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Research Article

Investigating and Optimizing the Effect of Primary Parameters on the Amount of Wear in AISI 631 Sheet

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ABSTRACT

Metal friction is a critical phenomenon that affects the performance and longevity of metal components. Understanding the factors that contribute to metal friction and finding effective ways to optimize its results are essential in various industries. To investigate metal friction and optimize results, an experimental design approach is employed. This approach involves systematically varying input parameters to assess their impact on frictional forces. By carefully controlling and manipulating these parameters, researchers can gain insights into the underlying mechanisms and identify strategies to minimize friction. In the test design method, by using the response surface method, a series of tests consisting of primary parameters are designed, and their results are checked and optimized on the amount of friction. This study focuses on investigating the effects of weight, length of the path, and the speed of the pin on wear using a wear-testing device. The results of the optimization process indicate that the optimal condition occurs when the weight is at its minimum value of 318.2 kg, the speed is at its minimum value of 0.9546 m/s and the path length is 2356.7 m. The results indicate an increase in wear with an increase in weight and length of the path. Additionally, Finite element simulation was done to check the results. The results of experimental operation and finite element simulation showed a good agreement.

1. Introduction

Metal wear is a significant concern in various industries, as it can lead to reduced performance, increased energy consumption, and even component failure. As a result of two metal pieces rubbing against each other, a force is created that resists this wear called friction force. This force compresses the two bodies together. Understanding the mechanisms and factors that contribute to metal wear plays a crucial role in improving the performance and longevity of metal components. Metal wear is a phenomenon that occurs when two metal surfaces come into contact and experience relative motion, resulting in material loss and surface damage. It is a critical concern in various industries, including manufacturing, automotive,

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aerospace, and machinery, as it can significantly impact performance, efficiency, and the lifespan of metal components. Over the years, numerous studies have been conducted to understand the wear behavior of metals and develop effective strategies to mitigate it. These studies have contributed to a comprehensive understanding of the factors influencing metal wear and have led to the development of advanced wear-resistant materials and surface treatments. The research conducted in this field has focused on various aspects of metal wear, including wear mechanisms, wear testing methods, measurement techniques, and the effects of different parameters on wear behavior. In this study, some of these studies are discussed.

There are various methods available for measuring and studying the behavior of material wear. Among these methods, the pin-on-disk method is the most common method of measurement [1, 2]. The pin-on-disk method is used for various types of materials and, in this article, we will discuss some studies that have used this method. The pin-on-disk method is widely used to measure the wear resistance of different metallic materials [3-5]. It is also used to study the wear characteristics of ceramics [6], composites [7], and materials with surface coatings [8]. This method provides valuable insights into the wear behavior of various materials. In addition to the pin-on-disk method, other methods are available for studying wear behavior of materials which are listed as follows: 1. Particle flow method: This method involves applying abrasive particles onto a sample to study its wear behavior [9, 10]. 2. Grinding stone method: The grinding stone method is another approach used to investigate the tribological behavior of materials [6]. 3. Zirconia pin in disk method: This method utilizes a zirconia pin in a disk setup to examine the frictional properties of materials [11]. Several studies have been conducted to examine the influence of different parameters on wear rate. Chaudhary and Kalyan [12] investigated the tool wear in the machining process. In this study, the impact of feed rate, cutting speed, and cutting depth on wear in SS 202 stainless steel was examined. The results of this study indicated that the use of a coolant resulted in a 37% reduction in wear compared to dry machining. Gupta et al. [13] studied the effect of coolant in the machining of 1040 steel compared to dry machining. They utilized tungsten carbide tools in their study. The results revealed a significant reduction of 55% to 65% in wear when coolant was used compared to dry machining. They attributed this reduction to the control of temperature-dependent wear mechanisms, such as the decrease in the wear threshold height and the depth of wear groove. Multiple factors, including hardness, loading type and method, microstructural and chemical characteristics, service variables such as contacting materials (e.g., lubricants and their specifications), speed, temperature, time, roughness, lubrication, and corrosion, have an influential impact on wear rate [14]. These studies shed light on the importance of considering various parameters and their effects on wear behavior when studying and analyzing material wear. Shoroudi and his colleagues conducted a study on wear in SiC/Al composite under constant velocity and varying pressure conditions. The results of this study indicate that the wear rate increases by increasing the pressure [15]. Additionally, Al-Bawalakheir [16] examined the friction and wear behavior of a composite disc under varying speeds and forces. This study also included a comparison with a cast iron disc. The results revealed that the wear rate increases with an increasing force of 50 to 100 Newtons, while the wear rate decreases by increasing the speed. The wear rate of the composite is higher than that of the cast iron. In other studies, the wear of aluminum with reinforcing particles and aluminum matrix composites was investigated using the pin-on-disc method [17, 18]. The results showed that the wear resistance of the aluminum matrix composite is lower than that of aluminum with reinforcing particles. Increasing the size and quantity of the particles increases the wear resistance of the reinforced aluminum. Another study examined the effect of load and temperature on the friction and wear behavior of aluminum-based composites with 10% and 20% SiC reinforcing particles [19]. The results of this study also indicated that the wear rate increases by increasing the force. It is important to note that increasing the speed reduces the wear rate. The study and investigation of wear phenomena through laboratory experiments and scientific research initiated by Mr. Fini [20] and began in the 1960s. In this study, the wear of metal surfaces by sand particles in gas flow was examined. Taliskioui and his colleagues [21] conducted a study to investigate the wear between train wheels and rails. They approached this activity from a materials perspective and utilized the concept of wear. Diana and her colleagues [22] examined the dynamic behavior of trains and the effects of wear on rail and wheel profiles. Tang and Chako [23] focused on the wear in hot rolling mill stations and, recognizing the significance of this issue, presented experimental wear diagrams for rollers in this process. The DIN 50320 standard defines four mechanisms of wear: chemical wear, adhesive wear, fatigue wear, and abrasive wear. In most machining and forming processes involving relative motion between the two bodies, adhesive and abrasive wear have the greatest impact on wear phenomena [24]. Walstrom and his colleagues [25] conducted a study comparing the wear of semi-metallic pads and asbestos pads against a gray cast iron rotor using a finite element software. The results of this study indicate that the wear of asbestos pads is more favorable compared to semi-metallic pads in this investigation. Gadkate and his colleagues [26] examined the experimental and simulated wear test of tungsten carbide pin on a hot rolled disc. Ardila et al. [27] investigated the influence of the ball material on friction and wear. Shisode et al. [28] investigated the modeling of the boundary wear of coated sheets in the forming of metal sheets. Liang et al. [29] investigated wear behavior in metal cutting process. The aim of the present study is to help understand the complex relationship between ball materials, friction, particle dynamics, and wear during micro-wear tests.

In this study, our focus is specifically on investigating abrasive wear. By analyzing and understanding the factors that influence abrasive wear, we can develop strategies to mitigate its effects and enhance the wear resistance of metal components. This research aims to provide insights into the mechanisms underlying abrasive wear and identifying strategies to minimize its impact. The investigation of abrasive wear involves various experimental and analytical techniques. Wear testing methods, such as the pin-on-disk or ball-on-disk configuration, are commonly employed to simulate real-world wear conditions and measure the wear rate. Additionally, advanced characterization techniques, including profilometry, microscopy, and spectroscopy, are used to analyze wear tracks, wear debris, and surface changes. Understanding the influence of these parameters is crucial in optimizing machining processes, selecting appropriate materials, and enhancing the durability and performance of components and products. By conducting comprehensive studies and analyzing the impact of different parameters, researchers can gain valuable insights into wear behavior and develop effective strategies for wear reduction and prevention.

2. Experimental Procedure

2.1. Materials and tools

In this study, the AISI 631 sheet was used to investigate the level of wear. This sheet has numerous applications in industrial and military fields, among others. Initially, to obtain the mechanical properties of this sheet, it was subjected to a tensile test. For the tensile test, a sample was prepared according to the E8 standard (Fig. 1). Then, the tensile test was performed using a tensile testing machine the results of which can be seen in Fig. 2. In this study, Hounsfield H50KS's tensile test machine was used with a rate of 0.01 s^{-1} at ambient temperature with a capacity of two tons.

In order to investigate the level of wear on the used sheets, a wear testing machine (Fig. 3) is utilized. In this machine, the sheet and pin are fixed in designated areas, and the reciprocating motion causes the pin to wear the sheet. After conducting the test, the wear results are

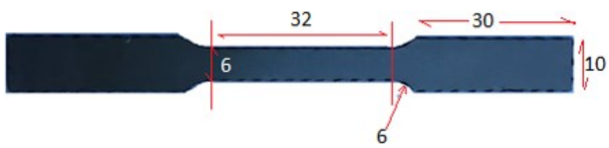

Fig. 1. Tensile test sample.

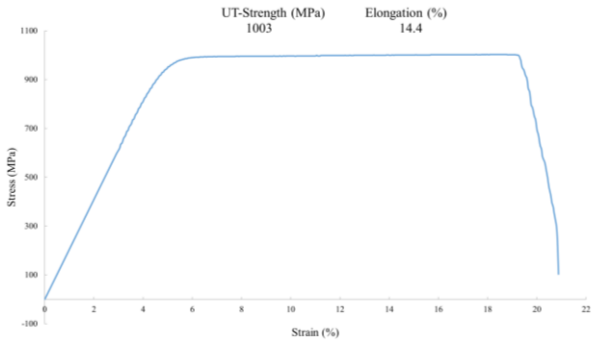

Fig. 2. Result of tensile test.

reported. For this purpose, the influence of pin velocity, weight and path length was investigated on the amount of metal wear using a pin-on-sheet test. To conduct this test on the sheets, they were prepared in a reciprocating motion path according to Fig. 4 with dimensions of 65 by 10 millimeters. The used pin in this study was in accordance with Fig. 5, and for each test, a new pin was used to prevent the influence of pin wear on the results.

2.2. Design of experiment

The Design of the experiment is an appropriate method for obtaining accurate information about the under-study factors and their impact on the results with the minimum number of tests. Nowadays, this method is widely used to reduce costs and obtain precise and practical information about various processes. In this method, the maximum amount of information is obtained with the minimum number of experiments. Using these methods helps reduce the cost of empirical testing and saves time. In this study, to investigate the effect of initial parameters (Table 1) on the amount of wear, a series of experiments were designed using the central composite design method, which is a set of

Fig. 3. Wear testing machine.

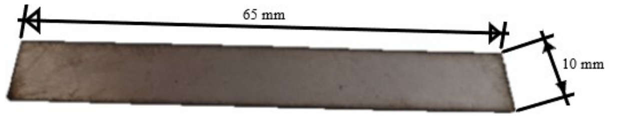

Fig. 4. Wear test sample.

Fig. 5. Wear testing pin.

response surface methods.

The range of initial parameters is based on previous studies and available equipment. Additionally, in order to obtain optimal results, some tests were conducted under critical conditions. For example, a path length of 500 meters was used, and the results can be observed in Fig. 6. The experimental design table (Table 2) used in this experiment consists of 20 tests designed according to the response surface methodology.

Table 1. The initial parameters

Factor	Name	Units	Type	Subtype	Minimum	Maximum
A	Force	kg	Numeric	Continuous	0.4	20
B	Speed	m/s			0.1	0.2
C	Path length	m			50	700

2.3. Results of wear measurement

The designed tests in the previous step were performed separately on the prepared samples for each test. As seen in Fig. 7, a wear measuring device was used to measure the amount of wear. This device includes a pin that moves back and forth on the sheet based on the defined parameters in each test to check the amount of wear.

Fig. 6. Influence of path length of 500 m on the metal friction.

Table 2. The design of experiments results

Run	A: Force (kg)	B: Speed (m/s)	C: Path length (m)
1	10.2	0.2	375
2	0.4	0.1	700
3	10.2	0.15	375
4	20	0.15	375
5	10.2	0.15	375
6	20	0.2	700
7	10.2	0.15	700
8	0.4	0.2	50
9	0.4	0.15	375
10	10.2	0.15	375
11	10.2	0.15	375
12	0.4	0.2	700
13	20	0.2	50
14	20	0.1	700
15	10.2	0.15	375
16	20	0.1	50
17	0.4	0.1	50
18	10.2	0.15	50
19	10.2	0.1	375
20	10.2	0.15	375

The wear measurement results are reported in Table 3. The resulting graph for some tests can be seen in Fig. 7.

3. Results and Discussion

3.1. Analysis of variance

The analysis of variance for the measured wear is shown in Table 4. In this table the significance of each variable is shown through the P-value, which measures the deviation of the data from the mean. Parameters that have a P-value less than 0.05 are considered influential and significant.

Examining the P-value for wear is an indicator of the validity of the proposed model in this study. Initially, the model is tested without any changes. The results of the analysis of variance can be observed in Table 4. The results suggest that although the model is acceptable in terms of the variance test, some parameters are not acceptable. To further investigate this experiment using software, it is better to perform the variance test again and eliminate the non-significant parameters. The results of the re-examined variance test can be seen in Table 5.

In this model, all the main factors are significant. According to the results, speed, path length and weight have the greatest impact on the amount of wear, respectively. It is also important to mention that among the interaction effects, the interaction between velocity and weight has the most significant effect on wear. Another useful tool for statistical validation is residual plots, as shown in Fig. 8. These plots indicate the normality of the data and whether they adhere to a specific relationship.

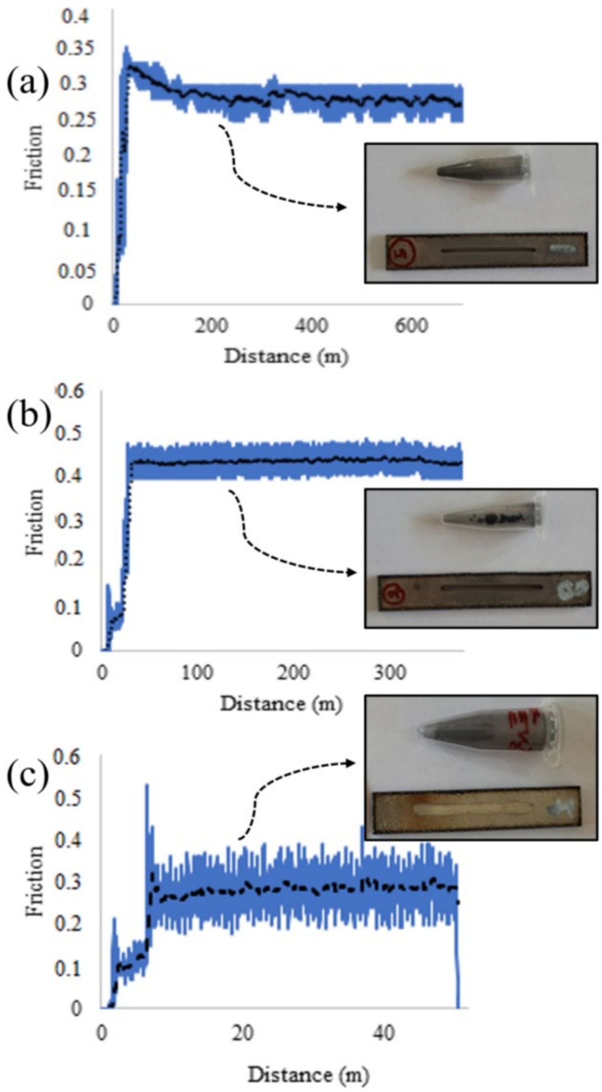

Fig. 7. Results of friction coefficient measurements and Influence of input parameters on the sheets of (a) sample 19, (b) sample 9 and (c) sample 18.

Table 3. The measured friction coefficient

Run	Friction coefficient
1	0.318614
2	0.424352
3	0.292295
4	0.436702
5	0.292275
6	0.438635
7	0.379385
8	0.459913
9	0.423535
10	0.292275
11	0.292275
12	0.789866
13	0.226186
14	0.300381
15	0.292275
16	0.221701
17	0.214640
18	0.256380
19	0.287974
20	0.292275

3.2. Regression equation

A regression equation is used to predict wear values based on the given influential parameters. The values and coefficients of the variables in the model equation indicate the magnitude and impact of these variables. The desired wear results can be obtained without conducting experiments using these models. These models can be used to make the necessary predictions for conducting experiments.

Final Equation in Terms of Coded Factors :

$$\text{Friction coefficient} = +0.2996 - 0.0689A + 0.0784B + 0.0954C - 0.0585AB + 0.0940\,A^2 \quad \textbf{(1)}$$

Final Equation in Terms of Actual Factors :

$$\text{Friction coefficient} = -0.054884 - 0.009082\,\text{force} + 2.78621\,\text{speed} + 0.000293\,\text{path length} - 0.119400\,\text{force*speed} + 0.000979\,\text{force}^2 \quad \textbf{(2)}$$

Table 4. The analysis of variance

Source	Sum of squares	df	Mean square	F-value	P-value	
Model	0.2886	9	0.0321	10.68	0.0005	Significant
A-force (kg)	0.0474	1	0.0474	15.79	0.0026	
B-speed (m/s)	0.0615	1	0.0615	20.48	0.0011	
C-path length (m)	0.0910	1	0.0910	30.29	0.0003	
AB	0.0274	1	0.0274	9.12	0.0129	
AC	0.0077	1	0.0077	2.57	0.1399	
BC	0.0081	1	0.0081	2.69	0.1323	
A^2	0.0320	1	0.0320	10.66	0.0085	
B^2	0.0010	1	0.0010	0.3272	0.5799	
C^2	0.0001	1	0.0001	0.0171	0.8987	
Residual	0.0300	10	0.0030			
Lack of fit	0.0300	5	0.0060	9.010E+07	< 0.0001	Significant
Pure error	3.333E-10	5	6.667E-11			
Cor total	0.3187	19				

Table 5. The repeated analysis of variance

Source	Sum of squares	df	Mean square	F-value	P-value	
Model	0.2714	5	0.0543	16.10	< 0.0001	Significant
A-force (kg)	0.0474	1	0.0474	14.06	0.0022	
B-speed (m/s)	0.0615	1	0.0615	18.23	0.0008	
C-path length (m)	0.0910	1	0.0910	26.97	0.0001	
AB	0.0274	1	0.0274	8.12	0.0129	
A^2	0.0442	1	0.0442	13.10	0.0028	
Residual	0.0472	14	0.0034			
Lack of fit	0.0472	9	0.0052	7.870E+07	< 0.0001	Significant
Pure error	3.333E-10	5	6.667E-11			
Cor total	0.3187	19				

3.3. Investigating the effect of main factors on friction coefficient

The effects of the main factors on wear are graphically shown in Fig. 9. According to the graphs, the overall wear rate decreases by increasing the weight. Increasing the path length and the speed of the pin movement leads to an increase in wear. Increasing the path length results in more interaction between the two moving bodies. This increase leads to higher pressure on the two bodies, as well as heat generation and sticking of the two surfaces. This results in an increase in the parallel force with the surface and an increase in the wear rate. It is also important to note that, based on the tensile test conducted, this material does not become hard and therefore an increase in path length can increase the wear rate due to the lack of hardening. Increasing the speed also leads to increased contact, temperature, and an overall increase in wear rate due to plastic deformation on the surfaces. Increasing the weight initially causes a decrease and then an increase in the overall friction coefficient. The trend of decrease and increase in the friction coefficient is because after a certain weight, the pin sinks into the material, and this leads to an increase in the friction coefficient. The overall decrease in the friction coefficient with increasing weight is due to the increase in the contact surface area between the pin and the plate and a decrease in pressure.

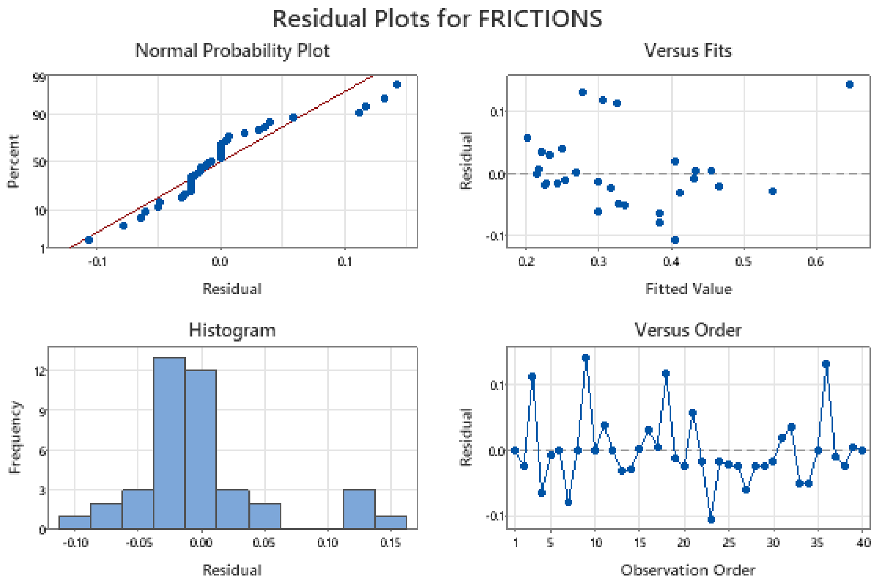

Fig. 8. Residual plots for design experiments.

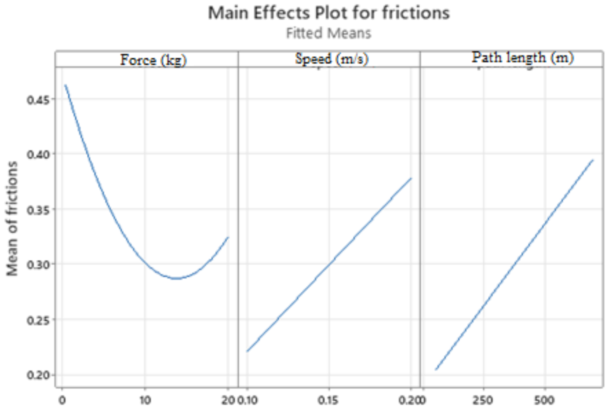

Fig. 9. Main effects plots.

3.4. Interaction between the main factors

The interaction between the parameters can be observed in Fig. 10. These graphs show the interaction of the parameters on the wear rate. The results of the investigation of the interaction effects of the input parameters on the friction coefficient are as follows:

The examination of the graphs indicates that weight and speed have an interactive effect that can be studied. Furthermore, the graphs indicate that the parameters of weight and path length, as well as speed and path length, do not have an interactive effect. The three-dimensional interactive effect can be observed in Fig. 11, which shows the influence of the parameters of speed and weight on wear. As can be seen, the friction coefficient increases with increasing speed. With an increase in weight from 0 to 10 kg, the coefficient of friction decreases, and with an increase in weight from 10 to 20 kg, the coefficient of friction increases. It is also worth

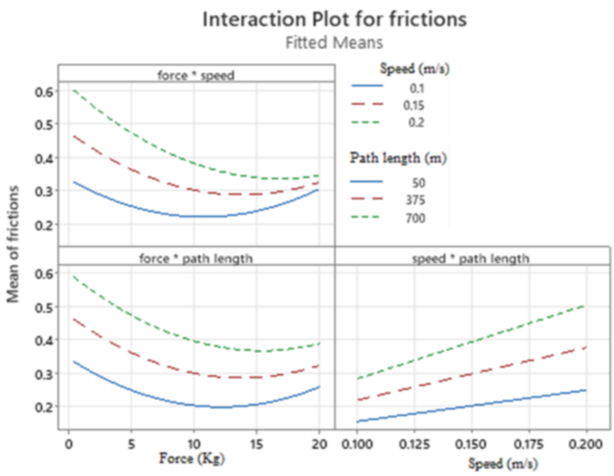

Fig. 10. Interaction plot.

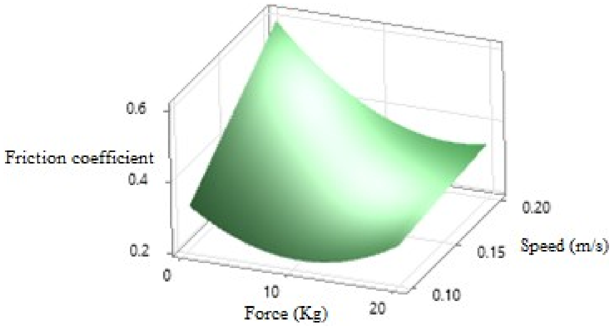

Fig. 11. Interaction curve between speed and force.

noting that these two parameters have a mutual effect and by increasing speed and also reducing weight. The amount of wear coefficient sharply increases.

3.5. Optimization

The purpose of optimization in this study is to investigate the initial parameters to minimize the wear rate. The maximum and minimum measured wear values are used for designing the experiments, as shown in Table 6.

The wear of metals is one of the important parameters in examining the useful life of components. The optimal conditions for the performance of the components are determined by selecting the minimum wear of metals. The results of the optimization process indicate that the optimal condition occurs when the weight is at its minimum value of 318.2072 kg, the speed is at its minimum value of 0.9546 m/s, and the path length is 2356.7439 m.

3.6. Simulation

In this study, the finite element software was used to simulate the wear test. For this purpose, a pin and a corresponding plate were designed in the "Part" section to match the real geometry used in the experiments. The specifications of the plate, corresponding to Fig. 3, were entered in the "Property" section, and in the assembly module, the components were positioned relative to each other (Fig. 12). In this figure, the sheet and the pin are drawn as they happened in reality on a pot. The pin is placed on the sheet in the illustrated manner and the test is then performed. After positioning the components relative to each other, the problem-solving

Table 6. The minimum and maximum measured friction coefficient

Name	Goal	Lower limit	Upper limit	Lower weight	Upper weight	Importance
A: Force (kg)	in range	0.4	20	1	1	3
B: Speed (m/s)	in range	0.1	0.2	1	1	3
C: Path length (m)	in range	50	700	1	1	3
Friction coefficient	Minimize	0.21464	0.789866	1	1	3

methodology in the "Step" module is defined as Dynamic, Temperature-displacement, Explicit. In the "Interaction" module, the surfaces and frictional connections between them are specified. In the "Load" module, the loading conditions and boundary conditions are determined. In this problem, the metal plate is fixed without moving in all three directions, and back-and-forth motion along the length of the plate is applied based on reality (which is achieved by defining a motion domain for the length direction). It is important to note that the initial temperature of all components is considered to be the ambient temperature at this stage. The C3D8T element type is used in the "Mesh" module, and the library used for this analysis is Coupled Temperature-Displacement. After meshing the components, the analysis is performed.

In this section, the surface view of the plate is shown after the pin moves along its length in the displayed figure. As expected, with the movement of the pin along the plate, the temperature of the plate's surface increases, indicated by the red coloration of the plate's surface. Over time, as it enters the plastic deformation zone, the shape of the plate changes, and surface wear begins (Fig. 13).

For one of the conducted tests in the design of experiments (Test No. 13), finite element simulation was performed, and the comparison results can be observed in Fig. 14.

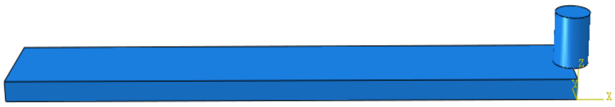

Fig. 12. Friction simulation.

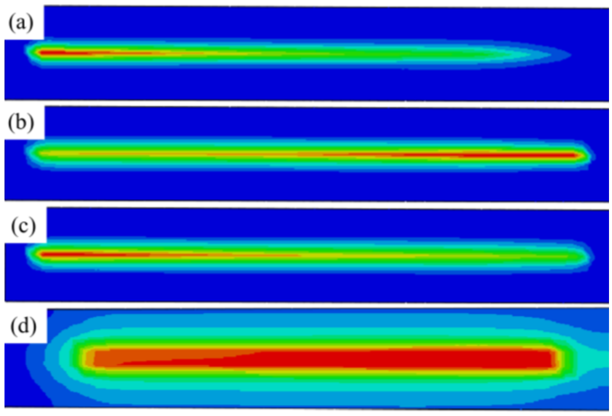

Fig. 13. Results of friction simulations; (a) the effect of the first movement of the pin on the sheet, (b) return of the pin to the starting point on the sheet, (c) the effect of continued movement and (d) the end of the movement of the pin on the sheet and its effect on the amount of friction.

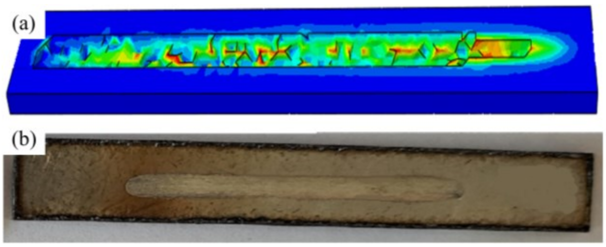

Fig. 14. Influence of input parameters on the machining forces optimization (a) simulation and (b) experimental test.

4. Conclusion

The purpose of this study is to investigate and optimize the metal friction of the AISI 631 plate to reduce failures and costs. The results are as follows.

- In the AISI 631 sample, as shown in the stress-strain diagram, the hardness did not increase by increasing the elongation neither did the force nor the stress.
- The tensile test results show that the used sheet in this study is not subjected to stain hardening. UTS of this sheet is 1003 MPa and its elongation is 14.4 %.
- Increasing the path length results in an increase in the friction coefficient in this metal.
- Increasing the speed of the pin movement on the surface increases the friction coefficient.
- Increasing the weight up to 10 kilograms reduces the friction coefficient, and from 10 to 20 kilograms, it increases.
- The ANOVA test results indicate the acceptability of the parameters, and the experiment has been conducted accordingly.
- The results of the experimental design operations indicate that the speed of the pin movement, followed by the path length, and then the weight has the greatest impact on the friction coefficient.

Conflict of Interests

The authors declare no conflict of interest in this research.

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