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The Effect of Drill Bit Features on Surface Quality, Drill Wear and Drilling Cost - Sustainable Drilling

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In drilling operations, hole quality is affected by factors such as drill diameter, drilling parameters, drill bit properties, workpiece material. A large portion of the drilling energy is converted into thermal energy, which can be measured as temperature. In this study, surface roughness of holes, drill tip wear and drill tip temperatures were determined using two different workpiece materials and three different drill tips. Furthermore, the costs of holes drilled with different drill bits were determined and interpreted based on drill bit characteristics. The results obtained can be optimized according to the process parameters and it has been shown that a more sustainable and much more economical manufacturing can be achieved by avoiding the use of additional reaming or internal grinding for the desired surface quality and eliminating negative environmental effects.

Keywords: Hole surface roughness, Drill bit temperature, Drill wear, Hole cost

1 Introduction

In the manufacturing industry, the drilling method is inevitable for the parts produced to be assembled and realized as an industrial product. In this context, hole drilling applications constitute 35% of all machining methods. Drilling parameters, drill bit properties and workpiece properties directly affect hole surface quality. The manufacturing characteristics of the drill bit, just like the drill bit geometry, also have an effect on the hole surface quality. In this study, 20 mm thick steel and aluminum workpiece plates were drilled with drill bits having different production properties and the effects on hole quality and drill bit wear were investigated. The effect of different drill bits with different manufacturing characteristics on the hole surface roughness at the hole entrance and hole exit was determined. Drilling energy depends on the cutting speed, feed rate, drill bit geometry and properties, as well as the workpiece material. In the study, drill bit temperatures were determined and interpreted according to drill types in drilling operations. Drill bit wear is an indicator of drill bit life. In this regard, the wear amounts of drill bits were measured and the cost effect per hole was determined depending on the tool life.

2 Literature Review

It is known that machining quality generally increases with increasing cutting speed. Accordingly, increasing cutting speed can provide better hole surface quality. However, it is also revealed in the literature [1] that high cutting speeds negatively affect hole cylindricity. It is seen in the literature that when drilling steel workpieces with coated drill bits, the hole surface roughness increases by 45% to 55% as the feed rate increases two or three times [2, 3]. According to the literature [3], when the hole depth increases two times at the same cutting and feed rate value, the hole surface roughness increases by 70%. In addition to reducing production costs and improving part quality by minimizing errors, appropriate parameters must be determined for sustainable production [4]. Surface roughness, an indicator of part quality, decreases with increasing cutting speed [4]. In the drilling process of a unalloyed steel workpiece with drill bits of different diameters and different point angles [5], it has been shown that the surface roughness decreases with increasing cutting speed and drill point angle, and the surface roughness increases with increasing drill diameter. Increased feed rate decreases surface quality. In steel material drilling [6], if there is a 50% increase in feed rate, the surface roughness increases by approximately 30%. It has been stated in the literature that in drilling operations with drill bits of different diameters [7, 8, 9], the surface quality of the hole surface deteriorates with the increase in feed rate and the surface roughness at the hole exit increases in all experiments. In other studies on drilling a stainless steel workpiece [10, 11, 12], it was stated that tool life decreased when the cutting speed or feed rate increased. The studies also stated that when the cutting speed was increased, the surface roughness quality of the holes increased, thus achieving better surface quality. Coated cutting tools have a positive effect on the workpiece surface quality due to their low surface friction coefficient. It has been noted in the literature that TiN coated drill bits produce approximately 23% better surface quality than other drill bits under the same drilling conditions [13]. It has been noted that coated drill bits produce less surface roughness, that increasing the feed rate increases surface roughness, and that coated drill bits provide three times longer tool life than uncoated drill bits [13]. Although it is known that there is more tool wear as the cutting speed increases, the amount of drill bit wear is presented quantitatively with the increase in cutting speed [14]. In the manufacturing industry, aluminum alloy workpieces are used as much as steel workpieces. It is stated that when three consecutive holes are drilled in an aluminum alloy workpiece, the surface roughness increases by 25% compared to when a single hole is drilled with an HSS drill bit, and the increase in surface roughness is due to tool wear [15]. In drilling an aluminum workpiece with TiN-coated HSS drill bits with different point angles [16], it was reported that the surface roughness increased fourfold when the cutting speed was increased twofold. In another study on this subject, [17], it was observed that when the feed rate was increased by 70%, the surface roughness increased two-fold. Compared to other drilling parameters, feed rate has the greatest effect on surface roughness [18,19]. In the research conducted on different aluminum materials used in the automotive and aviation industries, at different feed rates and different cutting speeds [19], hole surface roughness values were optimized and presented. It is stated that when the cutting speed is increased by 50% and the feed rate is increased by 2.5 times in the drilling of the aluminum workpiece with a HSS drill bit [20], a 166% change in the surface roughness value occurs. In another study, it was noted that when the cutting speed was increased by 60% and the feed was tripled, the hole surface roughness value increased threefold [21]. Under the same drilling conditions, hard metal drill bits appear to produce better hole surface quality than HSS drill bits. In the studies, it was observed that increasing the cutting speed decreased the hole surface roughness, while increasing the feed rate increased the hole surface roughness. As is known, the increase in feed rate increases the surface roughness. It is seen that tool wear also affects the surface roughness. Of course, a new sharp drill bit produces less surface roughness than a worn drill bit. In the literature, it is seen that high cutting speed and low feed rate are recommended to obtain better hole surface quality in drilling.

It is stated that when drilling a steel workpiece with a TiN coated carbide drill bit, the drill bit temperature is significantly affected by the drilling depth and cutting speed, while the feed rate does not have a significant effect [22]. In a study on temperature determination in drilling [23], a temperature of about 500°C was measured when drilling a tool steel workpiece with a 12 mm diameter carbide drill bit at a cutting speed of 100 m/min. In another study, it was stated that when drilling a stainless steel workpiece with HSS drill bits at different point angles, the drilling temperature increased as both the cutting speed and feed rate increased, and the highest drilling temperature was measured as 500°C when a 118° drill bit was used [24, 25]. In drilling operations, while high cutting speed and feed increase production, it also creates high cutting temperature. In dry drilling, high cutting temperature not only reduces dimensional accuracy and tool life, but also negatively affects the cylindricality of the hole. It is stated that as the feed rate increases, there is a maximum metal removal rate that helps to dissipate the maximum heat produced [26, 27].

In this study, workpieces made of two different materials were drilled with drill bits of three different specifications and their effects on hole surface roughness, drill bit wear and hole cost were investigated. Additionally, thermal values resulting from drill bit manufacturing features were measured and presented. The originality of the study is to investigate the effects of HSS drill bits, production features (coated, rolled, ground) on hole surface quality and tool life, to examine hole costs, and to ensure sustainable manufacturing by making more economical choices according to the expected surface quality.

3 Experimental Studies

Drilling operations were performed on a FIRST MCV300 CNC machining centre. Figure 1 shows the experimental design and experiment flow schematically. The drill bits used in the experimental studies are shown in Fig. 1(a), and the workpieces are shown in Fig. 1(b). To measure the temperature of the drill bits, a non-contact laser temperature measuring device, shown in Figure 1(c), was used. The CNC Machining Center where the work pieces and drill bits were placed and the experimental studies were carried out is shown in Fig. 1(d). After the drilling operations, the drill bits were transferred to the microscope seen in Fig. 1(e) to measure the drill wear, and the drilled parts were transferred to the surface roughness tester seen in Fig. 1(f) to measure the hole surface roughness. During the experiments, the temperature of the drill bits was measured with a laser measuring system focused on the hole exit, as shown in Fig. 1(g). Table 1 shows the general properties, standards (ISO 235/DIN 338) and appearances of the drill bits used in the experiments. In the experiments carried out without cutting fluid, three different types (rolled, polished, coated) HSS spiral drill bits with diameters of 8 mm and 10 mm were used. One of the workpieces used in the experimental studies was mild steel (AISI 1040). This steel is used in many different industries due to its medium strength and good forming properties. Thanks to its chemical composition, it provides a good balance between hardness, strength and machinability, and thanks to its mechanical properties, it offers high performance in parts that can be produced in various shapes and sizes.

This steel, which is widely used in parts requiring hardness and tensile strength thanks to its medium carbon content, is used in many sectors from automotive to construction.

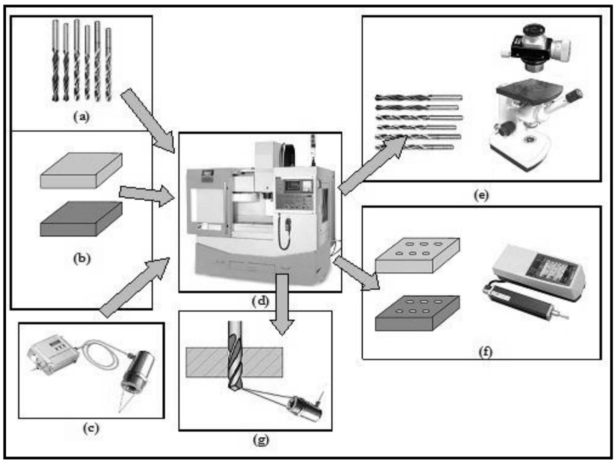


Fig. 1 *Schematic experimental design, experimental set-up and flowchart*

Tab. 1 *Features and standards of spiral drill bits used in experiments*

Wiews of drill bits	Properties of drill bits
	Rolled drill bits (N type - ISO 235) (Ø8 mm - Ø10 mm)
	Polished drill bits (N type - ISO 235) (Ø8 mm - Ø10 mm)
	TiN Coated drill bits (N type - ISO 235) (Ø8 mm - Ø10 mm)

Common areas of use are in the automotive industry, automotive components such as structural parts, gears, shafts. Another workpiece used in experimental studies was 7075-T6 type aluminum alloy. Since the main alloying element of this material is zinc, it gives it higher strength and higher strength-to-weight ratio. This material is characterized by its high strength, hardness and high fatigue strength. However, its machinability is somewhat more difficult than other aluminum alloys due to its higher strength. It is the lightest and strongest aluminum alloy, as strong as steel with good fatigue strength. This aluminum alloy is preferred and widely used in high strength constructions, aerospace and defence industries. In the experimental studies, AISI 1040 steel and 7075-T6 aluminum alloy were preferred as the workpiece material and their chemical compositions and mechanical properties are given in Table 2. Depending on the drill bit features and considering the relevant literature [2, 5, 13, 15, 16, 18, 21, 22], the feed rate was selected as constant 0.1 mm/rev and the cutting speeds were selected suitable to the material of the workpieces. Coated drill bits are recommended to be used at higher speeds than uncoated ones due to their higher performance. Under normal conditions, the cutting speed of coated tools can be increased by several times compared to uncoated tools, but the reason for the increase of approximately 25% in this study is that the industrial applications of this research can be done mostly on drill presses, not on machining centres.

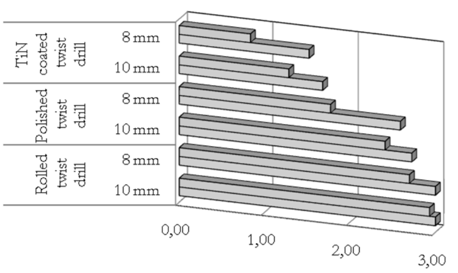
Tab. 2 *Chemical composition and mechanical properties of mild steel and aluminum alloy used in experiments*

Chemical composition of AISI1040				
C(%)	Fe(%)	Mn(%)	P(%)	S(%)
0.37	98.6	0.60	<0.04	<0.05
Chemical composition of 7075-T6				
Al(%)	Cr(%)	Cu(%)	Mg(%)	Zn(%)
87,1	0.18	1.2	2,1	5,1
Mechanical properties of materials				
	Tensile strength (MPa)	**Yield strength (MPa)**	**Hardness**	
AISI1040	525	290	155 (HV)	
7075-T6	462	385	135 (HB)	

3.1 Surface Roughness of the Holes

In drilling operations, the hole depth (thickness of the workpieces) was selected as 20 mm. A new drill bit was used in each experiment. The surface roughness of the holes was measured several times and the average value was determined. The surface roughness values of the holes (as arithmetic mean) were measured with a Mitutoyo SJ-210R Surface Roughness Tester. Hole surface roughness measurements were made at the hole entrance and hole exit to determine the effects of drilling parameters and drill bit wear. The thickness of the test pieces was 20 mm and the hole surface roughness was measured at a distance of 5 mm from the drill inlet and outlet. The surface roughness values obtained depending on the drill diameter, feature (rolled, polished, TiN coated) and workpiece material are shown graphically in Fig. 2 and Fig.3. Surface roughness values measured in steel workpiece holes are shown in Fig.2.

Hole Surface Roughness (μm-AISI 1040)

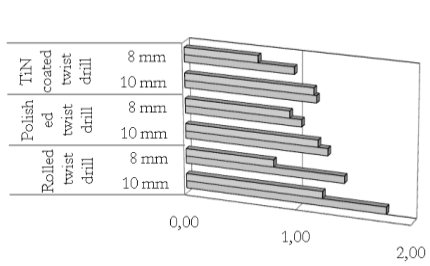


	Rolled twist drill		Polished twist drill		TiN coated twist drill	
	10 mm	8 mm	10 mm	8 mm	10 mm	8 mm
Hole entry	2,93	2,70	2,41	1,77	1,28	0,84
Hole exit	3,16	3,10	2,72	2,59	1,68	1,52

Surface Roughness (μm)

Fig. 2 *Surface quality obtained on steel workpiece with drills of different properties*

Hole Surface Roughness (μm-7075-T6)



	Rolled twist drill		Polished twist drill		TiN coated twist drill	
	10 mm	8 mm	10 mm	8 mm	10 mm	8 mm
Hole entry	1,218	0,786	1,178	0,930	1,140	0,655
Hole exit	1,773	1,408	1,264	1,034	1,164	0,970

Surface Roghness (μm)

Fig. 3 *Surface quality obtained on 7075-T6 aluminum workpiece with drills of different properties*

In the 7075-T6 aluminum alloy workpiece drilled with drill bits of different diameters and features, the lowest surface roughness at both the hole entrance and the hole exit was achieved with TiN coated drill bits, as seen in Figure 3.

For each diameter, the best hole surface quality was obtained with the use of TiN coated HSS drill bits. It is seen that the coating material contributes positively not only to the wear resistance of the drill bit but also to the hole surface roughness. It can be stated that better surface quality is achieved due to the low friction coefficient of the coating material and its facilitation of chip flow. In all drilling operations, it was observed that as the drill diameter increased in all drill bit types, the surface roughness at the hole exit increased.

It is stated in the literature [5] that the hole surface roughness increases with the increase in drill diameter. The hole surface roughness values measured as a result of this study are quite consistent with the relevant literature. In addition, it is stated in the literature [15, 20] that under all experimental conditions, greater surface roughness occurs at the hole exit. The results are also consistent with the literature [15, 20] in this respect.

It is stated in the literature [15] that the surface quality at the hole exit is 35-50% worse than at the hole entrance. Towards the end of the hole, due to the compression and/or friction of the chip inside the hole being drilled and the rapid initial wear zone of the drill bit, the surface quality at the hole exit is relatively worse.

In this study, it was observed that coated drill bits produced better hole surface roughness than uncoated drill bits, which is quite consistent with the relevant literature [20].

3.2 Wear of Drill Bits

After the experiments, the wear of the drill bits was measured according to the ISO 1993:3685 standard. To measure the wear of the drill bits, a workshop microscope with a precision ocular micrometer was used. Figure 4 shows the wear values measured on the drill bits. Minimum wear was determined in TiN coated drill bits used in drilling steel workpiece. As is known, TiN coating increases wear resistance. It was observed that in drill bits of all diameters with different properties, the least wear occurred in the TiN coated one, followed by the rolled drill bit. The results are also consistent with the literature [8] in this respect. In this study, it is thought that the reason why the highest wear is seen in polished HSS drill bits is that the sharper cutting edges wear out very quickly compared to the other drill bits. It is thought that the reason for the high wear in polished HSS drill bits, which have sharper cutting edges compared to other drill bits, is that wear occurs much faster than others. It is observed that the drill bit wear values measured in the study are compatible with the relevant literature. Also, it is stated in the relevant literature [13] that a coated drill bit provides approximately three times longer tool life than an uncoated drill bit. Since the hardnesses of the two metal materials used in this study are close to each other, the machinability of the 7075-T6 aluminum material is not very good, and it creates drill bit wear almost as much as drill bit wear in steel materials

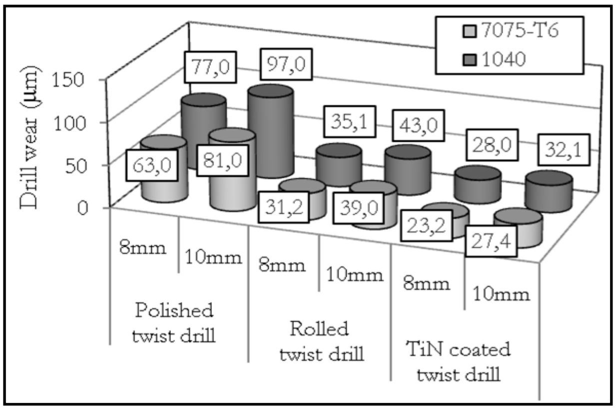


Fig. 4 *Wear values measured on drill bits*

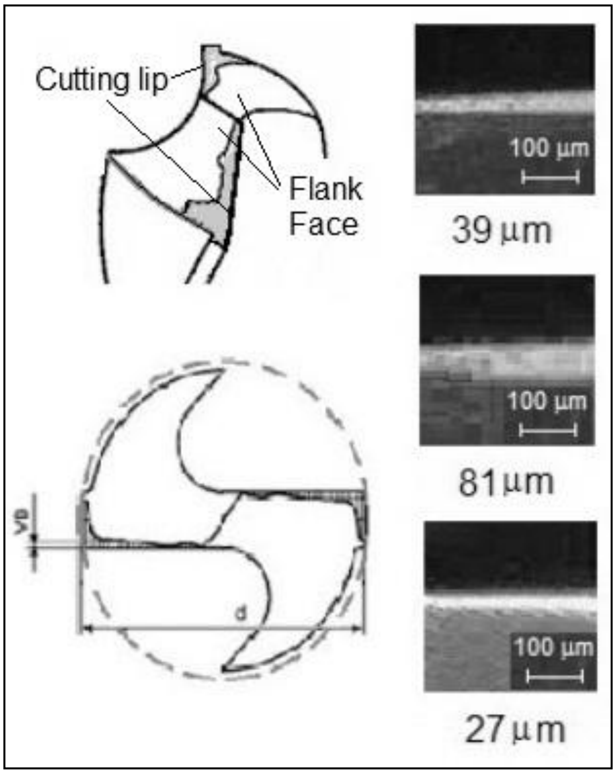


Fig. 5 *Wear images of drill bits with different properties*

7075 is an aluminum alloy containing zinc as the main alloying element. 7075 aluminum alloy material has excellent mechanical properties that provide high strength, high toughness and high fatigue resistance. This material has relatively less ductility and greater strength due to heat treatment, however, microsegregation makes it more brittle than many other aluminum alloys. These features make the hardness value of the 7075 aluminum alloy material close to mild steel. In the literature [14], when a mild steel workpiece is drilled, a drill tip wear value of 30 µm for a 5 mm diameter speed steel drill bit and 190 µm for a 12 mm diameter drill bit is noted. It is stated that the drill tip wear value increases as the drill tip diameter increases. It is seen that the drill bit wear values measured in this study are in good agreement with the literature [14]. The measurement of the average width of the wear area was made according to the ISO 1993:3685 standard. The wear images of drilling Al 7075 material with 10 mm diameter drill bits with different features are given in Figure 5.

Cost values based on unit drill bit wear according to drill type are given in Fig.6. As expected, the most drill wear is seen in polished drill bits, while the least drill wear is seen in coated drill bits.

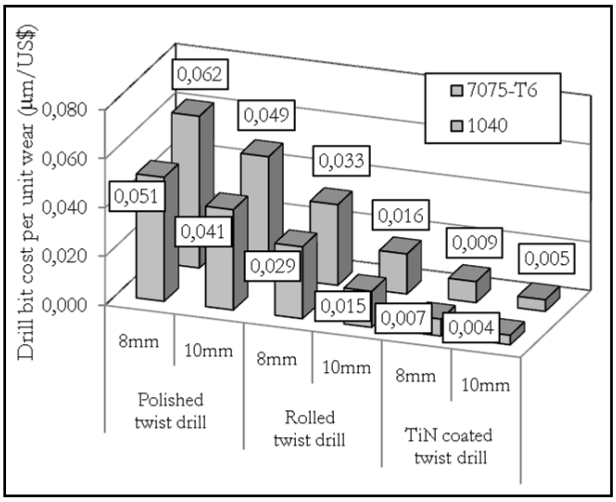


Fig. 6 *Cost variation due to wear depending on drill type*

Compared to the cost of rolled drill bits, which are much more widely preferred and used in the manufacturing industry around the world, polished drill bits are generally 1.17 times more expensive, while coated drill bits are 2.82 times more expensive. Considering these purchasing costs, the unit wear cost for rolled drill bits is $0.023, $0.050 for polished drill bits, and $0.006 for TiN-coated drill bits, as seen in Fig.6. For hole cost, the selection of TiN coated, polished or rolled drill bit is an important criterion. Based on the amount of wear that occurs relative to the Material Removal Rate (MRR), an estimate can be made for possible tool life and drill cost.

In this case, by making a cost analysis according to the desired surface quality and the amount of wear, by selecting the appropriate drill bit, by using a longer bit without the need for reaming and grinding inside the hole, sustainable manufacturing and green manufacturing can be achieved.

3.3 Drilling Temperature

During the experiments, the temperature of the drill bits was measured with a laser measuring system focused on the hole exit, as shown in Figure 1. Optis brand CT laser LT model non-contact temperature measuring device was used to measure the temperature of the drill bits. The sensitivity of the non-contact temperature measuring device is 0.1 °C and the temperature measuring range is between -50 °C and +975 °C.

During drilling, as a result of the energy transfer of mechanical energy to heat energy, the temperature values measured at the drill bits are given in Fig.7. It is seen that the temperature change rates vary between 2.1% and 3.2% for 8 mm and 10 mm drill bits.

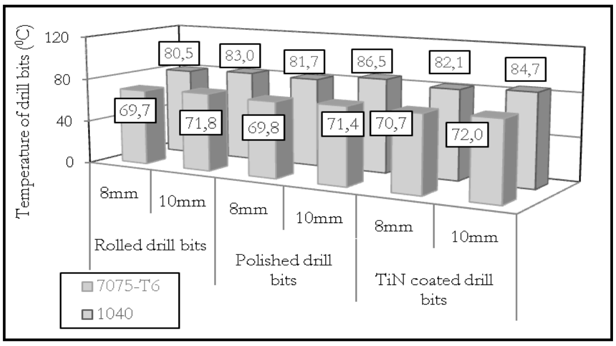


Fig. 7 *The measured temperature values of the drill bits*

Depending on the thermal conductivity values of the materials, there is a difference in the heat transfer to the cutting tool. In materials that can transfer heat well, the cutting tool temperature is lower. In addition, the low forming resistance also causes the formation of lower heat energy. In the literature, it is stated that approximately 10% of the total amount of heat generated during cutting is transferred to the cutting tool [28]. It is seen that the rate of temperature difference detected in the drilling of steel and aluminum materials is 18%. Due to the low forming resistance of the aluminum material and the higher thermal conductivity value than the steel, the temperature values are generally lower. In the literature, it is stated that If the drill diameter increases by 25%, the force requirement increases by 25%, and accordingly the power requirement increases at the same rate [29]. About 10% of the cutting energy is converted into heat energy. In general, approximately 10% of the heat generated during the cutting process is transferred to the cutting tool [28]. The difference in temperature values measured due to a 25% change in drill bit diameter is consistent with the literature.

4 Results and Discussions

In this study, the effects of drill bit properties on the surface roughness at the hole entrance and hole exit in dry drilling of steel and aluminum workpieces, as well as hole cost analysis depending on the wear of drill bits, were performed. In the study, workpiece materials commonly used in the manufacturing industry were preferred. Experimental conditions were determined according to relevant literature and industrial application conditions. Considering the averages of the surface roughness values determined at the hole entrance and exit, the following results were obtained.

- It was observed that when the steel workpiece was drilled with a coated drill bit of 8 mm diameter, the hole surface quality was 59.3% better than the rolled drill bit and 46% better than the polished drill bit; and when it was drilled with a coated drill bit of 10 mm diameter, the hole surface quality was 51.3% better than the rolled drill bit and 42.27% better than the polished drill bit.
- It was observed that when the aluminum workpiece was drilled with a coated drill bit of 8 mm diameter, the hole surface quality was 25.9% better than the rolled drill bit and 17.3% better than the polished drill bit; and when it was drilled with a coated drill bit of 10 mm diameter, the hole surface quality was 22.9% better than the rolled drill bit and 5.65% better than the polished drill bit.

In the study, it was determined that the hole surface quality decreased as the drill bit diameter increased, regardless of the workpiece material, in accordance with the literature.

In the experiments, the following results were obtained and interpreted by measuring the wear of the drill bits.

- In drilling a steel workpiece, it is observed that the 8 mm diameter coated drill bit shows 20.23% less wear than the rolled drill bit and 63.64% less wear than the polished drill bit. In drilling with a 10 mm diameter coated drill bit, it is observed that it shows 25.35% less wear than the rolled drill bit and 66.91% less wear than the polished drill bit.
- Drilling an aluminum workpiece with an 8 mm diameter coated drill bit resulted in 25.64% less drill bit wear compared to a rolled drill bit and 63.17% less drill bit wear compared to a polished drill bit. Drilling with a 10 mm diameter coated drill bit resulted in 29.74% less drill bit wear compared to rolled drill bits and 66.17% less drill bit wear

compared to polished drill bits. Consistent with the literature, drill bit wear increases with increasing drill bit diameter.

In drilling both workpieces, the best surface quality was achieved with TiN coated drill bits and minimum drill tip wear was observed with TiN coated drill bits. TiN coated drill bits provide advantages in terms of production costs thanks to their low wear values as well as high cutting speeds.

However, it should not be ignored that drilling aluminum workpieces with coated drill bits may cause negative results in the long term due to the reaction of the coating material with the workpiece material. According to the preferred process parameters, the results obtained can be optimized and it has been shown that a more sustainable manufacturing can be implemented by avoiding the use of additional reaming or internal grinding for the desired surface quality, eliminating negative environmental effects. Thus, green manufacturing and more sustainable manufacturing will be possible.

According to the literature, it is known that if the drill diameter increases by 25%, the force requirement increases by 25% and accordingly the power requirement increases at the same rate. Based on this energy balance, if 10% of the 25% rate is transferred to the cutting tool, the experimental results are quite consistent with the literature, since there is an average 2.5% rate between the measured temperature values. In this context, in future studies, the energy transfer phenomenon in the drilling process can be demonstrated in detail by using different cutting tool materials and different workpiece materials, by making calorimetric measurements as well as force and moment measurements.

According to market research companies [30], in 2020, the global expenditure on drill bits was $88 million, compared to $84 million on reamers.

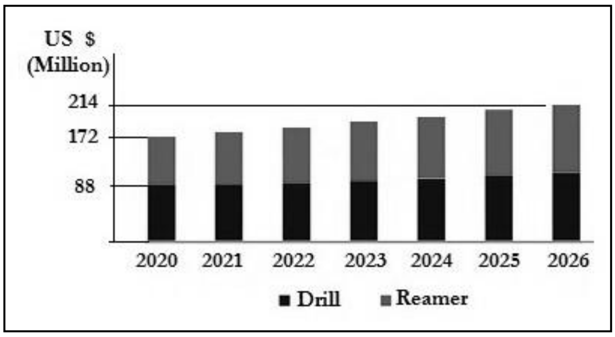


Fig. 8 *Drill bit and Reamer Market*

According to 2026 projections from market research companies, drill bit and reamer expenditures will each amount to approximately $107 million, as shown in Fig.8. Drilling operations are known to account for approximately 35% of the total manufacturing sector, as this is also noted in this study. In this case, if holes are created under suitable conditions and to the required quality (surface quality and circularity), reaming or internal grinding will not be required, resulting in more economical and sustainable manufacturing.

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