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Strenx 1100 Çeliğinin MMY Yardımıyla Sert Frezelenmesinde Enerji Tüketimi Üzerine Çalışma

Mustafa KUNTOĞLU

ÖZET: Strenx 1100, yüksek çekme ve akma dayanımı özellikleri sayesinde denizcilik, vinç ve nakliye gibi kritik mühendislik uygulamalarında kullanılan bir yapısal çeliktir. Mekanik özelliklerinden gelen avantajlarına rağmen, yine bu özellikler malzemeden talaş kaldırmayı güçleştirmektedir. Bu sebeple yüksek kesme kuvvetlerine ihtiyaç duyulması nedeniyle yüksek miktarda enerji tüketimi ortaya çıkar. Bu sorunun üstesinden gelmek için, son zamanlarda, birçok yazar minimum miktarda yağlama (MMY) destekli işleme öne sürülmüştür. Bu bağlamda, bu çalışma Strenx 1100 çeliğinin MMY destekli yüzey frezelemesinde tüketilen enerjiyi ölçerek analiz etmeyi amaçlamaktadır. Bu amaçla elde edilen deneysel sonuçlar 3 şekilde değerlendirilmiştir: grafikler üzerinden analiz, ANOVA tabanlı istatistiksel değerlendirme ve sinyal / gürültü (S / N) oranına dayalı optimizasyon. Deneylerde, Taguchi yardımıyla L9 ortogonal dizi tasarımı, üç seviyede kesme hızı, ilerleme ve talaş derinliği kullanılarak uygulanmıştır. Elde edilen bulgulara göre kesme hızı, katkı oranı (% 46.28) ve P değerine (0.048 <0.05) göre enerji tüketiminde en etkili parametredir, bu arada ilerleme hızı (% 23.6) ve kesme derinliğinin (% 27.8) tüketilen enerji üzerinde önemli katkıları vardır. Görünüşe göre, 3D grafikler incelendiğinde, tüketilen enerji için genel eğilimin, daha yüksek kesme hızı ve talaş derinliği değerleri ve daha düşük ilerleme değerleri için arttığı gözlenmiştir. Bu durum, S / N oranlarıyla elde edilen v_C=75 m/dak, f=0.25 mm, a_P=0.225 mm/dev optimal çözümlerle doğrulanmıştır. Gerçekleştirilen deneyler ve daha ileri analizler, sert malzemelerin MMY ile destekli işlemesinde endüstriyel uygulamalar için önemli bir rehberlik sağlar.

Anahtar Kelimeler: Strenx 1100, Enerji, MMY, Sert Frezeleme

Study on Consumed Energy of Strenx 1100 Steel During MQL Assisted Hard Milling

ABSTRACT: Strenx 1100 is a structural steel utilized in the critical engineering applications such as marine, crane and transportation thanks to its high tensile and yield strength properties. Despite its advantages coming from mechanical properties, hard-to-cut structure of this material makes difficult the metal removing. Therefore, high amount of energy consumption reveals due to the requirement of high cutting forces. In order to overcome this problem, recently, minimum quantity lubrication (MQL) supported machining have been introduced from many authors. In this context, this study aims to measure and analyze the consumed energy in MQL assisted surface milling of Strenx 1100 steel. For this purpose, experimental results were evaluated by three methods: analysis on graphs, ANOVA based statistical evaluation and signal to noise (S/N) ratio based optimization. In the experiments, with the help of Taguchi, L9 orthogonal array design was adopted using three levels of cutting speed, feed rate and depth of cut. According to the obtained findings, cutting speed is the most effective parameter according to contribution rate (46.28%) and P value (0.048<0.05), meanwhile feed rate (23.6%) and depth of cut (27.8%) have important contributors on the consumed energy during milling. Seemingly, general trend for the consumed energy is about to increase with higher values of cutting speed and depth of cut and lower values of feed rate according to 3D plots. This situation is confirmed with optimal solutions as v_C=75 m/min, f=0.25 mm, a_P=0.225 mm/rev achieved by S/N ratios. Conducted experiments and further analysis provide an important guidance for the industrial applications in MQL reinforced machining of hard materials.

Keywords: Strenx 1100, Energy, MQL, Hard Milling

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INTRODUCTION

With the consumption of natural sources, resource saving has been considered more importantly in nowadays. Eco-friendly and sustainable methods gained popularity with strict government prosecutions all over the world. Manufacturing industries are responsible for a great deal of part of the consumed energy according to the previous reports (Duflou et al., 2012; Park et al., 2009). Machining industries cover large part of this energy which also shows their potential for that purpose (Bilga, et al., 2016; Shokrani et al., 2018). The mechanical energy required for the machine tools is converted from the electrical energy which can be produced by renewable or non-renewable resources in principle (Omer, 2008). The second group leads to carbon emission which has extremely harmful effects on ecology of the planet (Mulyadi et al., 2015). Therefore, reducing energy demand will not only provide commercial income but also help to solve a global crisis (Liu et al., 2015). In addition, 99% of the environmental problems of machining processes originate from the electrical energy consumption (Qun and Weimin, 2012). In this context, many initiatives have been found in the past, especially for the new generation materials and methods as per the requirements of the industries. MQL is an increasing trend in the way of resource saving, eco-friendly and sustainable machining. As it will be explained in the later paragraphs, general outlook of the machinability studies of hard materials is demonstrated in Figure 1.

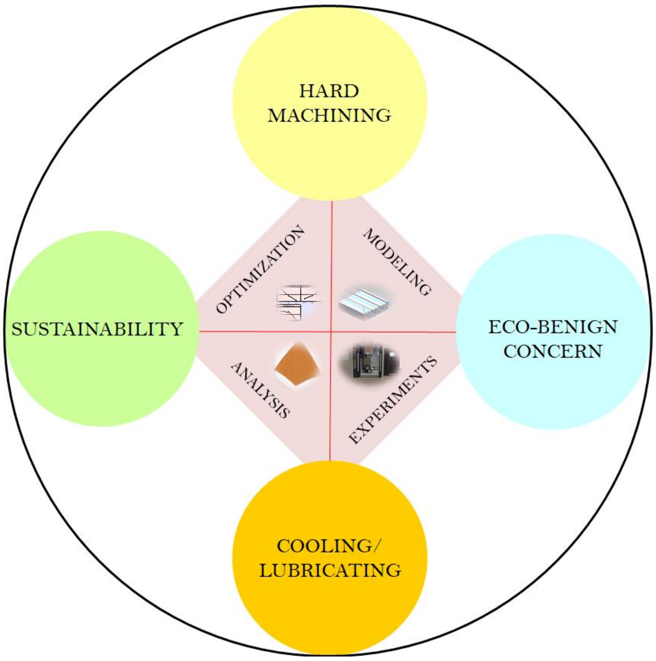

Figure.1. General outlook of the machinability studies of hard materials

A special type of the structural steel, Strenx 1100 is highly preferred for the constructions require light and strong mechanical properties. For example, load-bearing implementations viz. heavy vehicles, excavators, cranes and loaders are the well-established representatives (Lisiecka et al., 2017; SSAB, 2021). These large dimensional structures are created by welding of cut-to-length samples of Strenx 1100 steel due to its yield and tensile strength properties. For the well-manufactured joining of these structures, high precision welding grooves need further machining operations. Therefore, milling operation need to be applied for these sheet metal parts. However, hard-to-cut featured characteristic of Strenx 1100 make the machining operations difficult which necessitates detailed investigation. Similarly as mentioned on the last paragraph, in here, MQL is a good alternative in order to improve the machining quality of hard materials.

Hard materials are employed in industry due to high quality mechanical properties such as strength, resilience to corrosion and oxidation and long service conditions. However, compared to conventional materials, their special composition do not allow for the expected results which can be characterized with low surface integrity and tool life (Das et al., 2019; Kene and Choudhury, 2019; Sun et al., 2010). Main cause in here is excessive cutting forces and temperatures and their remarkably adverse effect on machinability (Hosseini et al., 2014). In order to surpass these challenges, cooling/lubrication systems have been developed especially for the last decade (Abbas et al., 2019; Benedicto et al., 2017; Gupta et al., 2018; Gupta et al., 2021). MQL is an eco-friendly and self-optimized technique which aims to send minimum amount of coolant/lubricant to the cutting zone with the help pressured air. A nozzle placed to the close point of the contact area between tool and workpiece and sprays the pulverized oil. Primary advantage of this method compared to traditional flood cooling is not only economical usage of the fluid but also being capable of providing tremendous improvement in machinability.

Due to the energy consumption is an important issue in engineering applications, optimization approaches have been introduced in CNC milling. Some researchers (Xu et al., 2016) concerned about the tool path strategy optimization for obtaining minimum energy consumption during milling of Ti6Al4V. Wang et al. utilized artificial bee colony algorithm for determining the milling parameters in order to reduce the energy consumption and milling time as well (Wang et al., 2020). On a comprehensive work, researchers performed classification of prediction study and informed that cooling/lubrication systems cover the 31% part of the all energies (Zhao et al., 2017). Zhang et al. focused on the effect of several milling parameters considering milling power for AISI 1045 steel (Zhang et al., 2020). A group of researchers investigated different models of machine tools on vertical milling of aluminum (Draganescu et al., 2003). They modeled electric motor for estimating the coefficients in order to determine consumed energy. AISI H13 hardened steel machining was investigated by milling also considering the tool wear situation in a study performed before (Liu et al., 2016). Sealy et al. correlated energy consumption and surface integrity during hard milling of AISI H13 (Sealy et al., 2016). Several studies in milling based on optimization, modeling and experimentally tested have been performed (Aramcharoen and Mativenga, 2014; Asrai et al., 2018; Li et al., 2013; Sealy et al., 2016; Yan and Li, 2013; Yoon et al., 2014) which need to be noted in here in order to show the effort in the area.

Energy consumption has been a significant issue in MQL assisted milling of a several type of hardened materials in the past. According to Mulyadi et al. MQL environment provide better energy efficiency and eco-benign opportunity in milling of H13 steel (Mulyadi et al., 2015). Referring to the response surface methodology and Taguchi methods, Mia modeled the milling operation for AISI 4140 steel under MQL environment (Mia, 2018). The author optimized the amount of lubrication using main effects plot and also determined minimum cutting energy conditions. According to the paper from Jamil et al. when comparing the energy efficiency of different cooling/lubricating conditions, MQL showed its superiority both down and up milling of Ti6Al4V (Jamil et al., 2021). Several parameters considered were tried by a researcher team (Vu et al., 2020) who performed experiments under MQL conditions for AISI H13 steel using cutting parameters and workpiece hardness. Khan et al. optimized energy consumption during small quantity cooling condition of milling process for AISI 1045 steel (Khan et al., 2019). In another work, Ti6Al4V milling was investigated using nanofluids in order to identify parameter effects (Jamil et al., 2020). Abbas et al. compared different cooling methods for power consumption in milling of stainless steel (Abbas et al., 2021). Despite a handful of papers intervened for the energy consumption issue in hard milling, none of them performed a work on Strenx 1100 steel to date.

With reference to the open literature, many initiatives have been done for solving the energy consumption issue of milling in a certain extent. Less work have been revealed for MQL assisted hard milling which needs further research in order to improve the machinability and understand the underlying mechanism. For this aim, this paper includes the milling of Strenx 1100 steel under MQL conditions in order to measure the effect of cutting parameters on consumed energy. It is believed that the study performed will be useful for the industrial applications in the way of sustainable manufacturing.

MATERIALS AND METHODS

Cutting Tool and Workpiece Materials Specifications

A special cutting inserts have been used in the experiments (KORLOY-APXT 1604 PDSR-MM TIN) for milling tests. Each cutting insert was utilized for one experiment. As cutting tool holder (MAS-403 BT 40 ER32 x 70) was used.

Unique properties of Strenx 1100 steel was selected as the workpiece material for surface milling experiments. The test samples have 32 HRC with the dimensions of 100 x 100 x 40 mm. The provided samples have chemical composition and mechanical properties as listed in Table 1 and Table 2 (Kuntoğlu, 2021a, 2021b; SSAB, 2021).

Table 1. Chemical composition of the Strenx 1100 steel (SSAB, 2021)

Element	Fe	C	Si	Mn	P	S	Cr	Cu	Ni	Mo	B
Composition	Bal.	0.21%	0.5%	1.4%	0.02%	0.005%	0.8%	0.3%	3%	0.7%	0.005%

Table 2. Mechanical properties of the material (SSAB, 2021)

Yield Strenght (min. MPa)	Tensile Strenght (MPa)	Elongation (min. %)
1100	1250-1550	10

Machine Tool and Experiments

Milling experiments were performed on a machine tool (DAHLIL). Three milling speeds, feed per tooth and milling depth values were operated fo the experiments. The machine tool was rigidly structured for keeping the consistency of the experiments. In addition, extensive preliminary test were carried out for selection of plausible parameters. Regarding the chip formation and chatter vibrations, some parameter groups were eliminated. Finally, nine experiments were performed with the help of Taguchi design. Utilized method, machine tool, energy measurement, MQL assisted milling and evaluation of the data are summarized as graphical abstract in Figure 2.

MQL system utilized in the experiments is separate units, one for the spreying to the cutting zone, nozzle, second for the supply unit for storage the liquid. KT 2000 coded oil was utilized and Werte supplying system for injection of the lubricant. The system has 0.0012 ml amount of lubrication with 0.1 s lubrication time. Spreying nozzle was mounted as close as possible (approximately 100 mm) to the cutting area. In Figure 2 MQL assistance and CNC machine tool can be observed.

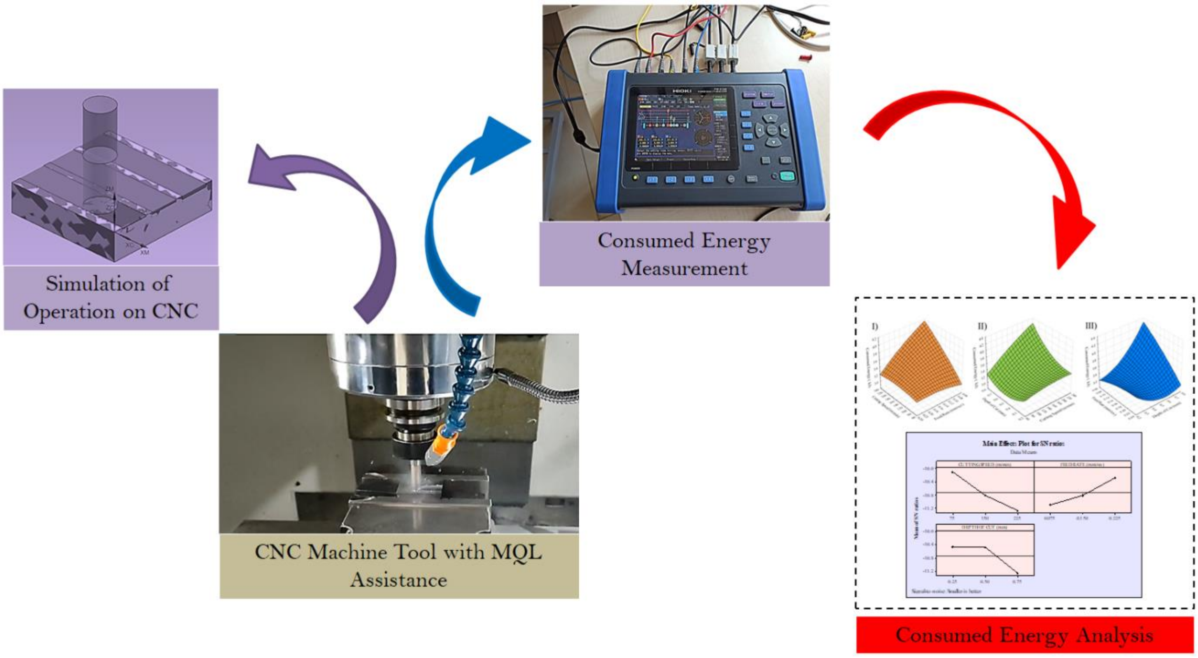

Figure.2. Experimental setup, measurement and graphical abstract

Taguchi Based Experimental Design

Taguchi method was proposed from Genichi Taguchi with the aim of minimum labor and experimental burden for a long time ago. The method also includes modeling and optimization opportunities for a wide range of engineering applications. Taguchi provides self-guaranteed design approach for the experimental tests by using its orthogonal arrays. With minimizing the noise factors, optimum solutions can be obtained with high accuracy. This method was applied in the past especially in manufacturing papers with compatible results. Table 3 summarizes the parameter levels for cutting speed, feed rate and depth of cut according to L_9 experimental design.

Table 3. Taguchi based experimental design

EXPERIMENT NUMBER	Cutting Speed v_C (m/min) A	Feed Rate f (mm/rev) B	Depth of Cut a_P (mm) C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Consumed Energy Measurement

Consumed energy was measured by a power analyzer (HIOKI PW 3198) having high quality standards (IEC 61000-4-30 Class A) (HIOKI, 2021). Obtained data can be easily transferred to Microsoft Excel software for data analysis. The device can measure current, power, voltage and power at the same time. A display enables to monitor the streaming data and waveforms during the cutting operation. The device can be easily connected to the any machine tool for primary DC and secondary AC measurement. Figure 2 illustrates the photo of the device.

RESULTS AND DISCUSSION

Conducted nine experiments, cutting conditions and obtained results of consumed energy are listed in Table 4 in detail. From this point of view, graphical analysis with 3D surface plots, optimization with S/N ratios based on Taguchi method and statistical analysis based on ANOVA are highlighted separately in the following sub-topics.

Table 4. Cutting parameters used in the experiments and obtained surface roughness values (Kuntoğlu, 2021a, 2021b)

EXPERIMENT NUMBER	v_C (m/min)	f (mm/rev)	a_P (mm)	Consumed Energy (kJ)
1	75	0.075	0.25	3.218
2	75	0.15	0.5	3.196
3	75	0.225	0.75	3.2
4	150	0.075	0.5	3.486
5	150	0.15	0.75	3.696
6	150	0.225	0.25	3.258
7	225	0.075	0.75	4.12
8	225	0.15	0.25	3.55
9	225	0.225	0.5	3.346

Graphical Analysis

It is known that the consumed energy for the metal cutting process is related with the required power. This depends on the compulsion of the cutting tool which can be attributed to material removal rate. It was observed that during milling of AISI 1045 steel, with increasing material removal rate, the required energy is increases (Yan and Li, 2013). As represented in Figure 3-a and 3-b, increasing cutting speed increases the consumed energy. During milling of hard material under MQL environment, cutting speed plays a role on energy consumption (Jamil et al., 2020). This can be explained by the effectiveness of cutting speed on material removal rate. It should be noted that at higher milling depth and lower feed rate values, this effect intensifies.

In Figure 3-a and 3-c, the increasing effect of lower feed rate values can be seen. It is attributed that higher values of feed rate reduces the milling time, having more influence of the contribution on material removal rate. In finish hard milling of AISI H13 steel, increasing cutting speed and lower levels of feed per tooth increases the cutting energy (Liu et al., 2018). At some values of depth of cut and cutting speed, feed rate shows fluctuating behavior however, it can be ignored.

General trend of the depth of cut effect is similar with cutting speed. as it can be seen in Figure 3-b and 3-c. It shows increasing effect on the consumed energy with higher values. This effect can be explained with the increasing material removal rate. Higher depth of cut and cutting speed values produces more cutting power, thereby higher cutting energy consumed (Vu et al., 2020). Also, the effect of depth of cut and cutting speed on energy consumption can be observed in hard milling of the Ti6Al4V alloy under MQL conditions (Jamil et al., 2021).

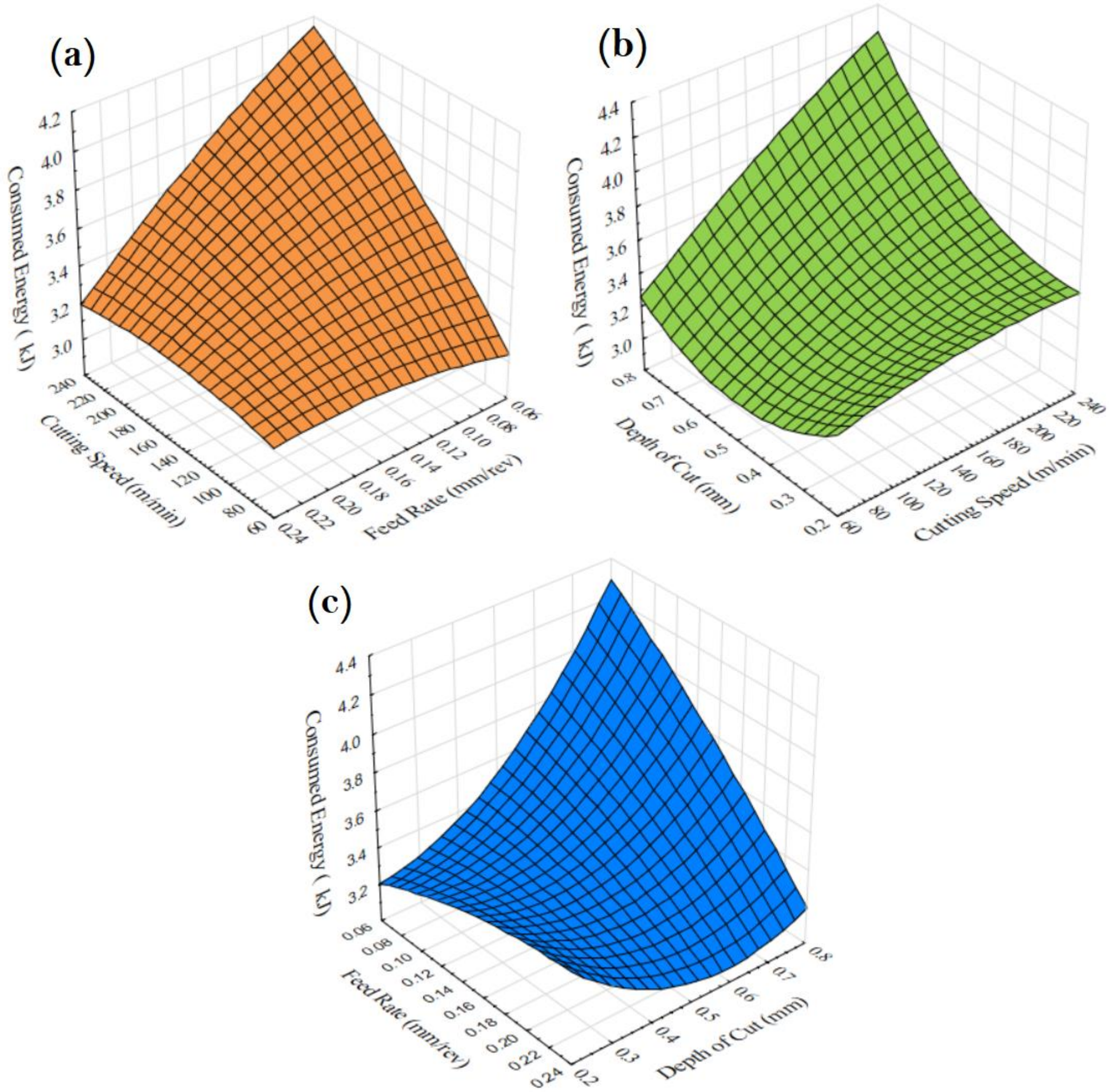

Figure.3. 3D plots for the combined effect of cutting parameters on energy consumption

Optimization of Parameters for Energy Consumption

Optimization of process parameters provides substantial information for the practical applications (Kuntoğlu et al., 2020; Kuntoğlu et al., 2020). A clear change is observable when comparing the effects produced by each parameter level. Figure 4 describes the optimum cutting parameters for energy consumption with applying the S/N ratios of Taguchi method. Actually, in here, individual effects of each input can be observed different from the 3D plots. However, considering these illustrations, similar effects can be clearly seen. Accordingly, lower cutting speed (75 m/min) and depth of cut (0.25 mm) and higher feed rate (0.225 mm/rev) values produces minimum energy. In addition, parametric influences can be discussed by these images and the dominant effect of cutting speed can be clearly seen. The findings are compatible with the 3D surface graphs.

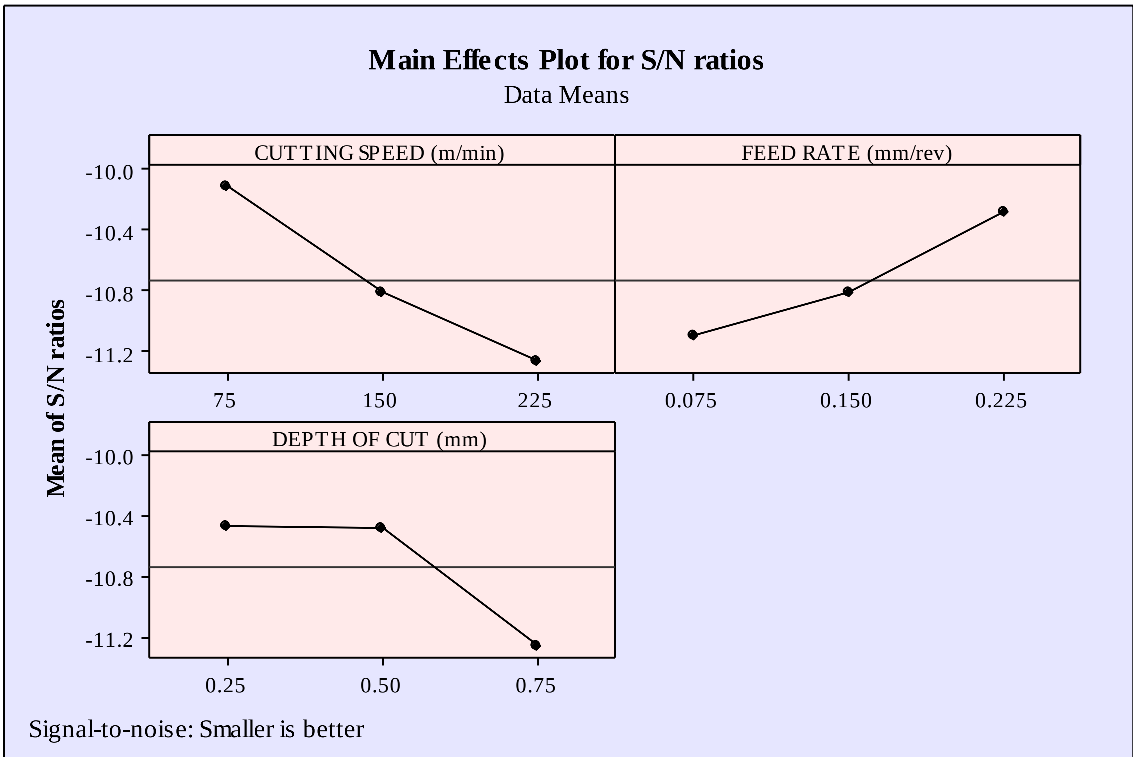

Figure.4. Optimum cutting parameters for minimum energy consumption

Analysis of Variance Results

Table 5 highlights the ANOVA results summarizing the effect of different statistical values. Basically, calculated sum of squares (SS) are converted to percent contribution (PC%) with dividing each parameter value to total value. Also, F value is calculated by dividing the each SS value to the residual error value. According to the PC%, cutting speed (46.28%) is the most influential factor on energy. After that, depth of cut (27.8%) and feed rate (23.6%) has significant contributions respectively. P value of the cutting speed (0.048<0.05) confirms its importance considering the 95% confidence interval (Kuntoğlu and Sağlam, 2019). And according to F value cutting speed comes first with the value of 19.91, followed by feed depth of cut (11.96) and feed rate (10.15). The main aim with ANOVA results is to quantify the former findings namely 3D surface plots and S/N ratios. Numerical results enlighten the parameter influences which will be useful in the future for determining their priority.

Table 5. Analysis of variance results for energy consumption

Source	DF	Seq. SS	Adj. MS	F value	P value	PC (%)
v_C	2	2.0132	1.0066	19.91	0.048	46.28
f	2	1.0268	0.51342	10.15	0.09	23.6
a_P	2	1.2099	0.60495	11.96	0.077	27.8
Residual Error	2	0.1011	0.05057	-	-	2.32
Total	8	4.3511	-	-	-	100

CONCLUSION

The obtained findings from this paper are listed below:

1. Statistical evaluation exhibited the major impact of cutting speed (46.28% with percent contribution, 0.048<0.5 with P value and 19.91 with F value) over feed rate (23.6% with percent contribution, 0.05<0.09 with P value and 10.15 with F value) and depth of cut (27.8 with percent

contribution, 0.05<0.077 with P value and 11.96 with F value). This implies that cutting speed optimization take significant part in milling's energy consumption reduction.

2. Minimum depth of cut (0.25 mm), cutting speed (75 m/min) and higher feed rate values (0.225 mm/rev) are recommended for obtaining low energy consumption at first. Respectively, each parameter play an important role on energy consumption such as: lower depth of cut reduces material removal rate, higher cutting speed produces lower cutting forces and higher feed rate reduces the machining time.
3. With respect to 3D surface plots, from 75 m/min to 225 m/min, from 0.225 mm/rev to 0.075 mm/rev and 0.25 mm to 0.75 mm, the curve of consumed energy shows mostly increasing trends. In this context, 3D graphs support the findings belong to statistical analysis and S/N ratios which shows the results are compatible and justifiable.

Conflict of Interest

The author declares that there is no conflict of interest.

Author's Contributions

The author declares that they have contributed equally to the article.

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