios, whereas the slenderness ratio has, in general, no significant influence on the hardness at lower and higher shot peening times.

3.3. Optimization of Fatigue Life and Hardness

The numerical optimization was provided by the Design of Experiment software to find out the optimum combinations of parameters in order to fulfill the requirements as desired. Therefore, this software was used for this optimization, based on the data from the predictive models for two responses, fatigue life and hardness, as a function of two factors: shot peening time and critical slenderness ratio. From the design summary given in Table 8 for main factors and responses, it can be seen that both fatigue life and hardness are modeled with a quadratic model.

To develop the new predicted models, a new objective function, named Desirability which allows to properly combining all the goals, was evaluated. Desirability is an objective function, to be maximized through a numerical optimization, which ranges from zero to one at the goal. Adjusting its weight or importance may alter the characteristics of a goal, and the aim of the optimization is to find a good set of conditions that will meet all the goals. Usually, the weights are used to establish an evaluation of the goal's 3D importance when maximizing desirability function; in this work, weights are not changed since the two responses (fatigue life and hardness) have the importance and are not in conflict within each other.

The ultimate goal of this optimization was to obtain the maximum response that simultaneously satisfied all the variable properties. Table 9 lists the constrains of each variable for numerical optimization of fatigue life and hardness. According to this table, three possible runs fulfilled these specified constrains to obtain the optimum values for fatigue life and hardness, as given in Table 10. It can be seen that all the runs gave desirability of 0.937. Figure 11 exhibits the bar graph for the dersirability, while Fig. 12 illustrates the 2D graph for desirability as a function of shot peening time and slenderness ratio. Figure. 13 shows the surface plot for desiability as a function of shot peening time and critical slenderness ratio. Figures 14 and 15 depict the optimum values of fatigue life and hardness, respectively. It can be noted from these figures that the desirability reaches the maximum value of 0.937 when the optimum value of fatigue life is 308.333 cycles (Fig. 14) and the optimum vaule of hardness is 24.8153 HRC as shown in Fig. 15.

Table 1,
Chemical compositions of carbon steel CK35 (wt%).

CK35	C	Mn	Si	S	P
Standard (DIN 50114)	0.32-0.39	0.5-0.8	0.15-0.35	Max 0.035	Max 0.035
Experimental	0.33	0.75	0.25	0.024	0.013

Table 2,
Mechanical properties of carbon steel CK35.

CK35	σu(MPa)	σy(MPa)	E(GPa)	G(GPa)	Poisson's ratio(υ)
Standard(DIN 50114)	550-700	> 392	201	79	0.3
Experimental	660	400	205	80	0.3

Table 3,
Levels of input factors used in respective coding.

Factor	Units	Low level(- 1)	High level(+1)	alpha-	+alpha
Shot peening time	**min**	12.50	27.50	5.00	35.00
Slenderness ratio	**-----**	96.5	99.5	95.00	101.00

Table 4,
Experimental design matrix for coded input factors and actual responses.

Standard No.	Run No.	Type of point	Shot peening time (min)	Slendress ratio	Fatigue life (cycles)	Hardness (HRC)
1	8	Factorial	-1.000	-1.000	268	21.8
2	2	Factorial	1.000	-1.000	310	26
3	1	Factorial	-1.000	1.000	263	21
4	12	Factorial	1.000	1.000	320	24
5	7	Axial	-2.000	0.000	320	18
6	11	Axial	2.000	0.000	307	21
7	9	Axial	0.000	-2.000	307	24
8	5	Axial	0.000	2.000	315	22
9	3	Center	0.000	0.000	293	24
10	13	Center	0.000	0.000	295	25
11	6	Center	0.000	0.000	298	25
12	4	Center	0.000	0.000	300	23
13	10	Center	0.000	0.000	300	24

Table 5,
Experimental design matrix for actual input factors and responses.

Standard No.	Run No.	Type of point	Shot peening time (min)	Slendress ratio	Fatigue life (cycles)	Hardness (HRC)
1	8	Factorial	12.50	96.50	268	21.8
2	2	Factorial	27.50	96.50	310	26
3	1	Factorial	12.50	99.50	263	21
4	12	Factorial	27.50	99.50	320	24
5	7	Axial	5.00	98.00	320	18
6	11	Axial	35.00	98.00	307	21
7	9	Axial	20.00	95.00	307	24
8	5	Axial	20.00	101.00	315	22
9	3	Center	20.00	98.00	293	24
10	13	Center	20.00	98.00	295	25
11	6	Center	20.00	98.00	298	25
12	4	Center	20.00	98.00	300	23
13	10	Center	20.00	98.00	300	24

Table 6,
ANOVA for Response Surface Quadratic Model (Fatigue Life)
Analysis of variance table [Partial sum of squares - Type III].

Source	Sum of squares	df	Mean square	F value	p-value	Prob > F
Model	10351.89	5	2070.38	341.67	< 0.0001	significant
A-Shot peening time	7154.08	1	7154.08	1180.63	< 0.0001	
B-Slenderness Ratio	36.75	1	36.75	6.06	0.0433	
AB	56.25	1	56.25	9.28	0.0187	
A^2	2150.39	1	2150.39	354.88	< 0.0001	
B^2	270.76	1	270.76	44.68	0.0003	
Residual	42.42	7	6.06			
Lack of Fit	3.62	3	1.21	0.12	0.9409	not significant
Pure Error	38.80	4	9.70			
Cor Total	10394.31	12				

Std. Dev.	**2.46**	**R-Squared**	**0.9959**
Mean	**291.23**	**Adj R-Squared**	**0.9930**
C.V.%	**0.85**	**Pred R-Squared**	**0.9915**
Press	**88.59**	**Adeq Precision**	**66.524**

Table 7,
ANOVA for Response Surface Quadratic Model (Hardness)
Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of squares	df	Mean square	F value	p-value Prob > F
Model	55.75	4	13.94	35.11	< 0.0001 significant
A-Shot peening time	21.33	1	21.33	53.75	< 0.0001
B-Slenderness Ratio	3.00	1	3.00	7.56	0.0251
A^2	31.38	1	31.38	79.06	< 0.0001
B^2	2.00	1	2.00	5.03	0.0551
Residual	3.18	8	0.40		
Lack of Fit	0.38	4	0.094	0.13	0.9614 not significant
Pure Error	2.80	4	0.70		
Cor Total	58.92	12			

Std. Dev.	**0.63**	**R-Squared**	**0.9461**
Mean	**22.92**	**Adj R-Squared**	**0.9192**
C.V.%	**2.75**	**Pred R-Squared**	**0.8870**
Press	**6.66**	**Adeq Precision**	**19.747**

Table 8,
Design summary for main factors and responses (Design model: Quadratic)

Factors	Name	Unit	Min.	Max.	Coded values	Mean	Std. Dev.
A	Shot peening time	min	5.00	35.00	-1.0000=12.50 +1.000=27.00	20.00	7.21
B	Slenderness ratio	----	95.00	101.00	-1.000=96.50 +1.000=99.50	98.00	1.44
Response	**Name**	**Unit**	**Min.**	**Max.**	**Mean**	**Ratio.**	**Std. Dev.**
Y1	Fatigue life	cycles	210	320	291.231	1.52381	29.4311
Y2	Hardness	HRC	17	25	22.9231	1.47059	2.21591

Table 9,
Constrains of each varaible for numerical optimization of the fatigue life and hardness.

Types of variables	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: Shot peening time	is in range	12.5	27.5	1	1	3
B: Slenderness ratio	is in range	96.5	99.5	1	1	3
Fatigue life	maximize	210	320	1	1	3
Hardness	maximize	17	25	1	1	3

Table 10,
Optimal conditions used to obtain the maximum fatigue life and hardness.

No.	Shot peening time (min)	Slenderness ratio	Fatigue life (cycles)	Hardness (HRC)	Desirability
1	25.74	96.50	308.833	24.8153	0.937 Selected
2	25.80	96.50	308.876	24.8117	0.937
3	25.54	96.50	308.668	24.8269	0.937

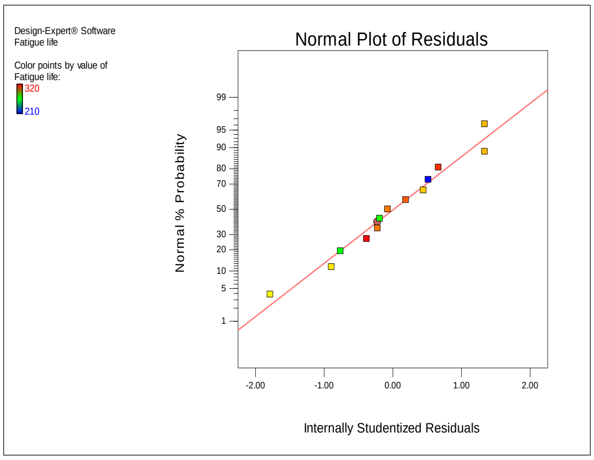

Fig. 1. Normal probability plot for fatigue life data.

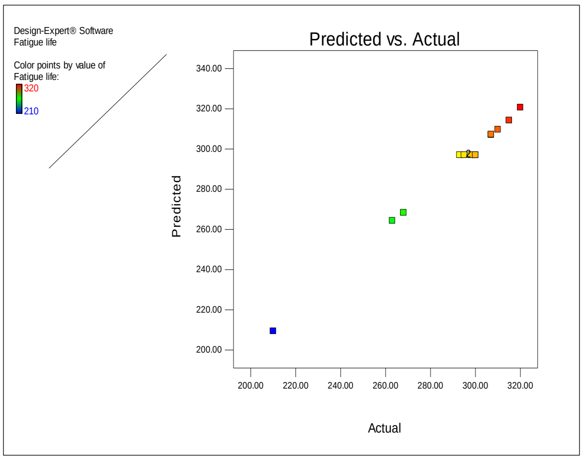

Fig. 4.Predicted versus actual fatigue life data for comparison.

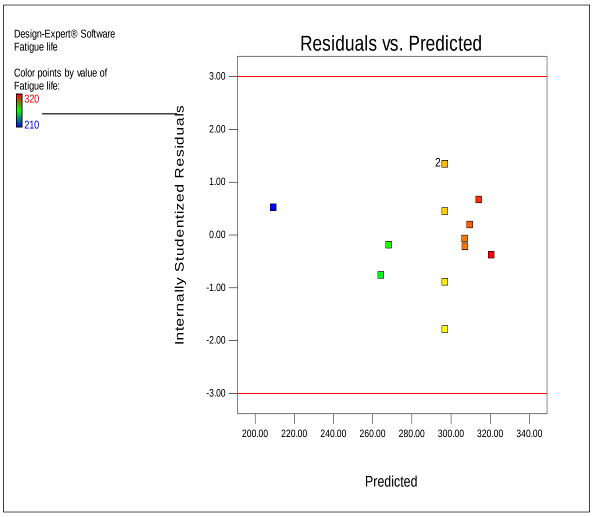

Fig. 2. Residual versus predicted responses for fatigue life data.

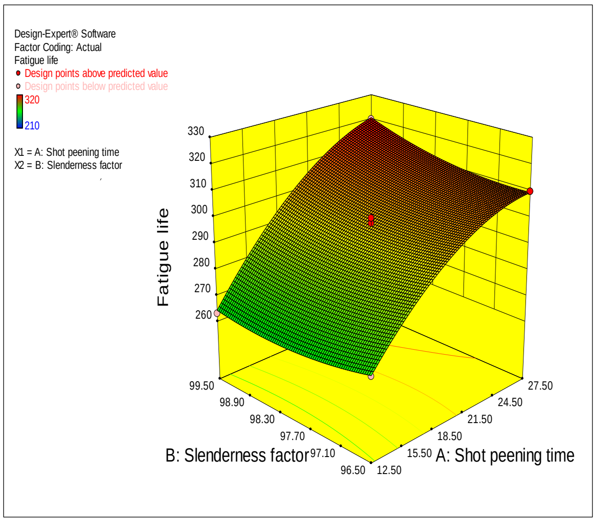

Fig. 5. 3D graph of fatigue life as a function of shot peening time (min) and slenderness ratio.

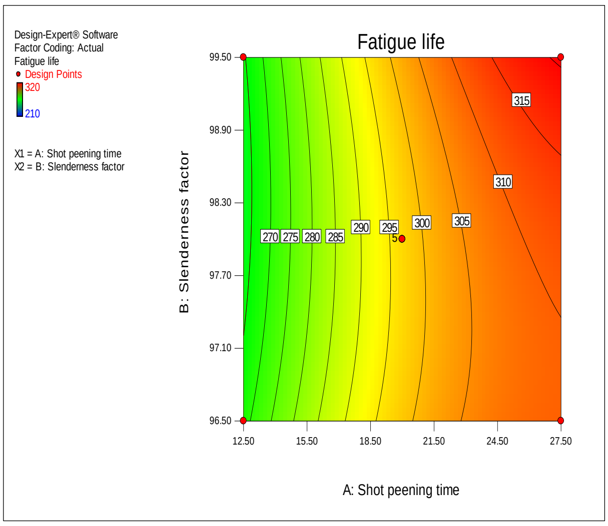

Fig. 3. Contour graph of fatigue life as a function of shot peening time (min) and slenderness ratio.

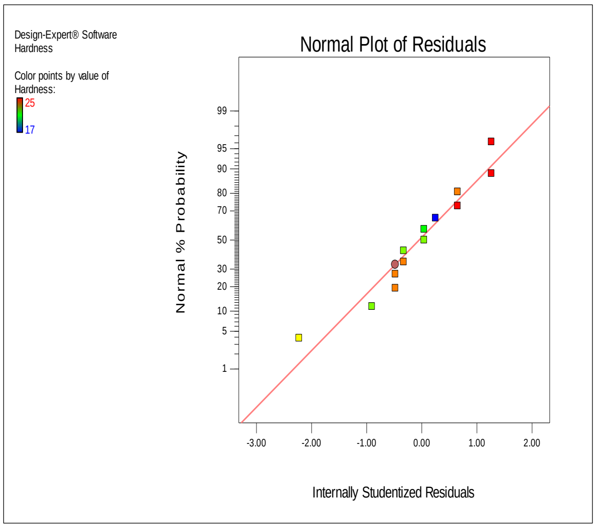

Fig. 6. Normal probability plot for hardness data.

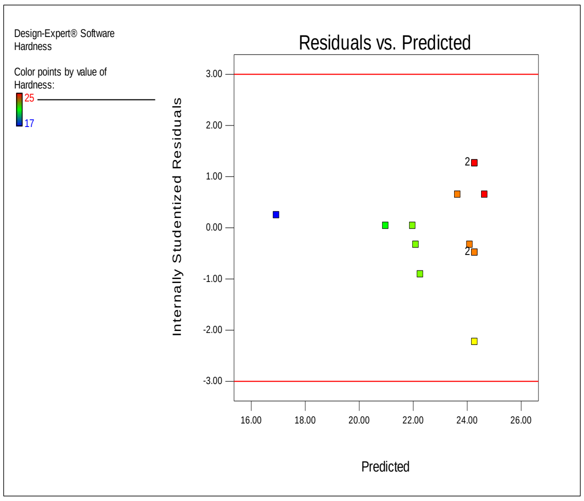

Fig. 7. Residual versus predicted responses for harness data.

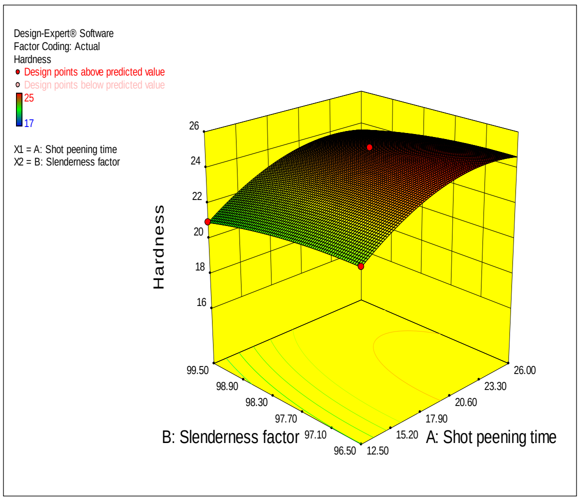

Fig. 10. 3D graph of hardness (HRC) as a function of shot peening time (min) and slenderness ratio.

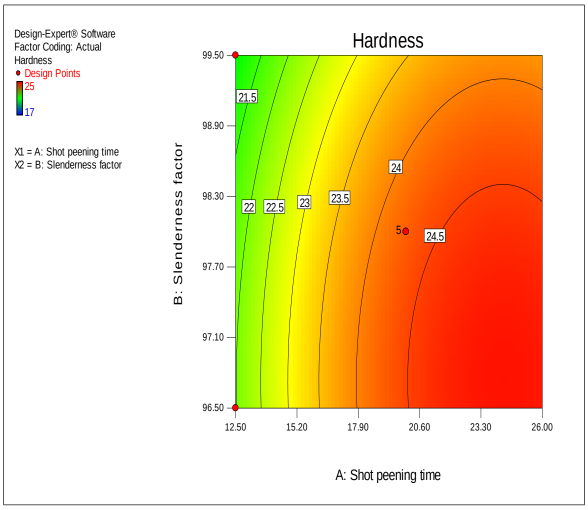

Fig. 8. Contour graph of hardness (HRC) as a function of shot peening time and slenderness ratio.

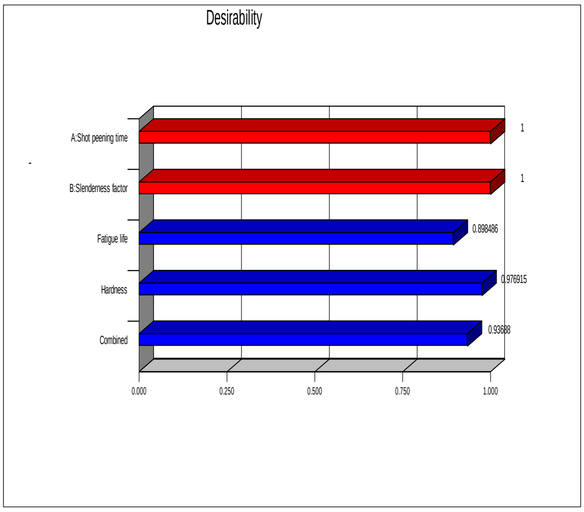

Fig. 11. Bar graph for the desirability.

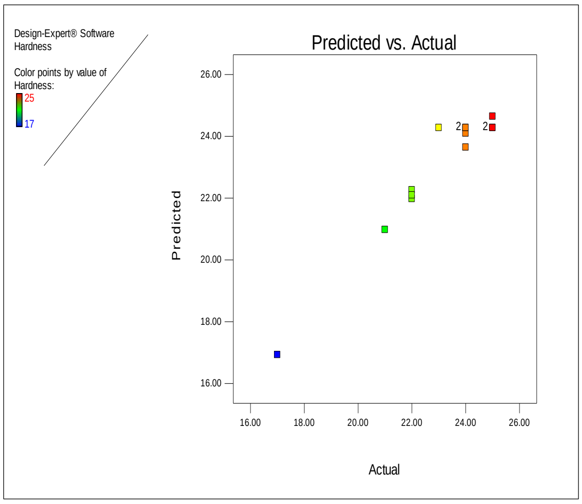

Fig. 9. Predicted versus actual hardness data for comparison.

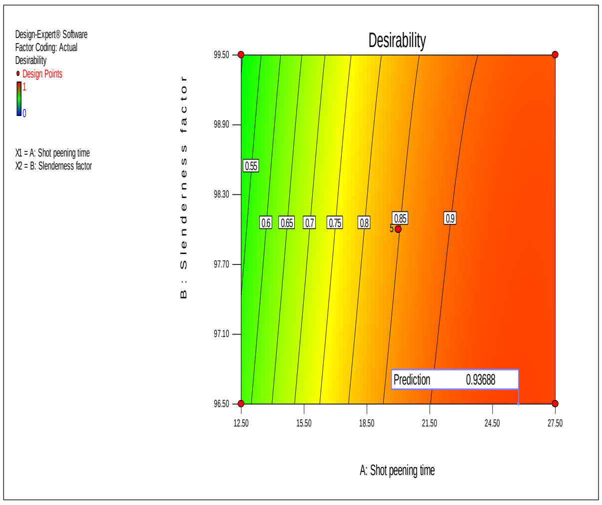

Fig. 12. 2D contour for desirability as a function of shot peening and slenderness ratio.

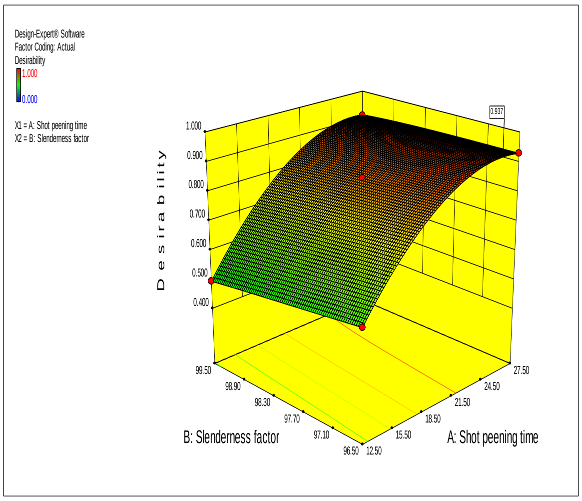

Fig. 13.3D surface plot for desirability as a function of shot peening time and slenderness ratio.

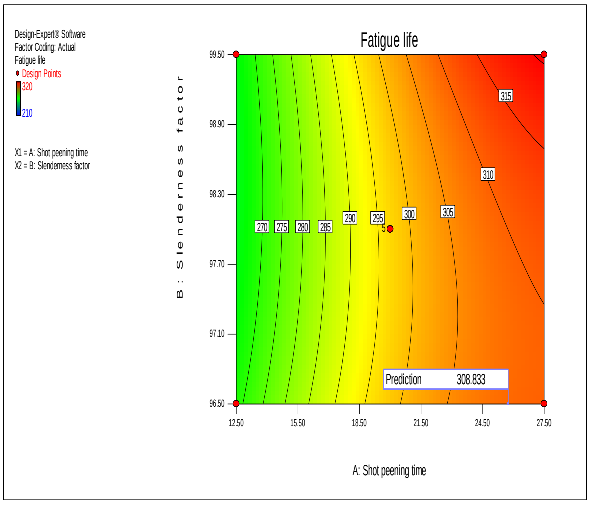

Fig.14. The optimum value of fatigue life (cycles).

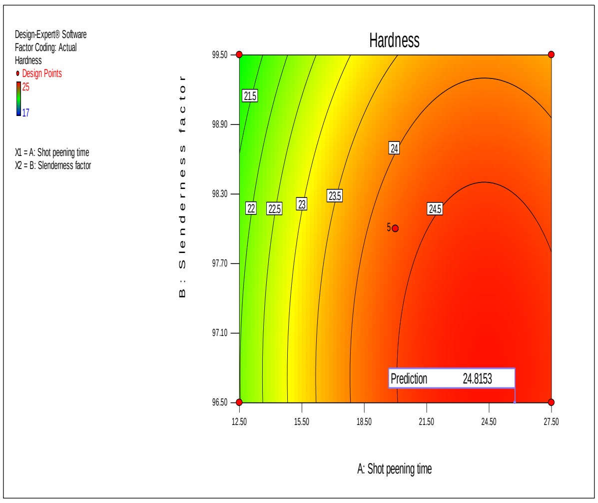

Fig. 15. The optimum value of hardness (HRC).

4. Conclusions

1. Quadratic equations for both fatigue life and hardness were developed at 95% confidence.
2. The shot peening time (SPT) has a great impact on fatigue life and hardness, while the slenderness ratio has a lower effect with 3 %.
3. Based on the response optimization, the optimum value of fatigue is 308.33 cycles and the optimum value of hardness is 24.8153 HRC with desirability reaching maximum value of 0.937.

5. References

[1] K. H. Al-Jubori,"Column Lateral Buckling Under Combined Dynamic Loading", PhD Thesis, University of Technology,2005.

[2] Mott Robert L., "Applied Strength of Materials", 3rd. Ed., Prentice Hall, Englewood Cliffs, New Jersy, 1996.

[3] [3] Caravallo A. L. M., and Voorwald, H. J. C., "Influence of Shot peening and Chord Chromium Electroplating on the Fatigue Strength of 7050-T7451 Aluminum Alloy", International Journal of Fatigue , Vol. 29, pp. 1282-1291, 2007.

[4] H. J. Mohamed Al-alkawi and Hussain Abdul Aziz, "An Appraisal of Euler and Johnson Buckling Theories Under Dynamic Compression Buckling Loading", The Iraqi Journal for Mechanical and Material Engineering, Vol. 7, No. 2, pp. 108-116, 2007

[5] K. Pal and S. K. Pal, "Soft Computing Methods Used for the modeling and optimization of Gas Metal Arc Welding: A Review", Int. Journal of Manufacturing Research, Vol. 6, No.1, pp. 15-29, 2011.

[6] Samir Ali Amin and Salah Sabeeh Abed-Alkareem, "Modeling and Optimization of GMAW Weld Geometry (Weld Bead and Penetration) for Steel AISI 1025", Third Scientific International Conference, Technical Education / Najaf, 2012.

[7] Montgomery, D. C., “Design and Analysis of Experiments: Response Surface Method and Designs”, New Jersey: John Wiley and Sons, Inc., 2005.

النمذجة العملية المثلى لعمر التصدع والصلادة للفولاذ الكاربوني (CK35) تحت تأثير احمال الانبعاج الديناميكية

أحمد نايف ابراهيم الخزرجي
قسم هندسة المكائن والمعدات/ الجامعة التكنلوجية
البريد الالكتروني: Dr_ahmed53@yahoo.com

الخلاصة

يهدف هذا البحث الى النمذجة المثلى لعمر الكلال والصلادة للفولاذ متوسط الكاربون (CK35) مسلط عليها انبعاج ديناميكي. تم استخدام مديات مختلفة من ازمنة السفع بالكرات وقيم مختلفة لنسب النحافة والتي كانت بين الاعمدة الطويلة والمتوسطة بوصفها عوامل مدخلة لإيجاد تأثيراتها على الصلادة وعمر الكلال بوصفها استجابات. تم الحصول على القياسات العملية للانبعاج ولزمن السفع بالكرات وتحليلها باستخدام برمجة التصميم العملي (DESIGN EXPERT 8) والتي استخدمت لأغراض الحصول على النمذجة المثلى. تم الحصول على الموديل الرياضي للاستجابات وتحليلها باستخدام تباين (ANOVA) للبرهنة على صلاحية النماذج. بأستخدام هاذ التباين تم الحصول على موديل رياضي من الدرجة الثانية . لقد وجد تقارب جيد بين نتائج هذه النمذجة المثلى والنتائج العملية مع مستوى موثوقية بمقدار ٩٥ %.