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Formation of Compressive Residual Stress by Face Milling Steel AISI 1045

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Abstract

Machining residual stresses correlate very closely with the cutting parameters and the tool geometries. This research work aims to investigate the effect of cutting speed, feed rate and depth of cut on the surface residual stress of steel AISI 1045 after face milling operation. After each milling test, the residual stress on the surface of the workpiece was measured by using X-ray diffraction technique. Design of Experiment (DOE) software was employed using the response surface methodology (RSM) technique with a central composite rotatable design to build a mathematical model to determine the relationship between the input variables and the response. The results showed that both the feed rate and the cutting speed are the significant factors controlling the surface residual stress, while the depth of cut had no influence. A quadratic empirical model was developed with a 95% confidence level, and a good agreement was found between the experimental and predicted results. A numerical optimization was then conducted through DOE program to find the optimum surface residual stress at the optimum cutting parameters, depending on the maximum desirability obtained. The optimum compressive surface residual stress (-224.361 MPa) was found at cutting speed of 69.2 m/min, feed rate of 0.4 m/min and depth of cut of 0.4 mm.

Keywords: *Face milling, Cutting parameters, Steel AISI 1045, Residual stresses, XRD; DOE, RSM, Modeling and Numerical optimization**.***

1. Introduction

Residual stress is defined as the stress state which exists in a body after all the external loads are removed. When assessing surface integrity, the residual stress is often considered as one of the most critical parameters, since it has a direct effect on the fatigue life of a machined component. The effects of residual stress could be both positive and detrimental on the deformation behavior, fatigue life, dynamic strength, chemical resistance and magnetic properties of the machined components. Tensile residual stresses on the surface of components dangerously affect the life of them in operating conditions [1].

Additionally, residual stress is the result of various mechanical and thermal events, which occur in the surface region during machining. It is usually found that the absolute value of the residual stress close to surface is high and decreases continuously with an increase in depth beneath the machined surface eventually vanishing. Residual stress may be tensile or compressive and the stressed layer may be shallow or deep, depending upon the cutting conditions, work material, and tool geometry [2]. The final stress state depends, therefore, on the relative importance of each of these three factors (mechanical, thermal and structural /phase transformation effects), which is determined not only by the physical and mechanical properties of the material to be machined, but also by the machining parameters employed. Consequently, it is very important to control the effect that each cutting parameter has in the final surface integrity of the machined part, in order to determine the most adequate machining parameters [3].

Mechanical loads mainly result in compressive stresses and thermal loads in tensile stresses in the materials subsurface. The combination of both determines the final residual stress state of the workpiece [4]. It was indicated that cutting speed, feed per tooth, workpiece angle, depth below the machined surface and some of their interactions are the significant factors to determine residual stresses durin end milling AISI H13 steel [5]. Machining residual stresses correlate very closely with the cutting parameters and the tool geometries [6]. Normally, the increase of cutting speed leads to increase the heat generated during the cutting process due to the increase of strain rate that resulted from the higher shear stresses. So, the major part of this heat is taken away with detached chip, whereas the remaining part transfers by conduction through the cutting tool to the machined part surface. Cutting speed increases the tensile residual stress on the surface. The heat generated from higher cutting speeds does not penetrate more deeply into the workpiece [7]. In milling, the feed rate influences the surface and subsurface residual stresses [8].

Many methods are widely used for the measurement of residual stresses, such as X-ray diffraction, hole-drilling method and other destructive methods. X-ray diffraction provides a powerful technique for the evaluation of residual stresses. The method has been successfully used in a wide variety of cases. This method is applicable to crystalline materials, like metals and ceramics. However, now the method can be applied to noncrystalline composite materials also by the introduction of an extremely thin layer of crystalline material during the fabrication. The ability of the method to measure stresses in the individual phases of a multiphase material is a major advantage of the technique [9]. To optimize the parameters, some tests defined through an experimental design system must be done for milling to change feed and cutting speed Cutting depth has a small influence on the surface characteristics [10].

Design of experiment (DOE) begins with determining the objectives of an experiment and selecting the process factors for the study. An experimental design is the laying out of a detailed experimental plan in advance of doing the experiment. In an experiment, we deliberately change one or more process variables (or factors) in order to observe the effect of the changes that have on one or more response variables. The statistical design of experiments (DOE) is an efficient procedure for planning experiments, so that the data obtained can be analyzed to yield valid and objective conclusions [11]. Response surface methodology (RSM) is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response [12]. RSM also quantifies relationships among one or more measured responses and the vital input factors. The version 8 of the Design Expert software was used to develop the experimental plan for RSM. The same software was also used to analyze the data collected [13].

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Therefore, the aim of this paper is first to obtain the prediction model for the residual stress (as a response) in terms of input cutting conditions (cutting speed, feed rate, and depth of cut) during face milling of medium carbon steel AISI 1045 and then to optimize these parameters for the purpose of minimizing the induced residual stresses.

2. Experimental Work

2.1. Material Verification

The cutting performance tests were performed on medium carbon steel AISI 1045 bars. The material chemical composition is shown in Table 1 together with that for the standard type. The average hardness of the bar is 93 HB. This material is selected to be used in this work, since it is suitable for a wide variety of automotive-type applications. For example, axle and spline shaft are two examples of automotive components produced using this material, where the turning is the prominent machining process used. The used material was then tensile tested to determine its mechanical properties, and the results are given in Table 2 in comparison with the standard type. Both tables indicate the conformity the used material with the standard one**.**

2.2. Preparation of Test Specimens

The supplied steel AISI 1045 was cut in form of blocks as specimens with 80 mm in length, 50 mm in width and 30 mm in height. Before conducting the face milling operations, the external surfaces of these blocks were first slightly milled to remove the original oxidation layers and surface defects, and then heated to (650 ºC) holding for 1 hour to relive all stresses by a stress relive process according to ASTM.

2.3. Machine Setup and Cutting Tool

In this work, the milling tests were carried out on a three-axis vertical milling machine “C-tek” model “KM-800L” located at the workshop center in General Company for Examination and Rehabilitation Engineering. Figure 1 shows the CNC milling machine used in the experimental operation together with the milling cutter and carbide inserts. The cutter is driven by a spindle on an axis perpendicular to the surface being milled. In all milling tests, a milling cutter of 63 mm in diameter was used, with three cutting edges each tipped with one carbide insert type (TTM).

2.4. Cutting Conditions

Three cutting parameters (cutting speed, feed rate, and depth of cut) were used in two levels (Table 3) to study the influence of using different cutting conditions on the residual stresses induced by milling steel AISI 1045. These two levels were chosen according to the practical experience and experimental data reported earlier [14].Twenty milling tests (runs) were carried out randomly at different cutting parameters according to the design matrix established by the DOE software as shown in Table 4 together with the values of the measured residual stress.

2.5. XRD Measurements

The X-ray diffraction method can give accurate measurements of the residual stresses on the surface, but it is not able to provide the distribution of the residual stresses of over the depth; also, destructive methods are inadequate because the specimen must be sectioned and cannot be used again. Thus, this method was used in the present research, since this technique is a widely employed for determining the residual stresses at the surface of a material. The residual stress measurement was conducted in the National Centre for Research and Construction Laboratories - Baghdad with the X-ray stress analyzer type (XRD-6000), as shown in Figure 2. A copper tube was used to measure the AISI 1045 steel. The results of all residual stresses measured at different cutting conditions are given in Table 4 showing that they were mostly compressive surface residual stresses type.

3. Results and Discussion

3.1. Mathematical Model of Residual Stress

A mathematical model of residual stress has been developed using RSM based on the experimental data. The quadratic response surface function was considered, since the situations where the curvature in the normal operating ranges is inadequately modeled by the first-order function often occur. RSM technique was used with a central composite rotatable design (CCD) for 2^3 factors, with 5 central points and $\alpha = \pm 2$ approach. Each cutting parameter was used at different coded levels of −2, −1, 0, +1, and +2, whereby each level used conformed to an actual value equivalent to the coded value. The software DESIGN EXPERT version 8 was used to develop the predicted model within a 95% confidence interval. To analyze the data, checking of goodness of fit of the model is very much required. The model adequacy checking includes the test for significance of the regression model, test for significance on model coefficients, and test for lack of fit. For this purpose, the analysis of variance (ANOVA) was performed.

To statistically analyze the results, the analysis of variance (ANOVA) for response surface quadratic model for residual stress was performed, as shown in Table 5. In this table, the model F-value of 25.29 implies the model is significant. The values of 'Prob > F' less than 0.0500 indicate that the model terms A, B, A^2, B^2 and C^2 are significant model terms, except the term C which is insignificant since its 'Prob > F value is greater than 0.0500. But, the term C was included in the model to keep the hierarchy of the model. Thus, this model indicates that the cutting speed (A) and feed rate (B) have the greatest impact on the residual stress, while the depth of cut (C) has no influence. The lack of fit was found insignificant since its 'Prob > F' is greater than 0.0500, this means this model is good with 95% confidence. Then, the final predicted quadratic model developed for the residual stress in terms of coded factors is:

$$\text{Residual stresses} = +42.07 - 32.99 * A + 73.66 * B - 16.40 * C - 28.30 * A^2 - 45.75 * B^2 - 69.33 * C^2 \quad \ldots (1)$$

And, the final equation in terms of actual factors:

$$\text{Residual stresses} = -1259.30603 + 5.46656 * \text{Cutting speed} + 1740.88068 * \text{Feed rate} + 3995.63636 * \text{Depth of cut} - 0.072192 * \text{Cutting speed}^2 - 1143.80682 * \text{Feed rate}^2 - 1143.80682 * \text{Feed rate}^2 - 6932.72727 * \text{Depth of cut}^2 \quad \ldots (2)$$

The results of the diagnostic checking of the model are presented in Figs. 3 and 4. The normal probability plot is shown in Fig. 3, revealing that the residuals fall on a straight line implying that the errors are distributed normally. While Fig. 4 depicts the standardized residuals with respect to the predicted values and these residuals do not show any obvious pattern and are distributed in both positive and negative directions, implying that this model is adequate.

Figure 5 illustrates the 2D contour graph of residual stress response as a function of cutting speed and feed rate at 0.3 mm depth of cut. It is noted that the increase in both cutting speed and feed rates generally affect on the type of formed residual stress. In other words, at higher feed rates and lower cutting speeds, the type of formed residual stress is tensile, whereas at higher cutting speeds and lower feed rates, a compressive residual stress type is formed. This means increasing the feed rate will increase the tensile residual stress, while increasing the cutting speed will increase the compressive residual stress. This is most probably attributed to the thermal effect associated with more material removal due to higher cutting forces at higher feed rates that resulted in more plastic deformation in the material, causing higher induced tensile stresses. But, at higher values of cutting speed, this thermal effect and plastic deformation will be more influential due to the cutting temperature increase with the cutting speed increase, resulting higher induced compressive residual stress.

Figure 6 shows the predicted actual residual stresses data versus the actual ones for comparison reason. This figure also indicates that the predicted values of residual stresses are close to the actual ones measured in the experiments. So, a good agreement was found between the experimental and the predicted results. Figure 7 manifests the 3D graph of residual stresses as a function of cutting speed and feed rate at 0.4 mm cutting depth. It can be noted that the increase of both cutting speed and feed rate individually results in an increase in the residual stress value, while the variation of depth of cut over the range (0.2 – 0.6) mm was found to be less effective on the formed residual stresses. However, the feed rate has a greater influence on the residual stress than cutting speed, thus increasing the possibility of formation of tensile residual stress, whereas increasing the cutting speeds promotes the formation of compressive residual stress.

3.2. Numerical optimization of Residual Stresses

The numerical optimization was performed by the Design of Experiment software, based on the data from the predictive model for one response, residual stress, as a function of three factors: cutting speed, feed rate and depth of cut. Table 6 gives the design summary for the input factors and response; it can be observed that the residual stress is modeled with a quadratic model.

For predicted model development, a new objective function, named Desirability was evaluated, 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. In this work, weights and the importance were not changed. Table 7 lists the constrains of each variable for numerical optimization of the residual stress. According to this table, five possible runs fulfilled these specified constrains to obtain the optimum value for residual stress, as given in Table 8. It can be noted that all the runs gave desirability of (0.875). Figure 8 depicts the bar graph for the desirability, while Figs. 9 and 10 reveals the 2D contour and 3D surface plot for desirability as a function of cutting speed and feed rat, respectively. In addition, Figs. 12 and 13 depict the optimum value of the minimum residual stress in 2D contour and 3D surface plot, respectively. It can be seen from these figures that the desirability reaches the maximum value of 0.875 when the optimum value of residual stress is (-224.361) MPa. Finally, for the face milling of steel AISI 1045, the optimum cutting conditions are found to achieve the best surface residual stresses within predetermined parameters. The optimum values of these conditions are cutting speed of 69.2 m/min of, feed rate of 0.4 m/min and depth of cut of 0.4 mm with a minimum surface residual stress of (-224.361) MPa was obtained.

Table 1,
Chemical compositions (wt%) of the used and standard medium carbon steel AISI 1045.

Alloy	C	Si	Mn	Cr	Mo	Ni	V	S	P	Cu
Standard (Max)	0.48	0.40	0.65	0.40	0.63	0.63	0.63	0.63	0.63	0.63
Used material	0.45	0.25	0.61	0.20	0.01	0.07	0.001	0.015	0.017	0.09

Table 2,
Mechanical properties of the used and standard medium carbon steel AISI 1045.

Alloy	Yield stress (MPa)	Ultimate tensile (MPa)	Elongation (%)	Hardness(HRB)
Standard	450-515	550-615	10-24	150 Max.
Used material	485	585	15	93

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

Factor	Units	Low level (- 1)	High level (+1)	-alpha	+alpha
Cutting speed	m/min	29.6	69.2	9.8	89.0
Feed rate	m/min	0.40	0.80	0.20	1.00
Depth of cut	mm	0.2	0.4	0.1	0.5

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

Standard No.	Run No.	Type of point	Cutting speed (m/min)	Feed rate (m/min)	Depth of cut (mm)	Residual stress (MPa)
1	8	Factorial	29.6	0.40	0.2	-116.1
2	20	Factorial	69.2	0.40	0.2	-189.1
3	13	Factorial	29.6	0.80	0.2	30.0
4	16	Factorial	69.2	0.80	0.2	-35.8
5	12	Factorial	29.6	0.40	0.4	-182.4
6	10	Factorial	69.2	0.40	0.4	-271.3
7	6	Factorial	29.6	0.80	0.4	42.0
8	1	Factorial	69.2	0.80	0.4	-97.7
9	7	Axial	9.8	0.60	0.3	-29.8
10	4	Axial	89.0	0.60	0.3	-110.0
11	5	Axial	49.4	0.20	0.3	-260.0
12	18	Axial	49.4	1.00	0.3	-19.4
13	15	Axial	49.4	0.60	0.1	-218.0
14	9	Axial	49.4	0.60	0.5	-250.0
15	11	Center	49.4	0.60	0.3	59.1
16	2	Center	49.4	0.60	0.3	39.1
17	17	Center	49.4	0.60	0.3	-21.7
18	14	Center	49.4	0.60	0.3	-7.5
19	3	Center	49.4	0.60	0.3	80.2
20	19	Center	49.4	0.60	0.3	105.7

Table 5,
ANOVA for Response Surface Quadratic Model(Residual Stress).

Source	Sum of squares	df	Mean square	F value	p-value Prob > F
Model	2.563E+005	6	42711.77	25.29	< 0.0001 significant
A-Cutting speed	17410.80	1	17410.80	10.31	0.0068
B-Feed rate	86818.62	1	86818.62	51.40	<0.0001
C-Depth of cut	4303.36	1	4303.36	2.55	0.1345
A^2	20139.90	1	20139.90	11.92	0.0043
B^2	52630.80	1	52630.80	31.16	< 0.0001
C^2	1.208E+005	1	1.208E+005	71.55	< 0.0001
Residual	21956.59	13	1688.97		
Lack of Fit	9632.30	8	1204.04	0.49	0.8245 not significant
Pure Error	12324.29	5	2464.86		
Cor Total	2.782E+005	19			
Std. Dev.	**41.10**	**R-Squared**	**0.9211**		
Mean	**- 7264**	**Adj R-Squared**	**0.8847**		
C.V.%	**56.58**	**Pred R-Squared**	**0.7782**		
Press	**61709.62**	**Adeq Precision**	**13.587**		

Table 6,
Design summary for main factors and response (Design model: Quadratic).

Factors	Name	Unit	Min.	Max.	Coded values	Mean	Std. Dev.
A	Cutting speed	m/min	9.80	89.0	-1.000=29.60 1.000=69.20	49.40	17.71
B	Feed rate	m/min	0.20	1.0	-1.000=0.40 1.000=0.80	0.60	0.18
C	Depth of cut	mm	0.10	0.5	-1.000=0.2 1.000=0.4	0.30	0.09
Response	**Name**	**Unit**	**Min.**	**Max.**	**Mean**	**Ratio.**	**Std. Dev.**
Y1	Residual stresses	MPa	-271.3	105.7	-72.635	N/A	121.01

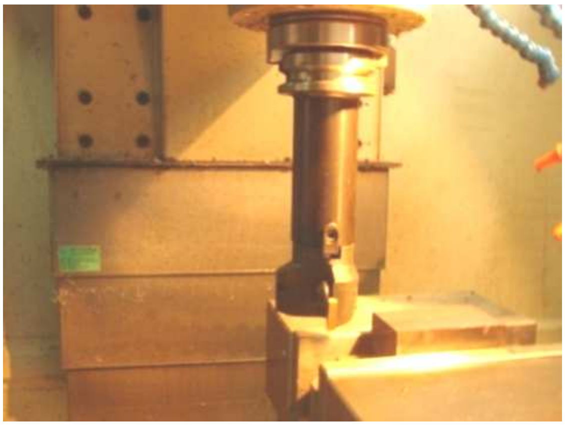
Table 7,
Constrains of each varaible for numerical optimizationof the residual stress.

Types of variables	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Cutting speed	is in range	29.6	69.2	1	1	3
B: Feed rate	is in range	0.4	0.8	1	1	3
C:Depth of cut	is in range	0.2	0.4	1	1	3
Residual stresses	mnimize	-271.3	105.7	1	1	3

Table 8,
Optimal conditions used to obtain the minimum residual stress.

No.	Cutting speed (m/min)	Feed rate (m/min)	Depth of cut (mm)	Residual stress (MPa)	Desirability
1	69.20	0.40	0.40	-224.361	0.875 selected
2	68.75	0.40	0.40	-222.314	0.870
3	69.13	0.40	0.40	-220.156	0.864
4	69.20	0.40	0.40	-191.561	0.788
5	65.22	0.40	0.40	-174.528	0.743

(a)



(b)

(c)

Fig. 1. (a) The CNC milling machine setup, (b) face milling cutter and (c) carbide inserts.

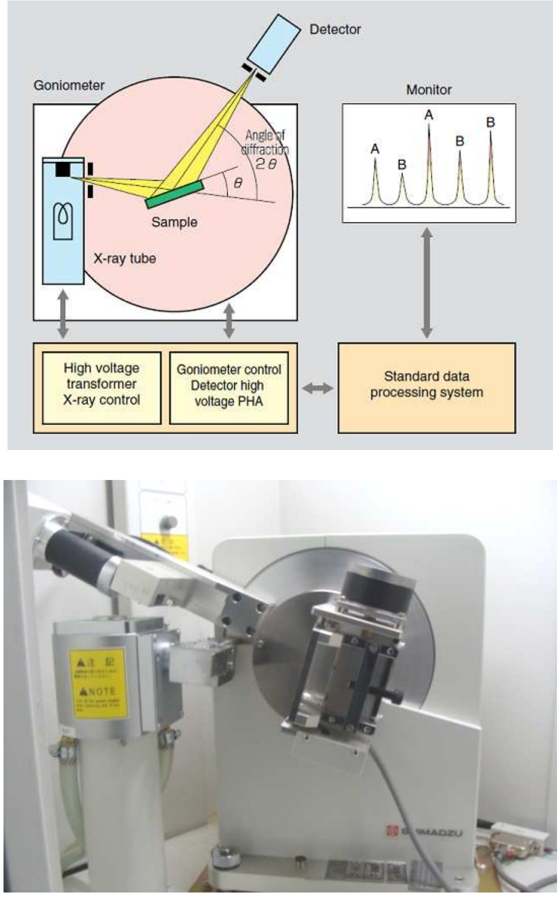


Fig. 2. X-ray stress analyzer (XRD-6000) used to measure the residual stresses.

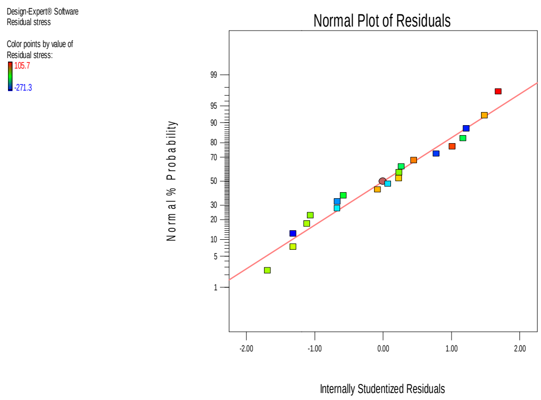


Fig. 3. Normal probability plot for residual stress data.

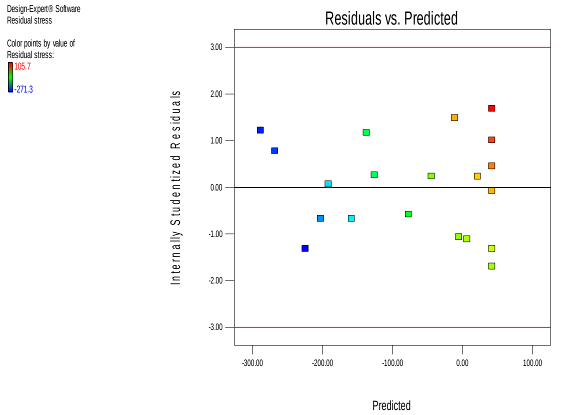


Fig. 4: Residual versus predicted responses for residual stress data.

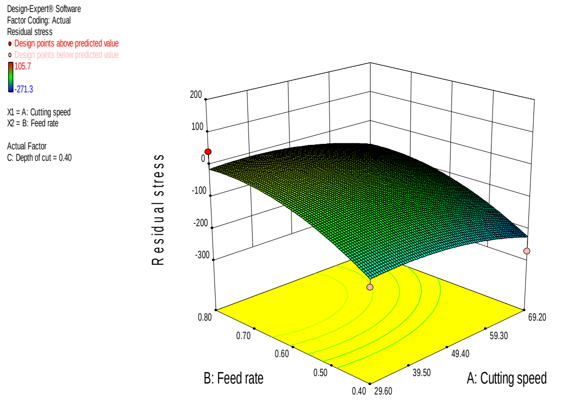


Fig. 7. 3D graph of residual stresses as a function of cutting speed and feed rate at 0.4 mm depth of cut.

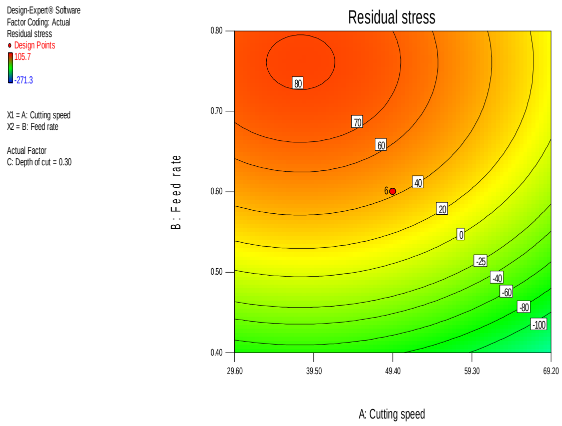


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Fig.5: Contour graph of residual stresses as a function of cutting speed and feed rate.

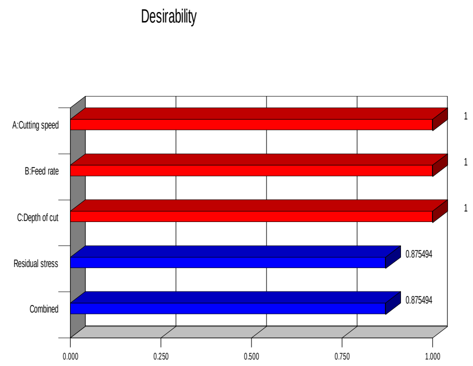

Fig. 8. Bar graph for the desirability.

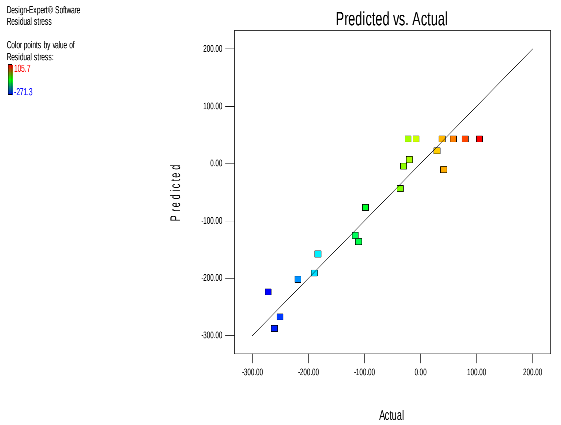

Fig. 6. Predicted versus actual residual stresses data for comparison.

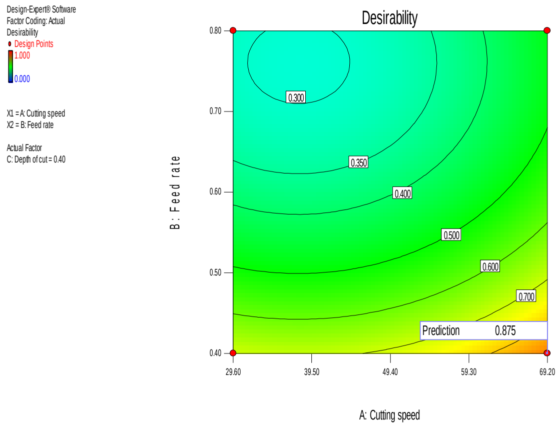

Fig. 9. 2D contour for desirability as a function of cutting speed and feed rate.

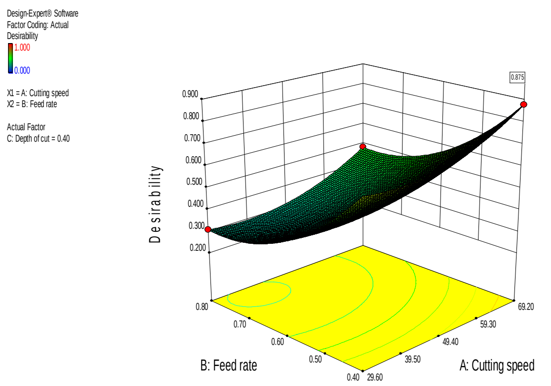

Fig. 10. 3D surface plot for desirability as a function of cutting speed and feed rate.

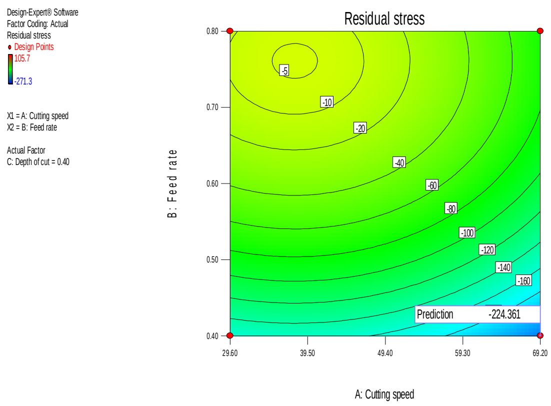

Fig. 11. 2D contour showing the optimum value of residual stress.

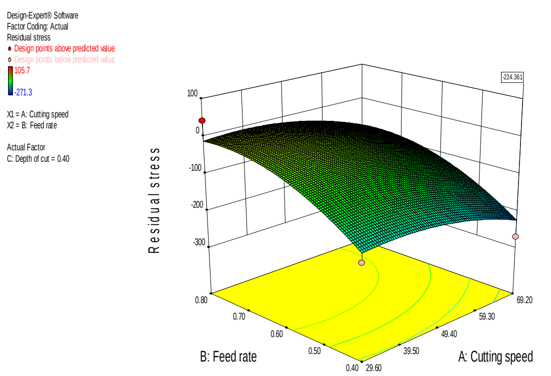

Fig. 12. 3D surface plot showing the optimum value of residual stress.

4. Conclusions

1. Quadratic equation for residual stress as a function of cutting speed, feed rate and depth of cut was developed, using RSM and DOE software, and its adequacy was checked and found good with a confidence of 95%.
2. The predicted model indicated that feed rate and cutting speed have greater effect on the induced residual stress, while the depth of cut is not influential. However, the feed rate was found more effective than cutting speed.
3. In this study, more compressive surface residual stress formed at higher cutting speeds, while less tensile residual stress induced at higher feed rates during face milling of steel AISI 1045
4. The quadratic model built by RSM technique is able to provide accurately the predicted and optimum values of residual stresses close to actual values that measured experimentally by the XRD method
5. By numerical optimization, the optimum value of residual stress was found to be (-224.361) MPa, with a desirability reaching the maximum value of 0.875 when the optimum cutting speed is 69.2 m/min, feed rate is 0.4 m/min and depth of cut is 0.4 mm.
6. This work showed that DOE with RSM is a powerful statistical tool for modeling and numerical optimization for predicting the residual stress induced by face milling process for any given input parameters.

List of Abbreviations

Abbreviator	Description
ANOVA	Analysis of Variance
CCD	Central Composite Design
DOE	Design of Experiment
MRR	Material Removal Rate
RSM	Response Surface Methodology
XRD	X-Ray Diffraction

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توليد الاجهادات الضغطية المتبقية بواسطة التفريز السطحي للصلب (AISI 1045)

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الخلاصة

ترتبط أجهادات التشغيل بشكل وثيق جدا" مع عوامل القطع والاشكال الهندسية لأدوات القطع . يهدف عمل هذا البحث الى التحقق من تأثير سرعة القطع ومعدل التغذية وعمق القطع على الاجهاد المتبقي السطحي للصلب (AISI 1045) بعد عملية التفريز الوجهي . تم قياس الاجهاد المتبقي على سطح المشغولة بعد كل عملية تفريز بأستخدام تقنية حيود الاشعة السينية (XRD) . تم تطبيق برنامج تصميم التجارب (DOE) بأستخدام تقنية منهجية الاستجابة السطحية (RSM) بتصميم دوارمركب مركزي (CCD) لبناء نموذج رياضي لأيجاد العلاقة بين المتغيرات الداخلة والاستجابة . أظهرت النتائج بأن كلا" من معدل التغذية وسرعة القطع عوامل مهمة تتحكم بالاجهاد المتبقي السطحي بينما لم يكن لعمق القطع تأثير . تم عمل نموذج تجريبي من الدرجة الثانية بموثوقية ٩٥% ووجد توافق جيد بين النتائج العملية والمتنبئة . بعد ذلك ، تم عمل أمثلية عددية خلال برنامج تصميم التجارب لأيجاد أمثل اجهاد متبقي سطحي عند أمثل عوامل قطع أعتمادا" على أقصى مطلوبية مستحصلة . وفقا" لذلك ، وجد أن الاجهاد المتبقي السطح الضغطي الامثل (224.361-) ميجاباسكال عند سرعة قطع (٦٩.٢) م/ دقيقة ومعدل تغذية (٠.٤) م/ دقيقة وعمق قطع (٠.٤) ملم .