EVALUATION OF THE EFFECTS OF CUTTING PARAMETERS ON THE SURFACE ROUGHNESS DURING THE TURNING OF HADFIELD STEEL WITH RESPONSE SURFACE METHODOLOGY

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Abstract: Hadfield steel (X120Mn12) is widely used in the engineering applications due to its excellent wear resistance. In this study, the effects of the cutting parameters on the surface roughness were investigated in relation to the lathe process carried out on Hadfield steel. The experiments were conducted at a cutting speed of 80, 110, 140 m/min, feed rate of 0.2, 0.3, 0.4 mm/rev and depth of cut 0.2, 0.4, 0.6 mm, using coated carbide tools. Regarding the evaluation of the machinability of Hadfield steel, a model was formed utilizing the response surface method (RSM). For the determination of the effects of the cutting parameters on the surface roughness, the central composite design (CCD) and variance analysis (ANOVA) were used. By means of the model formed as a result of the experimental study, it was demonstrated that among the cutting parameters, the feed rate is the most effective parameter on the surface roughness, with a contribution ratio of 90.28%. It was determined that the surface roughness increases with increasing feed rate. With respect to the effect on the surface roughness, the feed rate was followed by the cutting speed with a contribution ratio of 3.1% and the cutting depth with a contribution ratio of 1.7%.

Keywords: Hadfield Steel, Machinability, Surface Roughness, Response Surface Methodology

Hadfield Çeliğinin Tornalanmasında Kesme Parametrelerinin Yüzey Pürüzlülüğü Üzerindeki Etkilerinin Yanıt Yüzey Metodu ile Değerlendirilmesi

Özet: Hadfield çeliği (X120Mn12) sahip olduğu mükemmel aşınma direncinden dolayı mühendislik uygulamalarında yaygın olarak kullanılmaktadır. Bu çalışmada Hadfield çeliğinin tornalanmasında kesme parametrelerinin yüzey pürüzlülüğü üzerindeki etkileri araştırılmıştır. Deneyler 80, 110, 140 m/dak kesme hızı, 0.2, 0.3, 0.4 mm/dev ilerleme ve 0.2, 0.4, 0.6 mm kesme derinliğinde kaplamalı karbür takımlar kullanılarak gerçekleştirilmiştir. Halfield çeliğinin işlenebilirliğinin değerlendirilmesinde yanıt yüzey yöntemi (RSM) kullanılarak bir model oluşturulmuştur. Kesme parametrelerinin yüzey pürüzlülüğü üzerindeki etkilerinin belirlenmesinde merkezi tümleşik tasarım (CCD) ve varyans analizi (ANOVA) kullanılmıştır. Deneysel çalışma sonrasında oluşturulan modelle, yüzey pürüzlülüğü üzerinde kesme parametrelerinden ilerlemenin % 90,28 katkı oranı ile en etkili parametre olduğu ortaya konulmuştur. İlerlemenin artmasıyla yüzey pürüzlülüğünün arttığı görülmüştür. Yüzey pürüzlülüğü üzerinde etki bakımından ilerlemeyi % 3,12 katkı oranı ile kesme hızı, % 1,7 katkı oranı ile de kesme derinliği takip etmiştir.

Anahtar Kelimeler: Hadfield çeliği, İşlenebilirlik, Yüzey pürüzlüğü, Yanıt yüzey metodu

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1. INTRODUCTION

The presence of austenitic manganese steels is known for the last couple of ages. The Hadfield steels which were produced and improved firstly by A. Pourcel are known by the name R. A. Hadfield who made detailed studies on these alloys since 1878 (Maratray, 1995). These steels have extra ordinary working hardnesses under loads like continuous impact and friction (Collette et. al., 1957). They are widely used in various engineering applications like rail-road materials and in wear resistant machining parts due to their excellent wear resistance properties. They also find application field in the production of anti-magnetic characteristic electron industrial parts and experimental equipment of nuclear power plants (Canadinc et. al., 2005 and Gavriljuk et. al., 2005).

Surface roughness is an important parameter in the determination of the workpiece quality (Dhanasekar and Ramamoorthy, 2010). Nowadays new methods were developed to solve this problem. For the evaluation of tests, a model was developed to estimate the surface roughness with the response surface method (Choudhury and El-Baradie, 1997). The response surface method is a mathematical method between the independent and dependent variables (response) with respect to the experimental data (Deniz et. al., 2005). This method is based on the examination of the response surface in between the highest and lowest levels of independent variable according to the above-mentioned mathematical model (Chiang and Chang, 2007). RSM is presented with two or three dimensional response surface (Godfrey and Kumar, 2006). The correctness and effectiveness of the experimental process depends on the careful planning and carrying on of the experimental program (Gunaraj and Murugan, 1999). In the milling of mould surfaces to obtain a minimum surface roughness, Öktem and his colleagues developed a genetic algorithm for the purpose of determination of optimum cutting conditions by using RSM (Öktem et. al., 2005). Seman and his colleagues used RSM, in the machining of SiC reinforced metal matrix composites, to specify the effects of cutting parameters on the tool wear and surface roughness. They have developed a regression model and found the cutting speed and feed rate as the most effective parameter on the surface roughness among the whole parameters (Seman et. al., 2010). Yang and Tarng-Davim, by using Taguchi method, tried to determine optimum machining parameters in order to obtain the desired surface roughness and to increase tool life in the turning process (Yang et. al., 1998 and Davim, 2003). Grum and Slabe used factorial design and RSM to determine the different optimum heat treatment conditions of Ni-Co-Mo layered surfaces (Grum and Slabe, 2006).

2. MATERIALS AND METHOD

2.1. Experimental Materials and Equipments

Turning process was carried on with Johnford TC 35 (10 kW) CNC lathe of 3500 rev/min under dry cutting conditions. As the workpiece a Hadfield steel (30 HRC) of 60 mm diameter and 150 mm length was used. The chemical compositions of test samples were given in Table 1. In the tests SNMG 12 04 08-QM coated cemented carbide (Sandvik) cutting tools were used. To provide the initial conditions of each test, a new insert is used for each experiment. In the evaluation of surface roughness of machining surfaces average surface roughness (Ra) was used. Surface roughness measurements were made with the Perthometer M1 surface roughness device.

Table 1. Chemical composition of Hadfield steel

Mn	C	Si	P	S	Cr	Mo	Ni	Fe
12.4	1.16	0.448	0.028	0.0145	0.959	0.0144	0.0633	Balance

In the experimental study the effects of cutting speed, feed rate and depth of cut on the surface roughness were investigated. The cutting parameters which were used in the tests were given in Table 2.

Table 2. Cutting parameters

Cutting speed (Vc). [m/min]	Feed rate (f). [mm/rev]	Depth of cut (ap). [mm]
80	0.2	0.4
110	0.3	0.6
140	0.4	0.8

2.2. Planning the experimental investigation

The sequence of operations in the experimental study is given below.

1. Determination of the lower and upper limits of dependent variables (Vc, f and ap)
2. Formation of design matrix
3. Entering responses
4. Developing the mathematical model
5. Calculation of the polinomial coefficients
6. Controlling the validity of the developed model
7. Testing of the meaningfulness of regression coefficients
8. Presentation of the meaningfulness levels of input parameters and basic effects on the two and three dimensional contour graphs
9. Analysis of the results

2.3. Response Surface Method

The response surface method is a method of formation of a mathematical model depending on the relation between independent variables (control factors) and dependent variable (response) due to the results of the experimental data. The model is based on the examination of the response surface which is obtained according to the results of design matrix formed depending on the parameters between the highest and the lowest levels of factors. In the RSM method the relation between the response and the factors is not known. For this, first of all a suitable correlation is established between the response and the factors;

$$Y = F\ (Vc,\ f,\ ap) \tag{1}$$

In the equation 1 ‘Y’ is the desired response and ‘F’ is the response function. In order to estimate the response in the analysis, a quadratic polynomial model (quadratic model) (Vitanov, 2010. Bhattacharya and Sorkhel, 1999. Krajnik et. al., 2005) which is widely employed in the industrial applications was used. The quadratic model ‘Y’ was explained in the equation 2;

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} b_{ii} X_j + \sum_{i<j}^{k} b_{ij} X^2{}_{ij} \tag{2}$$

The purpose of developing a mathematical model is to establish the relation between the cutting parameters and surface roughness and to optimize the cutting parameters according to the test results. In the determination of the required parameters for the model, firstly optimum plan matrices were established. In the establishment of plan matrices the below equation 3 was used by making use of the coded values of the parameters;

$$U_1 = \frac{X_i - X_{io}}{\Delta X_i} \tag{3}$$

Coded value of U parameters, X_{io}; Average value of parameters, X_i; The real value of parameters, X_i ; Step interval of parameters, Here, the value of X_i=1,2,3 coded variables is obtained with the aid of conversion equation. Conversion equations were given in equation 4.

$$X_1 = \frac{V_c - V_{co}}{\Delta V_c}, \quad X_2 = \frac{f - f_o}{\Delta f}, \quad X_3 = \frac{a_p - a_{po}}{\Delta a_p} \tag{4}$$

X_1, X_2, X_3 values are cutting speed (Vc), feed rate (f), and depth of cut (ap) respectively. In the formation of experimental design, complete factorial central integrated design (CCD) technique was used. With complete factorial design the whole of the combinations of factors were designed at the surface center at three levels (high, +1, middle 0, and low 1). The coded values of parameters were given in Table 3.

Table 3. Cutting parameters and their levels

Symbol	Control parameters	Units	Levels		
			-1	0	1
Vc	Cutting speed	m/min	80	110	140
f	Feed rate	mm/rev	0.2	0.3	0.4
ap	Depth of cut	mm	0.4	0.6	0.8

In the central integrated design, depending on the X_1, X_2, and X_3 variables, 20 tests were carried on consisting of 6 center points. The design matrix which was established according to the cutting parameters and the test results are given in Table 4. In the establishment of the design, JMP 7.0 statistical analysis program was used.

Table 4. Design layout and experimental results

	Coded factors			Actual factors			Response variables
Test no.	X_1	X_2	X_3	Vc	f	ap	Y (Ra)
1	0	0	0	110	0.3	0.6	3.083
2	0	0	0	110	0.3	0.6	3.085
3	-1	1	1	80	0.4	0.8	6.504
4	-1	1	-1	80	0.4	0.4	5.194
5	1	-1	-1	140	0.2	0.4	1.556
6	-1	-1	-1	80	0.2	0.4	1.66
7	1	-1	1	140	0.2	0.8	1.53
8	-1	0	0	80	0.3	0.6	3.725
9	-1	-1	1	80	0.2	0.8	1.686
10	0	1	0	110	0.4	0.6	4.388
11	0	0	1	110	0.3	0.6	3.073
12	0	0	-1	110	0.3	0.4	3.324
13	0	0	0	110	0.3	0.6	3.083
14	1	1	-1	140	0.4	0.4	4.244
15	1	0	0	140	0.3	0.6	3.628
16	0	0	0	110	0.3	0.6	3.078
17	0	0	1	110	0.3	0.8	3.935
18	0	-1	0	110	0.2	0.6	1.585
19	1	1	1	140	0.4	0.8	4.656
20	0	0	0	110	0.3	0.6	3.204

3. RESULTS AND DISCUSSION

3.1. ANOVA Analysis

Anova table is a widely used model to test the meaningfulness of the factors and the interaction of the factors and the suitability of the model (Baş and Boyacı 2008). In the Anova table when 'Prob>F' is less than 0.05, model, factors and interaction of the factors are meaningful (Ko-Ta, 2008). Anova analysis results are shown in Table 5. When the Prob>F value is less than 0.05 the model is statistically meaningful. When the Prob>F values of dependent variables are less than 0.05, it indicates that the parameter has a meaningful effect on the response.

Table 5. Result of analysis of variance fort the surface roughness (Ra)

Source	Degree of freedom (DF)	Sum of Squares	F-Ratio	Prob. >F
Model	9	53.8902	522.569	<.0001
X1. (Vc)	1	0.28561	24.9258	0.0005*
X2. (f)	1	53.1025	4634.381	<.0001*
X3. (ap)	1	0.067733	5.9112	0.0354*
X1*X2	1	0.153181	13.3685	0.0044*
X1*X3	1	0.006216	0.5425	0.4783
X2*X3	1	0.014028	1.2243	0.2944
X1*X1	1	0.002087	0.1821	0.6786
X2*X2	1	0.189558	16.5431	0.0023*
X3*X3	1	0.033248	2.9016	0.1193
Lack of fit	5	0.02291	3436.52	<.0001
Pure error	5	0.000033	6.67E-06	
Total error	10	0.11458		
R	0.9978			
R (Adjusted)	0.9959			

From the ANOVA results it was seen that the interaction of cutting speed and cutting depth (X_1*X_3) and the square of the interaction of cutting speed and cutting depth $[(X_1*X_1), (X_3*X_3)]$ had Prob>F values less than 0.05 and this indicated that these independent variables were meaningless on the model. The arrangement of independent variables in the ANOVA results according to their meaningfulness was made and the results were given in Table 6.

Table 6. ANOVA for surface roughness after removing insignificant terms

Source	Degree of freedom (DF)	Sum of Squares	F-Ratio	Prob. >F	% Contribution	
Model	9	53.8902	522.569	<.0001		
X1. (Vc)	1	0.28561	24.9258	0.0005*	3.1209	
X2. (f)	1	53.1025	4634.381	<.0001*	90.28	
X3. (ap)	1	0.067733	5.9112	0.0354*	1.7064	
X1*X2	1	0.153181	13.3685	0.0044*	2.5245	
X2*X2	1	0.189558	16.5431	0.0023*	1.1621	
Lack of fit	5	0.02291	3436.52	<.0001	1.2053	
Pure error	5	0.000033	6.67E-06			
Total error	10	0.11458				
R	0.9978					
R (Adjusted)	0.9959					

According to the results in Table 6, the contribution rates specifying the effect of independent variables on the surface roughness are 90.28%, 3.12%, and 1.706% for the feed rate, cutting speed and cutting depth respectively. Prob>F value is close to zero and this makes the effect of related parameter on Ra more meaningful. When the contribution rates and the Prob>F values were taken into consideration It was seen that the most effective parameter on Ra was feed rate and then came cutting speed and cutting depth. The mathematical model which was developed according to the ANOVA results is given in equation 5.

$$Ra = - 0.96 - 0.0443 X_1 + 44.5 X_2 - 7.98 X_3 - 0.106 X_1 * X_2 - 0.0198 X_1 * X_3 + 10.8 X_2 * X_3 + 0.000352 X_1^2 - 37.3 X_2^2 + 6.74 X_3^2 \quad (5)$$

This mathematical model was arranged in accordance with the meaningfulness values of independent variables and the model in equation 6 was obtained.

$$Ra = - 0.96 - 0.0443 X_1 + 44.5 X_2 - 7.98 X_3 - 0.106 X_1 * X_2 - 37.3 X_2^2 + 6.74 X_3^2 \quad (6)$$

Real values (experimental) and calculated (estimated) values are shown in Fig 1. The correlation coefficient of the statistical model which was developed as a result of the analysis came out to be $R^2 = 0.97$ and this shows that the real and the estimated data are close to each other and the developed model is appropriate.

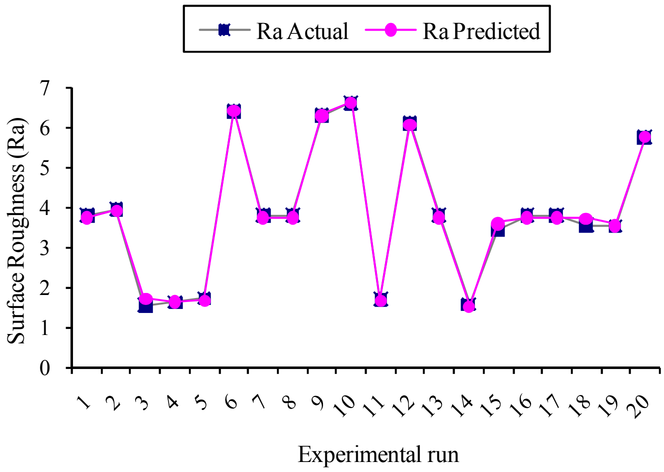

Figure 1:
Actual vs. predicted values of surface rougness (Ra).

3.2. Effect on performance evaluation of the machining parameters

The best way of specifying the effect between the dependent variables and response is the establishment of three dimensional response surface and contour graph. Cutting speed and the response surface of surface roughness depending on the feed rate is given in Fig. 2. From the response surface graph it is observed, that Ra values increase significantly with the increase of feed rate. Theoretical surface roughness is a function ([Ra= $f^2/(32.r)$] of feed rate (Shaw, 1984). As is stated in the literature surface roughness increases with the increase of feed (Işık, 2007). The increase of feed rate causes the cutting forces to increase. As a result of the increase in the cutting forces, vibrations and surface roughness increases. When looking at the surface roughness variation depending on the cutting speed, it was seen that Ra values decreased upto to 115 m/min cutting speed with the increase of cutting speed. The decrease in the surface roughness with the increase of cutting speed can be explained with the decrease of BUE formation due to high temperatures at the cutting area (Mohan, 2001). After the 115 m/min cutting speed it can be said that the increase in Ra values is due to the possible tool wear because of higher cutting speeds. It is clearly seen from the response surface graph that on the surface roughness variation, feed rate is more effective than the cutting speed. It was specified from the ANOVA results in Table 6 that the most effective parameter on the surface roughness was feed rate with 90.2% contribution rate and cutting speed was the second effective parameter with 3.12% contribution rate.

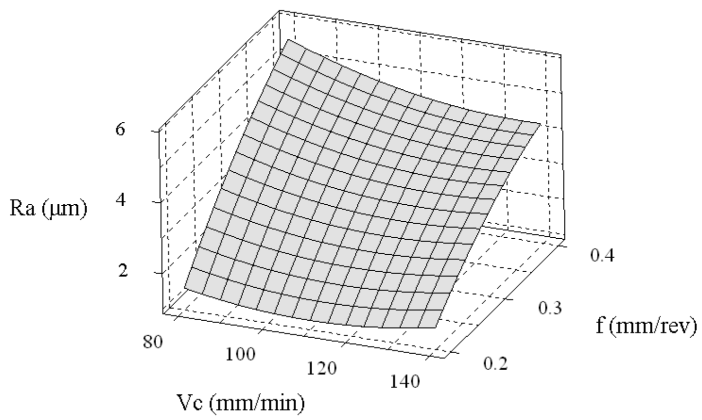

Figure 2:
Response surface of the surface roughness according to the variation in the cutting speed feed rate at a constant cutting depth of 0,6 mm.

The contour graph of surface roughness in accordance with the cutting speed and feed rate is given in Fig 3. The light colored area in the contour graph indicates the lowest values of Ra (<2 μm) while the dark colored area the highest values (>5 μm).

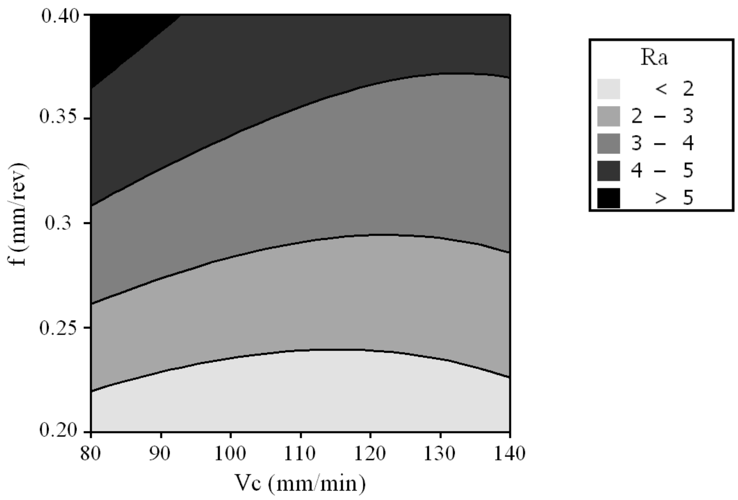

Figure 3:
Contour graph of the surface roughness according to the variation in the cutting speed feed rate at a constant cutting depth of 0,6 mm.

Cutting speed and response surface of surface roughness according to cutting depth variation are given in Fig 4. The trends in the cutting speed at the response surface and in the cutting depth are close to each other and this shows that these two parameters have the same effects on the surface roughness. The cutting speed in the ANOVA table and the sequence of cutting depth contribution rates 3.12%, and 1.7% verifies this. From the graph it is seen that Ra values increases with the increase of cutting depth. The increase in the cutting depth increases the chip volume machined per unit time. In connection with this, the increased cutting forces increase the vibrations and cause the average surface roughness values to increase (Savaş and Özay, 2009).

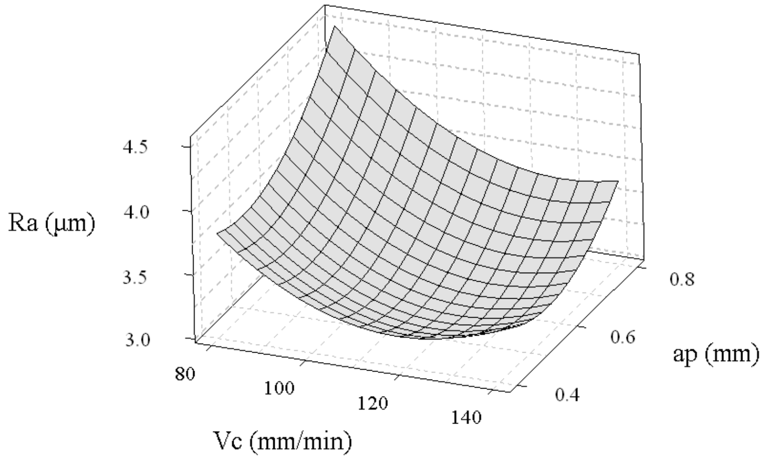

Figure 4:
Response surface of the surface roughness according to the variation in the cutting speed, cutting depth at a constant feed rate value of 0,3 mm.

The contour graph of cutting speed and surface roughness with respect to cutting depth variation is given in Fig 5. From this graph, the lowest Ra value was obtained at approximately 120 m/min cutting speed and 0.55 mm cutting depth.

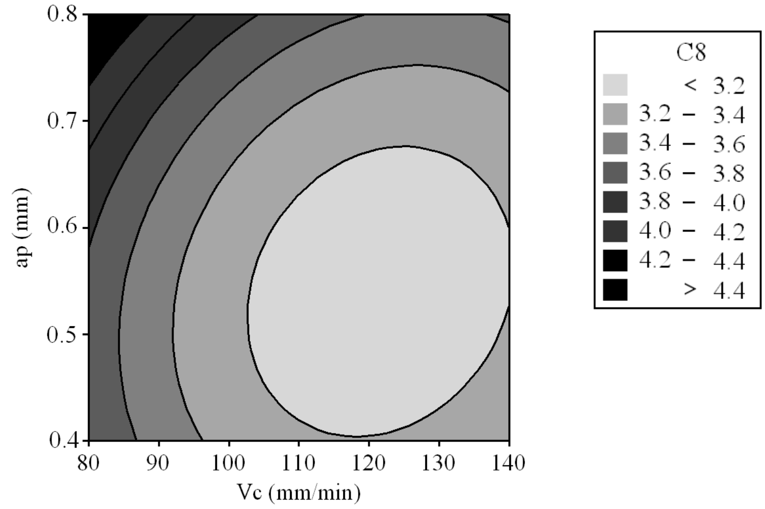

Figure 5:
Contour graph of the surface roughness according to the variation in the cutting speed, cutting depth at a constant feed rate value of 0,3 mm.

4. CONCLUSION

In the machining of Hadfield steels the effects of cutting parameters on the surface roughness were investigated by using the response surface method. The following results were obtained;

1. In the evaluation of the test results use of RSM technique was useful to explain the effects of each cutting parameter on machinability explicitly.
2. As a results obtained by using the RSM technique, it was also found that the feed rate was the most significant factor affecting the surface roughness with a percentage contribution of 90.2%.
3. The feed rate has been verified as the most important machining parameter for the surface roughness of Hadfield steels. This is a well know fact in the surface roughness literature and also in accordance to previous studies for this particular material and then came the cutting speed and cutting depth with contribution rates 3.12% and 1.7% respectively.
4. While the surface roughness increased with the increase in feed rate and cutting depth, a decrease in Ra values was observed up to 115 m/min cutting speed and after this speed Ra values increased.
5. The lowest surface roughness came out to be 1.53 μm at 140 m/min cutting speed, 0.2 mm/rev feed rate, and 0.8 mm cutting depth.

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