Düzce University Journal of Science & Technology

Research Article

Drilling Vanadis 4E with Coated Drills; Examination of Wear, Surface Roughness, and Chip Formation

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DOI:10.29130/dubited.1173170

ABSTRACT

Vanadis 4E is a versatile powder metallurgical tool steel widely used in today's market with high wear resistance and excellent yield properties. Drilling operations applied to materials are one of the operations commonly used in the machining industry. In drilling operations, coated or uncoated drills are used, which may vary according to the material used. This study applied drilling operation to Vanadis 4E powder metallurgical steel with TiN-coated HSS drills. In the study, Drills with diameters of 5, 8.5, and 10.5 mm, cutting speeds of 22, 23, and 24 m/min, and feed rates of 0.10, 0.12, and 0.14 mm/tooth was used. Nine experiments were carried out using the Taguchi L9 orthogonal array. After the experiments, the material was cut from the holes, and the roughness values were measured from the inner surfaces of the holes. In addition, hardness measurements were made from the material surfaces around the holes. The wear conditions of the drills used in the experiments were examined with an optical microscope after the experiment. The formations after each experiment were also examined. The best roughness value was obtained with the 5 mm diameter drill in the 1st experiment, the best roughness value was obtained in the experiments carried out with the 8.5 mm diameter drill in the 6th experiment, and the best roughness value was obtained in the 7th experiment for the 10.5 mm diameter drill. When the wear in the drills was evaluated, it was observed that the side surface and radial wear occurred.

Keywords: *Vanadis 4E, Drilling, Surface roughness, Chip formation, Wear*

Vanadis 4E'nin Kaplamalı Matkaplarla Delinmesinde; Aşınma, Yüzey Pürüzlülüğü ve Talaş Oluşumunun İncelenmesi

ÖZ

Vanadis 4E, yüksek aşınma direncine ve çok iyi sünme özelliğine sahip, günümüz piyasasında yaygın olarak kullanılan çok yönlü toz metalurjik takım çeliğidir. Malzemelere uygulanan delme operasyonları, talaşlı imalat sektöründe yaygın olarak kullanılan işlemlerden biridir. Delme operasyonlarında, kullanılan malzemeye göre değişiklik gösterebilen kaplamalı veya kaplamasız matkaplar kullanılmaktadır. Bu çalışmada Vanadis 4E toz metalürjik çeliğe TiN kaplamalı HSS matkaplarla delme operasyonu uygulanmıştır. Çalışmada; 5, 8.5 ve 10.5 mm çapta matkaplar, 22, 23 ve 24 m/dak kesme hızları ve 0.10, 0.12 ve 0.14 mm/diş ilerleme oranları kullanılmıştır. Taguchi L9 ortogonal dizisi kullanılarak 9 deney yapılmış, deneyler sonrası malzeme deliklerden kesilerek, delik iç yüzeylerinden pürüzlülük değerleri ölçülmüştür. Ayrıca, deliklerin çevresindeki malzeme yüzeylerinden sertlik ölçümleri yapılmıştır. Deneylerde kullanılan matkapların deney sonrası optik mikroskop ile aşınma durumları incelenmiştir. Her bir deney sonrası oluşumları da incelenmiştir. 5 mm çaptaki matkapla en iyi pürüzlülük değeri 1. deneyde, 8.5 mm çaptaki matkapla yürütülen deneylerde en iyi pürüzlülük değeri 6 numaralı deneyde ve 10.5 mm çaptaki matkapta ise en iyi pürüzlülük değeri 7. deneyde elde edilmiştir. Matkaplarda ki aşınmalar değerlendirildiğinde, yan yüzey ve radyal aşınmaların oluştuğu görülmüştür.

Received: 09/09/2022, Revised: 07/02/2023, Accepted: 10/02/2023

Anahtar kelimeler: *Vanadis 4E, Delme, Yüzey pürüzlülüğü, Talaş oluşumu, Aşınma*

I. INTRODUCTION

Powder metallurgy (PM) is a field in which materials or components are made from metal powders and covers many techniques. PM is a method that reduces material losses and lowers final product costs. PM is also widely used in the production of materials that are difficult to manufacture [1]. Steels produced by the PM method are widely used in the manufacturing industry. One of these steels is Uddeholm Vanadis 4 Extra SuperClean (Vanadis 4E) PM steel. Vanadis 4E offers very good machinability and grind ability compared to other high alloy PM tool steels and excellent quality for tools made from this material. Vanadis 4E is particularly well suited for applications where adhesive wear mechanisms may occur and for cutting and forming advanced high-strength steels [2].

Drilling processes are used in almost many areas of the machining industry. Drilling operations can be done with universal machine tools and CNC machines. CNC machines are widely used in machining in drilling for best performance, low production time, mass production, good surface quality, and long tool life. In these processes, it is critical to determine the cutting parameters suitable for the material being drilled. Careful handling of this critical process will ensure a delicate surface, long wear of the drills, and long tool life. The purpose of metal removal methods in modern manufacturing is to achieve higher machining accuracy and lower surface roughness with increased chip content [3]. Current conventional manufacturing methods for machining materials with hard machinability properties result in uneconomic outputs such as tool wear and machining time [4]. Therefore, it is necessary to determine the cutting parameters well in drilling processes [5].

When the literature is examined, it is possible to come across many studies covering drilling processes. Korucu and Samtaş, in their study, Vanadis 4E drilled powder metallurgical steel using three different diameters of uncoated HSS drills and different cutting parameters. The study investigated surface roughness, drill wear, and chip formation [6]. The Taguchi method is also used in drillability studies. In his study, Ozsoy investigated the effect of drilling parameters on thrust force on AISI 2080 steel. In the study, the Taguchi method optimized the cutting parameters to minimize the thrust force [7]. Vignesh et al., in their study, investigated the performance of drills by applying drilling operations to Stainless Steel 410 material with AlTiN-coated and uncoated HSS drills. Their study evaluated the effects of cutting parameters on material removal rate, surface roughness, and ovality [8]. Kanagaraju et al. investigated the drilling performance of super duplex stainless steel used in the marine, petrochemical, and petroleum industries and numerous industrial applications under the conditions of a minimal amount of lubrication technique based on environmentally friendly liquid carbon dioxide and biodegradable coconut oil [9]. Amrit et al. investigated the drilling performance of AISI 321 stainless steel using various cooling strategies (dry, wet, and 6 MQL conditions). Their study examined thrust force, torque, surface roughness, friction coefficient, chip formation, and wear mechanisms [10]. Doğan et al. studied drilling Fiber Metal Laminate piles under different conditions with conventional and non-traditional processing methods. [11]. On the other hand, Patel and Chaudhary conducted a study summarizing various delamination inspection and measurement techniques to improve composite materials' drillability [12]. Rubi et al. investigated the effects of drilling parameters on the drilling of LM6/B4C composite material and optimized the parameters using Gray Relational Analysis. [13]. Kumar et al. conducted a study on the drilling of fiber-reinforced composite materials. [14]. There are studies in the literature, especially on the drillability of steel materials, examination of the performances of drills with different coatings, optimization of cutting parameters in drilling processes, and the drillability of composite materials [15]- [24].

When the literature was examined, a drilling study using HSS drills belonging to Vanadis 4E material was found. In this study, TiN coated, and different diameter drills were used, and this study is different and original in content from the study in the literature. Considering the literature review, it was seen that there was no other drillability study using Vanadis 4E.

In this study, drilling operations were carried out on Vanadis 4E steel using three different diameters of the TiN-coated drills, three cutting speeds, and three different feeds. The Taguchi L9 orthogonal array was used for the experimental design, and 9 experiments were carried out. After the experiments, roughness measurements were made on the drilled surfaces, and outer edge and radial wear were examined by taking images of the tips and side surfaces of the drills after each experiment. The chip formations that occurred at the end of each experiment were photographed and analyzed. Additionally, the effects of cutting parameters on wear and surface roughness were examined by analysis of variance and three-dimensional plots.

II. MATERIAL AND METHOD

A. DRILLING EXPERIMENTS

As the cutting tool, HSS drills in the DIN 338 norm with a tip angle of 118˚, TiN coating and three different diameters (5, 8.5 and 10.5 mm) were used in the study. The technical catalog of the material and the literature were considered in the selection of drill diameters. The drilling operations were carried out with a First MCV-300 CNC vertical processing center (Figure 1).

As the material to be drilled, Vanadis 4 Extra powder metallurgical tool steel with dimensions of 80x40x30 mm from the firm Uddeholm was used. Tables 1 and 2 show the material's mechanical properties and chemical composition [2].

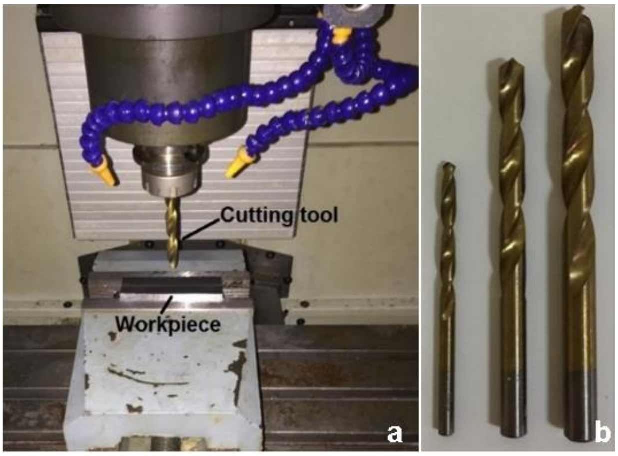

Figure 1. *Experimental setup and cutting tools (a. Experimental setup, b. Drills)*

Table 1. *Mechanical properties of the Vanadis 4E material*

Mechanical Properties			
Density	**Modulus of elasticity (*GPa*)**	**Hardness Brinell**	**Thermal conductivity**
7.70 gr/cc	205	230	30 W/m-K

Table 2. *Chemical composition of Vanadis 4E*

Component Elements Properties (per cent weight, %)						
C	Cr	Fe	Mn	Mo	Si	V
1.4	4.7	85.9	0.40	3.5	0.40	3.7

B. MEASUREMENT OF SURFACE ROUGHNESS

The surface roughness was measured using a Mitutoyo SJ-301 model surface roughness device (Figure 2). Using the Taguchi L9 orthogonal array, 9 experiments were conducted, and the roughness measurements were repeated twice from the holes' entry and exit. The average of these two measurements was used in the study.

C. EXAMINATION OF WEARS

After each drilling experiment, the drills' outer edge and radial wear were examined. In the examinations, a Nikon Eclipse LV150N model microscope was used.

D. EXPERIMENTS

This study conducted drilling operations on Vanadis 4E powder metallurgical steel using three different diameter drills. The Taguchi L9 orthogonal array was used in the experimental design, and 9 experiments were conducted. Three experiments were carried out for each drill bit. In determining the cutting parameters, the catalog information of Uddeholm Vanadis 4E was utilized [2]. In the experiments, wet drilling was performed by using boron oil. After the experiments, the material was cut from the center of the drilled zones, and the roughness values of the hole surfaces were measured (Figure 2). Table 3 shows the experimental design and experimental results.

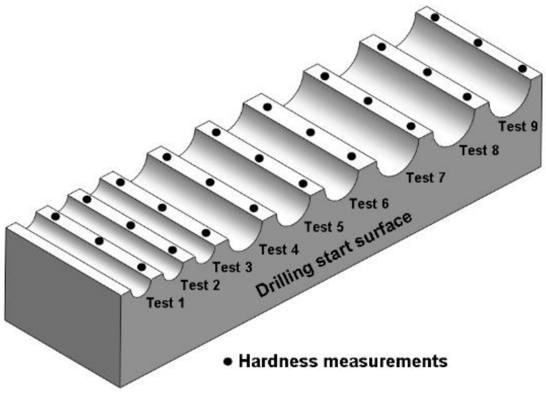

Figure 2. *Hardness measurements*

Table 3. *Surface roughness values obtained from the experiments*

Test no.	Cutting parameters			Experimental results		
	A Cutting tools (Diameter, D, *mm*)	B Cutting speed (*V, m/min*)	C Feed rate (*f, mm/rev*)	Ra (μm)	Wear (*mm*)	Hardness (*Brinell*)
1	5	22	0.1	1.100	0.228	158
2	5	23	0.12	1.620	0.291	166
3	5	24	0.14	1.925	0.362	174
4	8.5	22	0.12	2.515	0.288	183
5	8.5	23	0.14	2.380	0.273	178
6	8.5	24	0.1	0.945	0.233	182
7	10.5	22	0.14	1.920	0.217	174
8	10.5	23	0.1	2.540	0.148	178
9	10.5	24	0.12	1.955	0.180	179

While drilling the material, it was seen that the tool had difficulty and resonated. For this reason, Brinell hardness measurements were made with the Hartip 3000 portable hardness tester from three regions where each hole is located (Figure 2). These measurements are shown in Table 3. The hardness values given in Table 3 are the average values of these three measurements. The technical catalogs expressed that the hardness value of this steel sold by soft annealing could reach approximately 230 HB [2]. However, this reached up to 183 HB in the measurements, and different hardness values were measured from different points. This situation is directly effective on drillability performance. This effect is discussed in detail in the interpretation section. Additionally, Table 3 shows the wear values measured from the outer edges of the drills. Here, the lowest wear value for the drill bit with a diameter of 5 mm was 0.228 mm at the cutting speed of 22 m/min and feed rate of 0.1 mm/rev, that for the drill bit with a diameter of 8.5 mm was 0.233 mm at the cutting speed of 24 m/min and feed rate of 0.1 mm/rev, and that for the drill bit with a diameter of 10.5 mm 0.148 mm at the cutting speed of 23 m/min and feed rate of 0.1 mm/rev.

III. INTERPRETATION OF THE EXPERIMENTAL RESULTS

A. INTERPRETATION OF THE ROUGHNESS MEASUREMENTS

After the drilling process, the part was cut in half from the center of the holes and made ready for measurements. The measurements were taken from the entry and the hole exit. Table 3 shows the averages of these measurements. Figure 3 shows the photographs of the surfaces measured for roughness and the plot of the average roughness values.

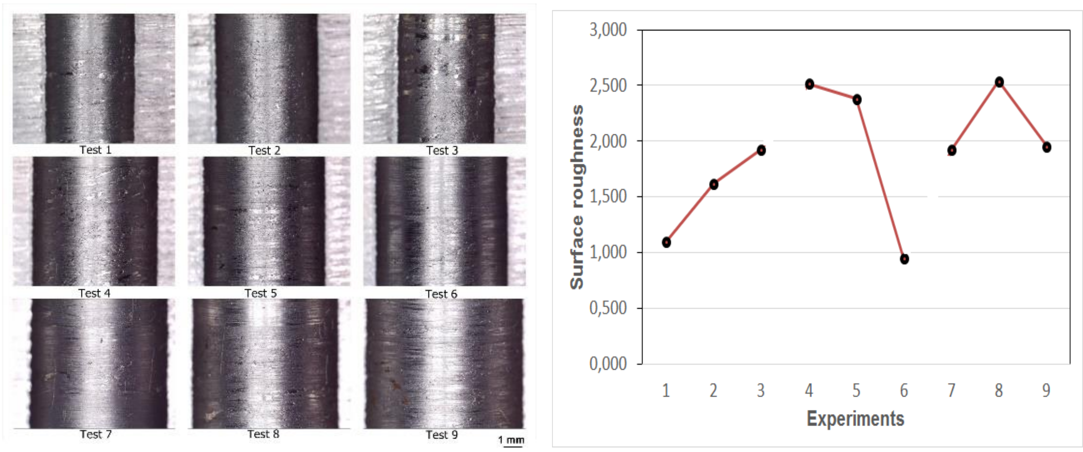

Figure 3. *Roughness measurement surface images and plots*

Figure 3 shows the images of the surfaces whose roughness measurements were taken by a microscope (20x) and the plot of the roughness values obtained from the experiments. Here, in the first three experimental drilling processes performed with the 5-mm drills, the minimum surface roughness value was obtained in the first experiment (22 m/min and 0.1 mm/rev). On the other hand, the highest roughness value was obtained in experiment 3. This situation is also seen in the surface photographs in Figure 3. In the experiments carried out with the 8.5-mm drills, the lowest roughness value was observed in the 6th experiment (24 m/min and 0.1 mm/rev). The lowest roughness value for the 10.5-mm drills was obtained in the 7th experiment (22 m/min and 0.14 mm/rev). The roughness values increased as the feed rate increased for the 5mm and 8.5mm drills. This is different with 10.5 mm drills. The lowest roughness of 10.5 mm drills was measured at the highest feed. This is attributed to the hardness values that change at different material points. On the other hand, it is seen that the roughness increases as the cutting speed increases in 5 mm drills. This is the opposite for 8.5 and 10.5 mm drills, and the roughness value decreases as the cutting speed increases in these diameters. It can be said that the chip formation in unit time increases with the increase in drill diameter and cutting speed. Therefore, there is an increase in roughness values due to the difficulty of chip evacuation. [25].

B. INTERPRETATION OF WEARS

In an examination of wear, images were taken with an optical microscope (20x) from the drills' outer edges and tip parts. Figure 4 shows the microscopic images taken from the side surfaces and tips of the drills with diameters of 5, 8.5, and 10.5 mm. In the side surface images, outer edge wear was examined by looking at the edging of the drill bit. Radial wear was examined for the tip images. The wear values indicated in Table 3 are the edge wear measurements of the drills. In Figure 4, the radial (tip wear) images are also given beside the edge wear.

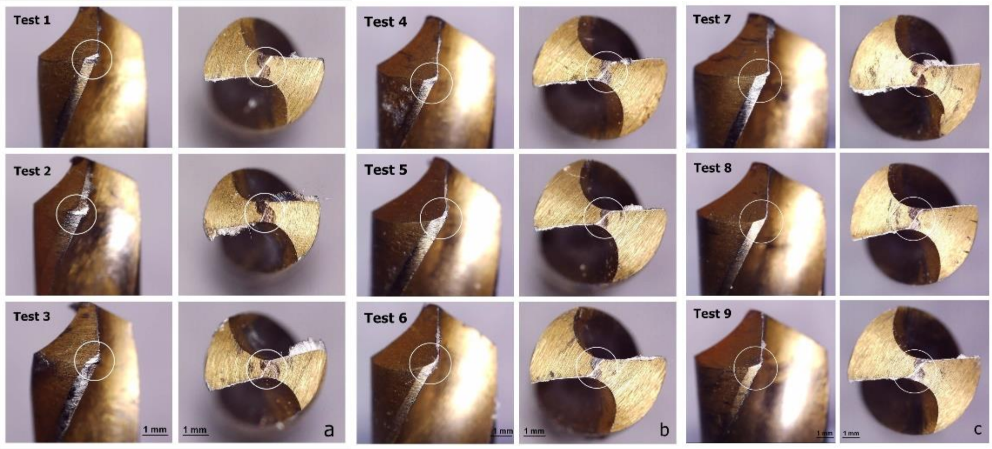

Figure 4. *Examination of the outer edge and radial wears for the drills with diameters of 5 mm (3a), 8.5 mm (3b), and 10.5 mm (3c)*

It was observed that the hardness values of the material that was used in the experiments varied at some points. Hardnesses were measured at each test's hole's beginning, middle, and end (Figure 2). In these measurements, the hardness measurements taken for each hole were different from each other. Therefore, different hardness values during drilling directly affect the test results. After the experiments, Brinell hardness measurements were made from the hole edge, and these values are shown in Table 3. As seen in Figure 4, there was outer edge wear on the drills in all experiments. The highest wear in the drill bit with a diameter of 5 mm was 0.228 mm in experiment 1, in the drill bit with a diameter of 8.5 mm was 0.233 mm in experiment 6, and the lowest wear in the drill bit with a diameter of 10.5 mm was 0.148 mm in experiment 8. In the literature, reducing the cutting speed and lowering the feed rate are recommended to reduce wear, including flank and notch wear [26]. In this study, the cutting speeds and feed rates were determined based on the technical catalog information of the firm from where the workpiece was obtained. When Figure 4 and Table 3 are evaluated in terms of radial wear, radial wear was not observed in experiment 1 and experiment 3, but radial wear was observed in other experiments. This is attributed to the variation in the hardness of the material.

C. INTERPRETATION OF CHIP FORMATION

Figure 5 shows the chip formations that occurred during the experiments. In test 1, torn chip formation was observed at the beginning of drilling, but needle-type chip formation was observed. Torn chips are evacuated without letting them roll, but they may be easily coiled around the drill bit [26], [27]. Needle-type chips are formed due to vibration or brittle material. These are acceptable forms of chips. However, they may lead to chip accumulation by stacking onto each other [27], [28]. In the experiments in test 1, it was observed that these chips were easily evacuated from the hole.

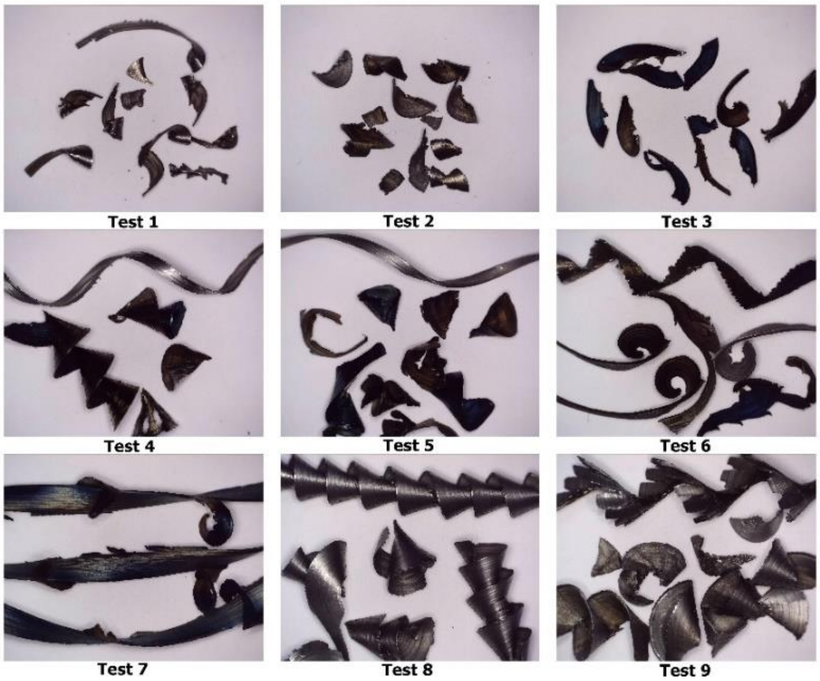

Figure 5. *Chip formations obtained from each experiment*

As seen in Figure, in test 2, semi-shell chips were formed. This type of chip form is a chip form that is formed by breaking with the effect of discharge channel and hole side walls and occurs at high feed rates. [27], [28]. It is believed that this chip formation occurred in test 2 due to the feed rate increase and hardness in this zone. In test 3, torn and semi-shell chips were formed, and the increased feed rate was thought to have caused this outcome. In test 4, in the first experiment with the drill bit with a diameter of 8.5 mm, spiral and torn chip formation was observed. In spiral-type chips, if the chip is broken after curling a few times, this is acceptable. In this experiment, the spiral chip formation also broke after curling a few times. In test 5, torn chips were formed at the beginning of drilling, then spiral-type chips and semi-shell chips at the end. This was attributed to the increased hardness in the area of the hole. In test 6, torn chip formation was observed, and the chip was broken without being elongated. This is the desired situation. In test 7, torn chip formation was observed, and the chip was broken without being elongated. In test 8, spiral-type chip formation was observed; again, it was broken without elongating. This is the desired chip form. In test 9, spiral chips at the beginning and semi-shell chips at the end of drilling were observed. The formation of different chip forms in each experiment was attributed to the changing levels of the hardness of the material on different surfaces.

D. EFFECTS OF CUTTING PARAMETERS

The effects of the cutting speeds and feed rates selected for the experimental design on the surface roughness and wear values were examined with three-dimensional plots. Figure 5a shows cutting speed and feed rate effects on surface roughness.

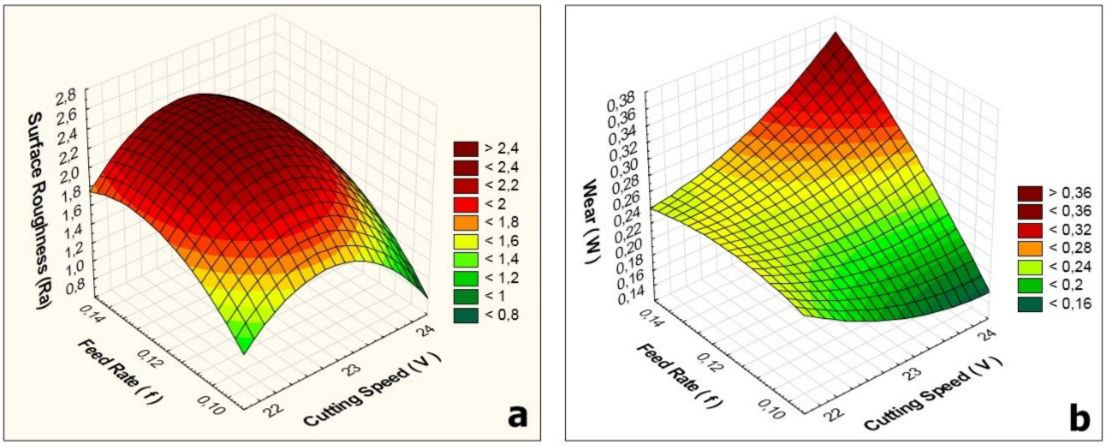

Figure 6. *Effects of cutting speed and feed rate on wear and surface roughness*

Figure 6a shows that the surface roughness values increased as the feed rate increased. However, roughness decreased at the feed rate of 0.10 mm/rev and cutting speeds of 22 m/min and 24 m/min. As the feed rate and cutting speed increased, the roughness values increased. The plot shows that the highest surface roughness value occurred at the cutting speed of 23 m/min and feed rate of 0.14 mm/rev, while the lowest value occurred at the cutting speed of 22 m/min and feed rate of 0.10 mm/rev. Low feed rates and low cutting speeds are recommended in practice for the best performance in drilling operations, which is similar to the literature [26]. Figure 6b shows cutting speed and feed rate effects on wear. Here, the highest amount of wear occurred at the cutting speed of 24 m/min and feed rate of 0.14 mm/rev. The lowest wear value was obtained at 24 m/min cutting speed and a feed rate of 0.10 mm/rev. As seen in the plot, the wear values increased as the cutting speed and feed rate increased. TiN-coated drills show high performance in achieving low surface roughness in drillability applications. This is attributed to the surface lubrication properties and low coefficient of friction of the TiN coating [29].

E. ASSESSMENT OF EFFECTS BY ANALYSIS OF VARIANCE

Table 3 shows the results of the analysis of variance on the cutting parameters. The analysis of variance was carried out by considering the 95% confidence interval.

Table 4. *Assessment of cutting parameters by analysis of variance*

Variance source	**Degree of freedom (*DoF*)**	**Sum of squares (*SS*)**	**Mean square (*MS*)**	**F -Value**	**P-Value**	**Contribution (%)**
Surface roughness (Ra-µm)						
D	1	0.5425	0.5425	1.72	0.246	20.48
V	1	0.084	0.084	0.27	0.627	3.17
f	1	0.4483	0.4483	1.42	0.286	16.93
Error *(e)*	5	1.5735	0.3147			59.42
Total	8	2.6482				100
Wear (W, mm)						
D	1	0.01679	0.01679	13.23	0.015	50.46
V	1	0.00029	0.00029	0.23	0.651	0.88
f	1	0.00984	0.00984	7.76	0.039	29.59
Error *(e)*	5	0.00634	0.00126			19.07
Total	8	0.03326				100

As seen in Table 4, the cutting tool was the most effective factor in surface roughness, with a value of 20.48%. The feed rate of 16.93% followed this. The cutting speed provided the lowest effect by 3.17%. As drills with three different diameters were used in the experiments, it is possible to say that the feed rate was the most influential factor among those that affected surface roughness. As seen in Table 4, the most influential factor on wear was the cutting tool, with a value of 50.46%. The second most effective factor was the feed rate of 29.59%, followed by the cutting speed of 0.88%. Here, excluding the cutting tool from the analysis would be right. Therefore, it is possible to say that the feed rate was the most influential factor in wear.

IV. CONCLUSIONS

In this study, drilling operations were performed on Vanadis 4E powder metallurgical steel using drills with three different diameters, cutting speeds, and feed rates. The Taguchi L9 orthogonal array was used for the experimental design, and 9 experiments were conducted. The experimental results were analyzed by interpreting the roughness and wear images and using three-dimensional plots and analysis of variance. The results obtained from this study may be listed as follows:

- During drilling, different parts of the workpiece resonated, and as a result, hardness measurements were made near the holes. The hardness measurements showed that the experiment material had different hardness values, which made one think that it would be suitable to apply stress relief annealing before machining the parts.
- Considering the surface roughness results, in the first 3 drilling experiments carried out with the 5-mm drill bit, the minimum surface roughness value was obtained in experiment 1 (22 m/min and 0.1 mm/rev), while the highest roughness value was obtained in experiment 3. This is also seen in the surface images shown in Figure 2. In the experiments carried out with the 8.5-mm drill bit, the lowest roughness value was obtained in experiment 6 (24 m/min, 0.1 mm/rev). In the experiments carried out with the 10.5-mm drill bit, the lowest roughness value was obtained in experiment 7 (22 m/min and 0.14 mm/rev).
- Examining the wear, it was observed that there was outer edge wear on the drills in all experiments. There was no radial wear in experiments 1 and 3, while radial wear occurred in the other experiments. This situation was attributed to the varying hardness values of the material.
- Considering chip formations, it was observed that chips in the form of tears, spirals, semi-shells, and needles were formed, which was attributed to the different hardness values of the material. The most suitable chip formation occurred in test 2 for the 5-mm drill bit, test 4 for the 8.5-mm drill bit, and test 8 for the 10.5-mm drill bit.
- In the three-dimensional plots, it was seen that increasing the cutting speed and feed rate led to an increase in the surface roughness values. In the same plots, the lowest roughness value was seen at the feed rate of 0.10 mm/rev and cutting speed of 22 m/min.
- Based on the wear plot, the highest wear value occurred at the cutting speed of 24 m/min and feed rate of 0.10 mm/rev. In the same plot, the lowest wear value was achieved at the feed rate of 0.10 mm/rev and cutting speed of 24 m/min.
- Looking at both plots, it is understood that the feed rate of 0.10 mm/rev should be selected for low wear and roughness values.
- In the analysis of variance carried out for wear and surface roughness, the most effective parameter was found as the feed rate. Here, as drills with three different dimensions were used, the cutting tool was not included in the analysis.
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It is recommended to eliminate internal stresses by applying stress relief annealing before drilling the Vanadis 4E steel used in this study. Future studies may test the machining performance of this material by applying surface milling, pocket milling, and slot milling.

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