<u>*Araştırma Makalesi*</u>   <u>*Research Article*</u>

Tool Flank Wear Analysis for MQL Assisted Milling of Strenx 1100 Structural Steel

Mustafa Kuntoğlu[1*],

[1*] Selcuk University, Faculty of Technology, Departmant of Mechcanical Engineering, Konya, Turkey, (ORCID: 0000-0002-7291-9468), mkuntoglu@selcuk.edu.tr

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Abstract

Strenx 1100 structural steel has unique material properties enables to utilize in important engineering applications such as marine and heavy vehicles. Due to the surface integrity of the parts produced by this material is of paramount importance, tool wear condition needs to be considered as well. As being applicable and easy to measure, tool flank wear (V_B) is widely preferred in the field and reflects the remaining tool life. Minimum quantity lubrication (MQL) has been preferred most recently in machining operations especially for the hard-to-cut materials to improve the machinability characteristics. This paper contains experiments and further analysis of tool flank wear during MQL assisted milling of the Strenx 1100 steel. Cutting speed, feed rate and depth of cut were included in the experimental plan and Taguchi L_9 design was adopted. Measured wear results were evaluated with 3d surface plots, analysis of variance (ANOVA) and optimization of parameters were carried out depend on signal to noise (S/N) ratio. Accordingly, cutting speed is the first parameter affecting tool flank wear about 53.2% and followed by feed rate about 35.77%. Parametric optimization depend on S/N ratio shows that first order of theall cutting parameters need to be selected for minimum tool flank wear which is observed on 3d graphs that the increase in the amount of wear with higher parameter levels. This comprehensive analysis is a guide for the practical applications in the industry as providing the limitations during applying a wide range of cutting parameters.

Keywords: Strenx 1100 Steel, Tool flank wear, MQL, Milling, Hard Machining.

Strenx 1100 Yapısal Çeliğinin MMY Destekli Frezelenmesinde Serbest Yüzey Aşınması Analizi

Öz

Strenx 1100 yapısal çeliği, deniz araçları ve ağır araçlar gibi önemli mühendislik uygulamalarında kullanılmasına olanak sağlayan benzersiz malzeme özelliklerine sahiptir. Bu malzemeden üretilen parçaların yüzey bütünlüğü büyük önem taşıdığından, takım aşınma durumunun da dikkate alınması gerekir. Uygulanabilir ve kolay ölçülebildiği için, takım serbest yüzey aşınması (V_B) bu alanda yaygın olarak tercih edilir ve kalan takım ömrünü yansıtır. İşlenebilirlik özelliklerini iyileştirmek adına özellikle kesilmesi zor malzemeler için son zamanlarda işleme operasyonlarında minimum miktarda yağlama (MQL) uygulanmaktadır. Bu çalışma Strenx 1100 çeliğinin MMY destekli frezelemesi sırasında serbest yüzey aşınması analizini ve deneylerini içerir. Kesme hızı, ilerleme ve talaş derinliği deneysel plana dâhil edilmiş ve Taguchi L_9 tasarımı benimsenmiştir. Ölçülen aşınma sonuçları 3 boyutlu yüzey grafikleri ile değerlendirilmiş, varyans analizi (ANOVA) ve parametrelerin optimizasyonu sinyal / gürültü (S / N) oranına bağlı olarak gerçekleştirilmiştir. Buna göre, kesme hızı serbest yüzey aşınmasını yaklaşık% 53.2 oranında etkileyen ilk parametredir ve bunu yaklaşık % 35.77 ile ilerleme izlemektedir. S / N oranına bağlı parametrik optimizasyon, minimum serbest yüzey aşınması için kesm parametrelerinin birinci sırasının seçilmesi gerektiğini göstermektedir. Bu kapsamlı analiz, çok çeşitli kesme parametrelerinin uygulanması sırasında sınırlamaları ortaya koyduğu için endüstrideki pratik uygulamalar için bir kılavuz niteliğindedir.

Anahtar Kelimeler: Strenx 1100 Çeliği, Serbest Yüzey Aşınması, MMY, Frezeleme, Sert işleme.

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* Corresponding Author: mkuntoglu@selcuk.edu.tr

1. Introduction

Structural steels are generally preferred for their improved properties in load bearing applications. This type of steel requires good weldability in order to create large scale parts utilized for transportation. However, additional machining operation needs to be performed for manufacturing of welding grooves. Strenx 1100 is a member of the structural steel family characterized with high tensile and yield strength which makes it appropriate in many sector such as marine engineering, excavators, heavy vehicles and cranes (Kurc-Lisiecka, Piwnik, & Lisiecki, 2017; SSAB, 2021). Beyond its explicit advantages, Strenx 1100 can be accepted as hard-to-cut material with ingredients and mechanical properties. Typically, due to their sheet-metal form, several modifications can be performed by milling operation for industrial applications.

Hard materials have been demanded growingly from the industries especially in the last decade (Davim, 2011; Grzesik, 2008). Compared to conventional materials, they present challenging issues such as poor surface integrity and excessive tool wear (Umbrello, Micari, & Jawahir, 2012). The problem is originated from high cutting forces and temperatures at the cutting area (Tönshoff, Arendt, & Amor, 2000). The cutting tool is experienced surplus mechanical and thermal loads primarily that pave the way for rapid deformations. Since the machined surface is of paramount importance (Şahinoğullari & Luş, 2021), cutting edge needs to be considered at least that much (Niaki & Mears, 2017). To date, some attempts have been made with taking precautions to overcome these problems (Chandrasekaran & M'Saoubi, 2006). MQL assisted machining is a known and effective way which conveys the pulverized oil to the cutting zone with the help of pressured air (Dong & Duc, 2019; Sen, Mia, Mandal, & Mondal, 2019). Oil granules make easier to separate the chip from main material with decreasing the coefficient of friction when it is compared with dry cutting conditions (Çetindağ, Çiçek, & Uçak, 2020). Therefore, cutting forces and temperatures are reduced considerably. This procures to achieve longer cutter life, less energy consumption and sustainable machining environment (Bermingham, Sim, Kent, Gardiner, & Dargusch, 2015; Jang, Jung, & Seok, 2016). Toward flood cooling, MQL allows for employing minimum fluid which reduces environmental and economic burden as well (Gupta et al., 2021). By this way, adverse effect of the chemicals in the lubricants can be avoided for the humans, nature and living creatures. MQL technology has been integrated to different machine tools successfully from many researchers in the past for the mentioned advantages and contributions.

The literature review shows that a plenty of paper published were focused on the improvements obtained by MQL. A group of them have been studied about the tool wear and related mechanisms before during hard milling operation. Mia worked on the milling of AISI 4140 with MQL for optimum conditions and they stated the deviation in surface quality was revealed owing to the flank wear (Mia, 2018). Muaz and Choudhury carried out a study on experimental investigation of milling of AISI 4340 steel comparing lubrication strategies (Muaz & Choudhury, 2019). On another study, MQL adopted hard milling of AISI D2 was modeled for measuring effectiveness of parameters in order to determine tool life (Iqbal, Ning, Khan, Liang, & Dar, 2008). A performance measurement was performed based on different ingredients of MQL during milling of Hastelloy C276 (Günan, Kıvak, Yıldırım, & Sarıkaya, 2020). The best tool life was determined according to cooling strategy along with tool wear types and triggering mechanisms. Zhang et al. investigated tool wear mechanisms during milling of hard H13 steel under different cooling environments (Zhang, Li, & Lv, 2014). Bashir et al. indicated the optimum cooling conditions in order to achieve longer tool life and machining characteristics for hardened AISI 4140 steel (Al Bashir, Mia, & Dhar, 2018). They exhibited the supremecy of MQL system clearly on obtaining better tool life. A comparative study was carried out for the best oil mixtures during MQL based hard milling of Inconel 690 (Sen, Gupta, Mia, Pimenov, & Mikołajczyk, 2021). The best tool wear and machinability conditions were reached by palm and castor oil. Najiha and Rahman compared flood and MQL conditions during end milling of aluminum alloy. A detailed tool wear analysis and flank wear evaluation was performed and showed the benefits of MQL employment (Najiha & Rahman, 2016). A MQL assisted end milling operation modeling study was proposed from the authors (Sen, Mia, Mandal, Dutta, & Mondal, 2019) which showed the possibility of high accuracy prediction of tool flank wear and a group of machining variables. Singh et al. applied evolutionary techniques for wear optimization in milling of Inconel 718 (Singh, Gupta, Mia, & Sharma, 2018). It was a comparison study based on different cooling conditions which demonstrated the effectiveness of MQL over other techniques. Seemingly, a plenty of paper published on the flank wear analysis using several workpiece materials in MQL assisted milling operation in the past. A general comment made about these papers on the superiority and effectiveness of MQL technique.

Although there have been a number papers on hard milling with MQL assistance, no paper was encountered focused on the sustainable milling of Strenx 1100 construction steel. Therefore, this paper aims to investigate the tool flank wear progression. Data analysis were carried out with 3D surface plots, S/N ratio based optimization and ANOVA.

2. Material and Method

2.1. Material Properties

The workpiece utilized in the experiments is a special type of structural steel titled as Stenx 1100. Test materials are appropriate for milling operations provided by the manufacturer. Thus, chemical composition and mechanical properties can be procured *(SSAB, 2021)*. Table 1 and Table 2 listed these properties separately. The dimensions of the samples (32 HRC) were 100 x 100 x 40 mm. To meet the requirements of standard experiments, fresh cutting tools were used for each test. Tool holder with the code 403 BT 40 ER32 x 70 (MAS) and cutting tool inserts with the code number of APXT 1604 PDSR-MM TIN (KORLOY) were chosen.

Table 1. Ingredients of the material (SSAB, 2021)

Elements	Amounts
C	0.21
Si	0.5
Mn	1.4
P	0.02
S	0.005
Cr	0.8
Cu	0.3
Ni	3
Mo	0.7
B	0.005

Table 3. Experimental design

v_C Cutting Speed (A)	f Feed Rate (B)	a_P Depth of Cut (C)
75	0.075	0.25
75	0.15	0.5
75	0.225	0.75
150	0.075	0.5
150	0.15	0.75
150	0.225	0.25
225	0.075	0.75
225	0.15	0.25
225	0.225	0.5

2.2. Machine Tool Properties and Physical Tests

Cutting speed, feed rate and depth of cut were defined in the experiments. Physical tests were done on CNC (DAHLIL). Instead of 27 experiments, Taguchi design was used and totally 9 physical tests were performed which is explained in following. Before the experiments, some observations during preliminary tests helped for determination of final values. In this procedure, a number of initial parameters were approved considering chatter vibrations and undesired chip formation. All of the experiments were executed as three times and eventually the arithmetic average value was calculated.

2.3. MQL System

MQL supply was fed from the depository unit (Werte) having 24 V AC/DC voltage and 4 bars pressure. For the lubrication, KT 2000 oil was utilized and conveyed to the machine environment and nozzle 50 ml/h with the amount of lubrication in unit time. Nozzle placement was arranged closely to the cutting area targeting the contact zone. MQL nozzle adopte to the machine tool is demonstrated in Figure 1.

2.4. Experimental Design

Due to the high material wastage and high costs of the utilized material, Taguchi based experimental design is capable of limiting the extreme consumes (Taguchi, 1987). Main purpose of this method is to provide minimum number of experiments according to the selected parameters group in the pool. Taguchi is an approved method used for optimization and experimental design (Kıvak, 2014). Typically, Taguchi reduces extra costs, labor and time within the purpose of high quality and efficiency. This also achieves minimum energy consumption and wastage which pave the way for sustainable manufacturing. In this work, in place of all experiments, L_9 orthogonal array was utilized. Taguchi based experimental design is exhibited in Table 3 which contains the adopted parameters as well.

Taguchi addresses two main operational function namely S/N ratio and objective function. Taguchi aims to reduce noises in order to reach minimum number of tests simultanously. Also, for determination of performance of the targeted responses, standart deviations are calculated using objective function (Kechagias, Aslani, Fountas, Vaxevanidis, & Manolakos, 2020). According to the demand from the target response, some equations are used for determination of the optimum value which can be maximization, minimization or normalization (Kuntoğlu & Sağlam, 2019). Due to the expectation from the wear development is as low as possible, smaller is better type objective function needs to be calculated as demonstrated in the following equation:

$$S/N = -10 \log \left[\frac{1}{x} \sum_{i=1}^{x} z_i^2 \right] \qquad (1)$$

2.5. Tool Flank Wear Measurement

The flank wear expands on the tool surface in vertical and horizontal directions. Wear depth is the main determinative of the severeness level (Siddhpura & Paurobally, 2013). Since the propagation may fluctuate on the area, either maximum depth or average depth is taken as the flank wear value. In this paper, former one was chosen as the main tool wear. Flank wear measurements were obtained on microscope (Leika) after each experiment. Figure 1 represents the measuring of the flank wear with macro and micro photos of cutting edge. Also, machine tool and MQL system are represented as an experimental image. After the measurement of wear, detailed analyses were performed as it will be explained in the next section.

3. Results and Discussion

Tool flank wear is accepted as the main tool life criteria as develops intersection of the main cutting edge and flank surface ("ISO 3685-1993(E). Tool life testing with single point turning tools," 1993). With higher wear values at this area, tool loses its cutting ability which leads to higher cutting forces and cutting tool geometry changes. In addition, chatter vibrations may show it as a result of the variable cutting conditions. With the progression of this type of wear, other wear types may be triggered resulting in the failure of cutting edge.

Figure 2 demonstrates the flank wear conditions on the flank surface for 9 experiments. Except for the flank wear, other wear

types were not observed clearly. All measurements have been taken with the same zoom rate and lightness in order to protect the safety of the measurements.
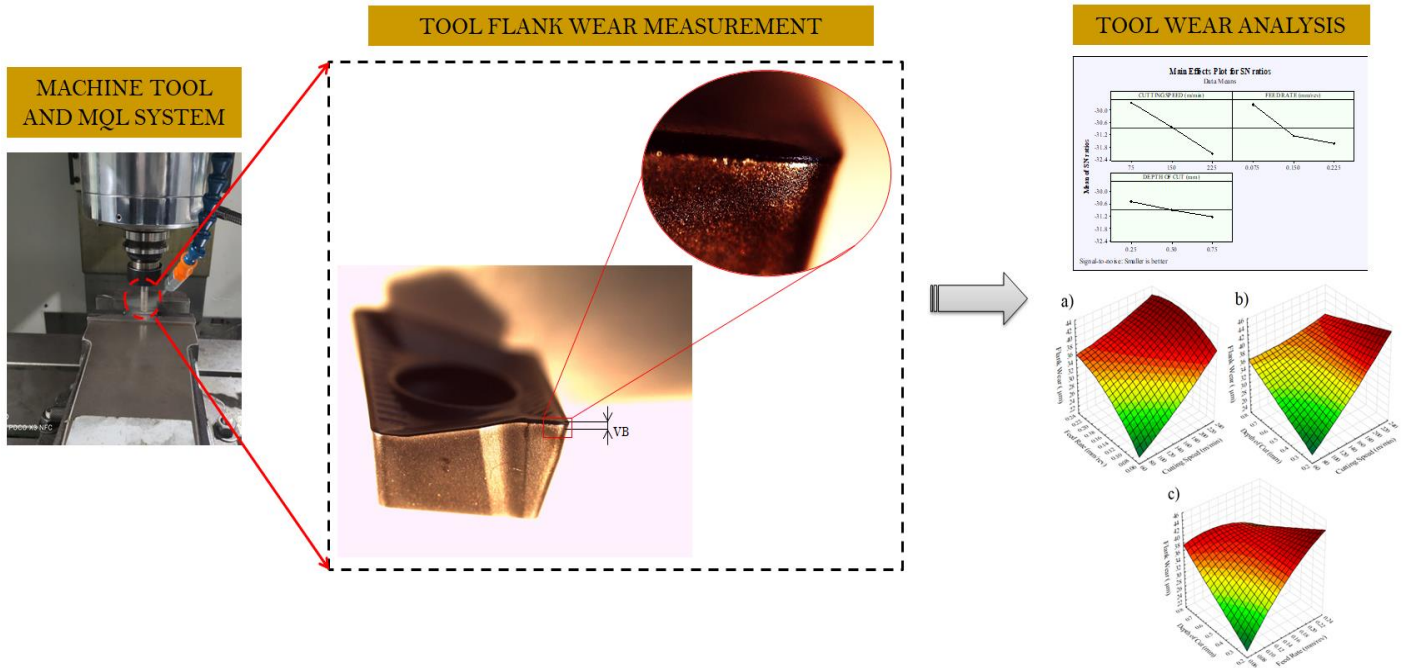

Figure 1. Measuring of flank wear and graphical abstract

3.1. Tool Wear Mechanism

As being a natural event, tool wear develops on the cutting tool during metal removing as a result of load factors such as mechanical, thermal, chemical and oxidation (Coromant, 1994; Kuntoğlu & Sağlam, 2019). According to different areas of the cutting tool edge, each factor is effective depend on the occurring mechanism. It is actually depend on the contact area between tool and workpiece, chips formation, temperature gradient, stress distribution and ingredients of the materials. As a result, four different types of wear mechanisms reveal while machining. Abrasive, adhesive, diffusion, oxidation and fatigue wear may occur separately or together. Flank wear is attributed to the abrasive and adhesive wear mechanisms primarily (Aslan, 2020). Abrasive wear is characterized as the hard particles ruptured from the cutting tool and workpiece abrade the cutting face with squeezing between tool and workpiece during chip removing. Adhesive wear on the other hand is triggered by the cohesion of the soft particles of workpiece to the cutting tool and bring along the tool material during rupturing from the material.

3.2. 3d Surface Plot Based Analysis

Basically, tool life is an important representative when determining the total costs of a manufacturing chain. Despite there are many contributing factors from beginning the material supply to the assembly process, tool condition is an effective variable with its hidden and open impacts. Owing to the importance of cutting geometry, whole cutting procedure is affected from the wear situation of the cutting tool. But the main concern should be the part quality which heavily depends on the tool health. Therefore, progressive flank wear need to be considered for the success of the cutting process.

Figure 3 demonstrates the 3D surface plots for the combined effect of of cutting parameters on flank wear during milling of Strenx 1100 steel. During cutting of hard materials, difficult-to-cut and high strength structure requires high cutting forces.

However, compelling the chip to separate from the main material leads to high cutting temperatures, unstable stress distribution and on the next cycles accelerates tool wear progression. High cutting speeds make easier chip removing and increases coefficient of friction at the same time. In the context of this study, MQL assistance prohibited the rapid increase of flank wear as it can be seen in the Figure 3a-c. Considering the upper limit of the flank wear is about 0.2 mm in general, maximum wear land was observed in the range of 22-46 µm.

In Figure 3a, cutting speed and feed rate with high values increases up the flank wear value dramatically to the boundary conditions. It was also found from the authors (Sen, Mia, Mandal, Dutta, et al., 2019) in hard milling. Agreeing the feed rate is a kind of speed of the cutting tool, it is expected that higher feed rate and cutting speed elevate the cutting temperatures with the increase of friction.

When Figure 3b is considered, the effect of higher values of cutting speed can be observed especially for the lower depth of cut values on the progression of flank wear. On the small cutting speed values, the change from 0.25 to 0.75 mm of depth of cut speed up the flank wear which is attributed to the high material removal rate. However, with the increase of cutting speed and especially for the maximum values, high depth of cut reduces flank wear rate (Astakhov, 2007). Considering the incluence of depth of cut compared to cutting speed, this reduction can be neglected.

For the Figure 3c, similar observations can be performed with the 3a and 3b as cutting parameters exhibit the same behavior. However, it should be noted that dramatic impact of depth of cut is observed clearly compared to Figure 3b. It is thought that high cutting depth enables the contact of tool-workpiece materials which is important to keep the cutting geometry due to the hardness of the steel. Similar result was found from Sen et al. during milling of hard material (Sen, Mia, Mandal, Dutta, et al., 2019). Lower values may lead to loss of

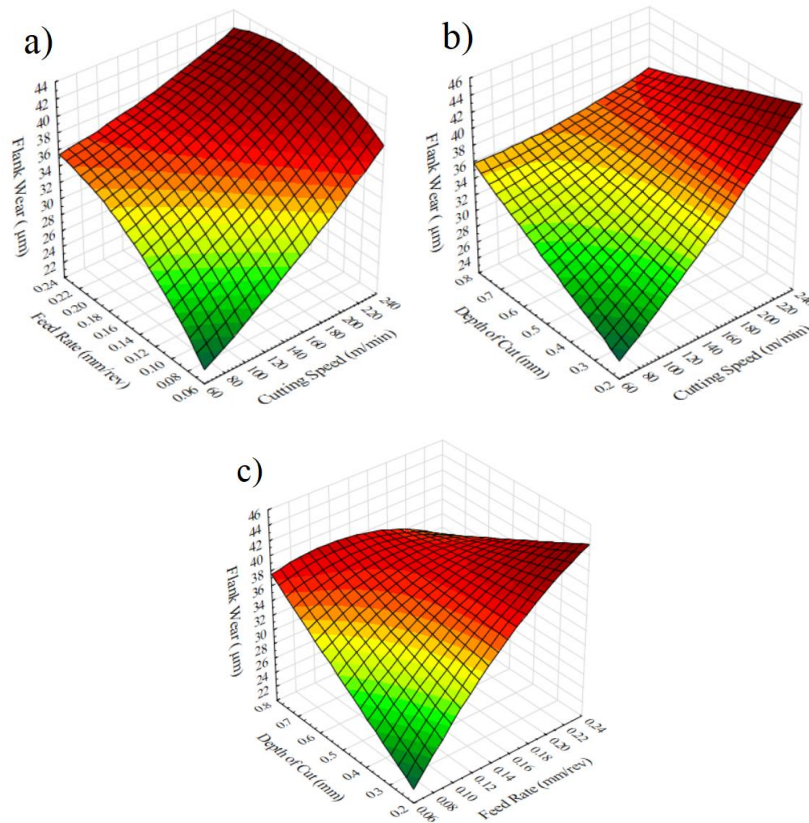ideal cutting conditions and undesired chip form, unbalanced load distribution and cutting forces.

Figure 3. 3D plots of the combined effect of inputs on flank wear

3.3. Parametric optimization for flank wear

Parameter optimization is crucial step on data analysis. In addition, it is considerably determinative on the general performance of cutting tool. Thus, optimum conditions should be obtained for any response parameter in the way of better machinability.

Taguchi optimization is reliable and accepted method for determining the best milling parameters. In Figure 4, main effects plot for S/N ratios are presented. Due to S/N ratio is calculated with ratio of signal power to noise power, higher values are accepted as the best, in here the minimum value. As it can be seen, lower values of cutting speed, feed rate and depth of cut produce the best flank wear value (v_C= 75 m/min, f=0.075 mm/rev, a_P=0.25 mm). Accordingly 24.2 μm is the minimum flank wear value in MQL assisted milling of Strenx 1100. In addition, it can be said that the questionable situation of depth of cut effect in 3D plots is clearly seen thanks to Taguchi based optimization.

3.4. ANOVA for Flank Wear

Anova provides the importance or the contribution rate of the design parameters on response parameter. Main advantage of this method is the several options for statistical measurement. Namely, statistical evaluation can be carried out by percent contribution (PC) which is calculated with dividing the sum squares (SS) of each parameter to the total SS value. Also, F value shows the impact and calculated with division of SS of parameters to the SS value of error. P value is a representative finding each parameter either they remain in the statistically important range in the 95% confidence interval.

When looking to the Table 5 for the Anova findings, PC value demonstrates that cutting speed is the most effective parameter about 53.2% and followed by feed rate which is influential about 35.77%. Depth of cut has negligible importance on tool flank wear seemingly (4.69%). F values also support these results (8.39>5.64>0.74). Statistical findings verified the previous results as demonstrated in the 3D plots and Taguchi based optimization.Therefore, it is noteworthy to mention that a comprehensive analysis is performed for the optimization of milling conditions for flank wear of Strenx 1100 steel under MQL environment.
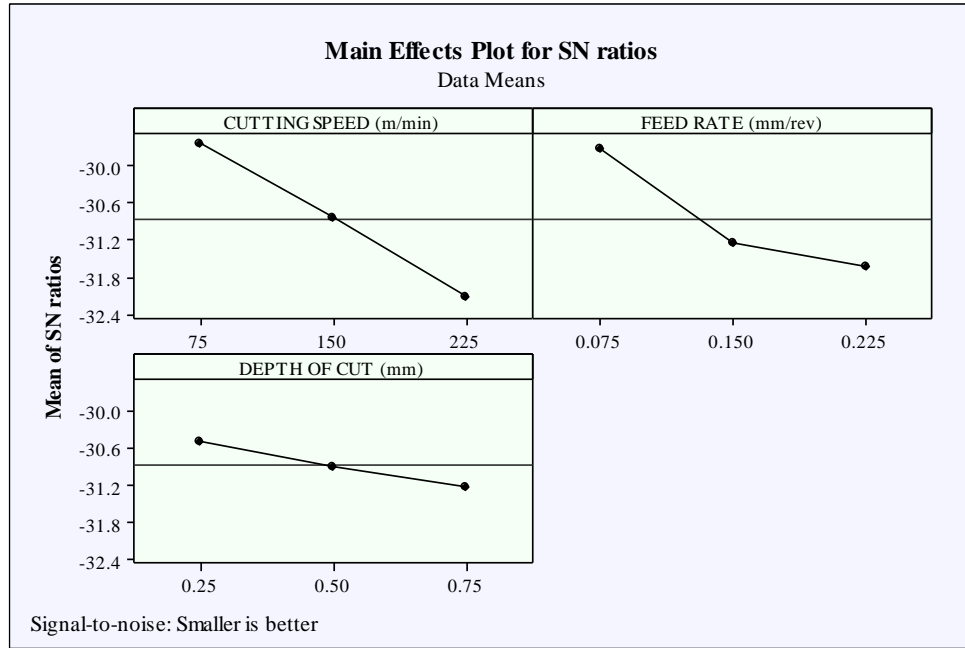
Figure 4. Optimum cutting parameters for minimum flank wear

Table 5. ANOVA results for flank wear

Source	Degree of Freedom	Sequential sums of squares	Adjusted sums of squares	F value	P value	Percent Contribution (%)
Cutting Speed	2	9.162	4.5810	8.39	0.106	53.2
Feed Rate	2	6.1582	3.0791	5.64	0.151	35.77
Depth of Cut	2	0.8081	0.4040	0.74	0.575	4.69
Residual Error	2	1.0920	0.5460	-	-	6.34
Total	8	17.2202	-	-	-	100

4. Conclusions and Recommendations

A comprehensive analysis and evaluation for the construction steel, Strenx 1100 was carried out under MQL conditions during milling. Key findings from the study are summarized in the following:

- Cutting speed is the most effective parameter on flank wear with 53.2% contribution according to ANOVA which can be supported with 3D surface plots. Also, higher cutting speed produce higher flank wear which exhibits the minimum value of cutting speed should be selected for wear optimization.
- Feed rate follows the cutting speed in effectiveness with the contribution ratio of 35.77%. It is also recommended that lowest feed rate value need to be considered for minimum flank wear.
- Seemingly, depth of cut has no important effect on flank wear.
- Minimum flank wear value can be obtained with the application of the group of cutting parameters namely, v_C= 75 m/min, f=0.075 mm/rev, a_P=0.25 mm.
- The outlined findings belong to ANOVA, 3D plots and optimization promote each other which demonstrate the

validity of the selected methodology for the analysis of milling of Strenx 1100 construction steel.
- It can be concluded that the proposed method, evaluation with graphs, optimization plots and statistical analysis are compatible with each other and can be applied to hard milling operations.
- MQL assisted milling operations can be applied to several hard materials namely construction steels in the future considering their value in the industry.

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