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RESEARCH PAPER

Experimental investigation of hard spline milling using a newly developed disk cutter

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Abstract

Machining hardened steels is a common requirement in various industries. This includes gearing and spline cutting on hardened steel parts at high speeds. Traditionally, gearing tools were made of high-speed steels, which made them suitable only for gearing at low cutting speeds with coolant. However, hard gearing using disk cutters with interchangeable carbide inserts is a new and flexible method for machining various types of splines and gears without special equipment. In this research, a disk cutter with four carbide cutting inserts is designed and manufactured. Experimental analysis is performed to assess the applicability of the developed cutter in machining splines on hardened steel axle shafts. Workpieces made of DIN 60SiMn5 steel with a hardness of 46 HRC and AISI 1552 steel with a hardness of 61 HRC are machined using two types of carbide inserts in wet and dry cutting conditions. Results show achieved surface roughness values in the range of 0.161 µm < Ra < 0.376 µm, which is an indication of a very good surface quality. Also, ANOVA methods are used to assess the impact of input parameters on machined surface roughness and cutting tool wear. The analysis shows that surface roughness is most affected by insert type, while use of coolant is the most effective parameter on tool wear. This research also proves applicability of dry milling as a sustainable and environmentally friendly method for spline cutting on hardened steels.

Keywords: Disk Cutters, Hard Gearing, Dry Machining, Spline Milling

1. Introduction

Gear and spline production are among the more complex processes in the manufacturing industry. This leads to great efforts towards optimization of these processes. Traditional methods for manufacturing of gear and spline parts require special machine tools and custom-built cutting tools. However, a more recent trend in industry is towards using special tools with replaceable inserts for producing these parts. This new method enables using conventional machine tools and inserts for cutting various types of gears and splines. Also, while traditional gear cutting tools, such as hob cutters, where made from high-speed steels and allowed cutting metals with a maximum hardness of around 25 HRC, new cutters can use different types of inserts and thus, facilitate cutting parts with hardness values exceeding 45 HRC [1].

Wear and breakage of carbide tools was studied by Gong et al. [2]; they performed milling tests on H13 tool steel (30-35 HRC) and SKD11 steel (58-62 HRC) using CVD coated carbide tools. Their results demonstrated the effect of workpiece hardness on cutting insert breakage; milling the hardened SKD11 workpiece led to high impact stresses and consequently, caused rapid initiation and progression of cracks, and breakage in the cutting inserts.

Hard machining of gear and spline parts has been the focus of many researchers. Fukunaga et al. [3] studied hard gearing using a carbide hob on AISI 1045 parts with hardness values of 53-56 HRC. The hob module values were in the range of 0.8 - 1.25 mm and gearing was performed in a dry environment. Experimental results proved the high

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quality of parts manufactured using carbide hobs; gear tooth quality exceeded that of ground gears and conformed to AGMA Grade 11-12 standard.

Sari et al. [4] performed gearing and finishing of 16MnCr5 gears using a fly cutter with four different types of inserts, namely a cemented carbide insert, a powder metallurgy high-speed steel insert, a cermet insert, and a PCBN insert. Tool wear analysis when cutting at various cutting speeds in the range of 250 – 2250 m/min showed that carbide inserts are the most capable ones in dry gearing at high speeds.

Another study on hard gearing was performed by Karpuschewski et al. [5]; a K30 carbide insert with AlCrN coating is used for high speed gearing on AISI 5115 parts. Three different gear modules were selected for this study. Results proved that these inserts are capable of cutting gears with speeds as high as 800 m/min and depth of cut values as high as 0.26 mm.

Hard gearing was also the focus of a study by Glaser et al. [6]. In this study, gearing was performed on 18CrNiMo7 workpieces with two hardness values of 30 HRC and 58 HRC using the Invomilling™ method on a 5-axis milling center. Despite its numerous advantages, the main disadvantage of this method is the requirement for special and expensive tools and machinery, which makes this method not optimal for small shops.

Nevertheless, a review of the available literature showed that research on machining hard gear and spline parts has mostly focused on using hobs or fly cutters, and despite its extensive applications, hard gear and spline machining using disk cutters with replaceable inserts has not been the topic of choice for researchers in this field. Therefore, in this paper, a special disk cutter is designed and manufactured, and its application in hard machining spline parts is examined. DIN 5481 splines were cut on 60SinMn5 parts with hardness values of 46 HRC and AISI 1552 parts with hardness values of 61 HRC. These parts are used as drive shafts in automotive applications. Using tungsten carbide inserts, splines were cut at various feed rates and speeds with and without coolant. Results proved applicability of the developed disk cutter in hard milling of splines in real industry applications.

2. Development of Spline Disk Cutter

Splines are machine parts that facilitate transfer of torque between two shafts that can move with respect to each other. Applications of these parts include automotive transmissions, automotive oil pumps, gas turbine shafts, shafts in farm equipment, and drive shafts in passenger and commercial vehicles. DIN 5481 is among the most commonly used spline forms, particularly in automotive applications. Teeth in this standard are equilateral triangular shapes with pressure angles of 30° (Figure 1).

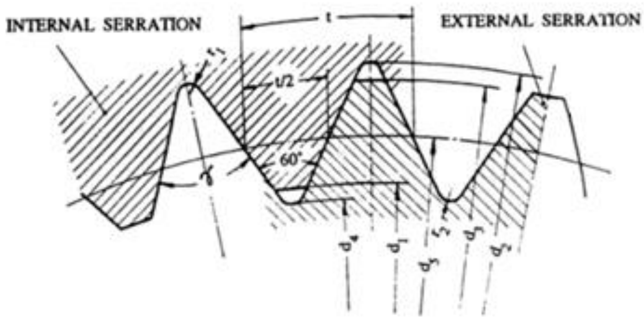


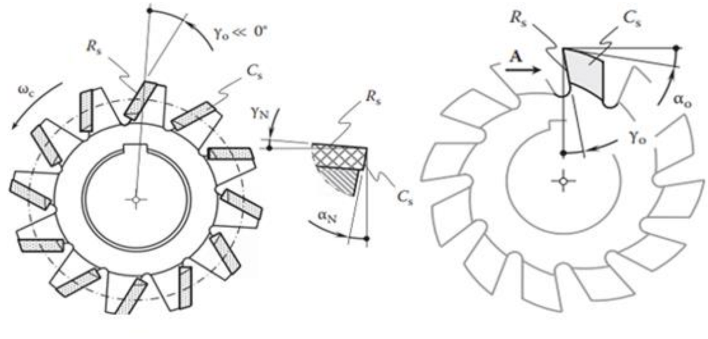
Figure 1: Spline tooth shape according to DIN 5481 [7].

Splines are manufactured through rolling, hobbing, or milling using disk cutters. Spline cutting using disk cutters with replaceable inserts is a flexible method used for cutting various gear and spline forms on hard materials without the need for special machine tools. Using these cutters, splines and gears of different tooth shapes can be machined by replacing the type of cutting inserts.

The disk cutter developed in this work is a cutter with four cutting inserts which can be used on horizontal milling centers. The cutter is designed to facilitate installation of 60° triangular inserts, which matches the DIN 5481 spline tooth shape.

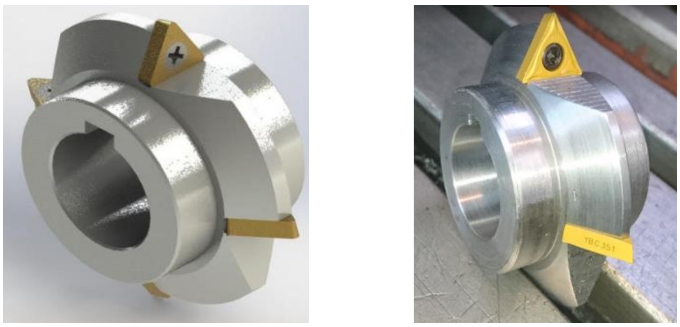
As shown in Figure 2, rake angle in a disk cutter is defined as the angle between the tool rake face (R_s) and the vertical surface. Disk cutters used for rough milling or semi finishing of gears are usually made with positive rake angles ($\gamma_0 > 0°$) and cutters made for finishing gears on hard materials are generally made with negative rake angles

($\gamma_0 < 0°$) [8]. Using cutters with positive rake angle reduces the insert life and increases chipping probability while reducing the cutting forces and required cutting power. Negative rake angles, on the other hand, increase the tool life and are more suitable for withstanding the impact forces during cutting hard materials. Since the cutter developed in this work is to be used for spline milling on hard materials, it is designed with a negative rake angle of -7°. Figure 3 shows the developed spline milling disk cutter.



(a) (b)

Figure 2: Rake angle (γ_0) in spline disk cutters: (a) negative rake angle, (b) positive rake angle [8].



(a) ***(b)***

Figure 3: Developed disk cutter: (a) CAD model, (b) Manufactured cutter with inserts installed.

3. Experimental Investigation

3.1. *Workpiece Materials and Equipment*

Two driveshaft parts made of 60SiMn5 and AISI 1552 are used as workpieces for experimental investigation of applicability of the developed cutter (Figure 4). Workpieces are first machined on a lathe to a diameter of 42 mm and length of 50 mm. Chemical compositions of the alloys is obtained and described in Table 1 and Table 2.

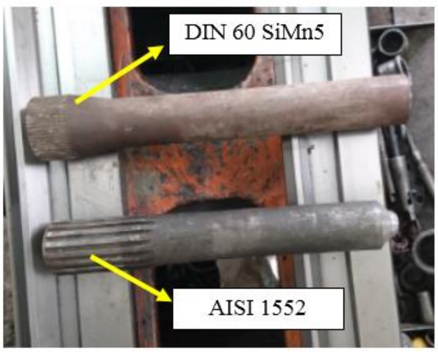


Figure 4: Workpiece materials used in experiments.

Table 1: Chemical composition of 60SiMn5.

Element	Fe	C	Si	Mn	P	S	Cr	Mo	Ni	Cu
wt. %	95.7	0.6	1.468	1.239	0.015	0.023	0.373	0.038	0.103	0.091

Table 2: Chemical composition of AISI 1552.

Element	Fe	C	Si	Mn	P	S	Cr	Cu	Sb
wt. %	97.622	0.486	0.192	1.241	0.022	0.032	0.045	0.090	0.222

Hardness tests were performed on the workpieces with a load of 150 kg and a loading period of 10 s. Results of 3 tests were averaged to obtain the part hardness values. The 60SiMn5 and AISI 1552 workpieces had hardness values of 46 HRC and 61 HRC, respectively. Facing of the parts showed a depth of more than 6 mm for the hard layer on the surface.

For the cutting tests, tungsten carbide triangular inserts with a vertex angle of 60° were employed. Two types of inserts, namely TCMW 16T304 uncoated inserts without chip breaker and TCMT 16T304 HM coated inserts with chip breaker, were used as shown in Figure 5.

Figure 5: Tungsten carbide cutting inserts used in experiments: (a) TCMT 16T304 HM coated with chip breaker, and (b) TCMW 16T304 uncoated without chip breaker [9].

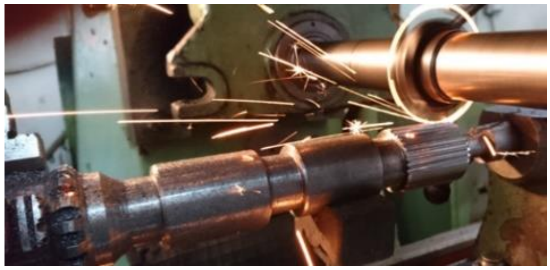
3.2. *Experimental Procedure*

Experiments are designed using the Taguchi method with five input parameters, namely cutting speed, feed rate, workpiece material, cutting insert, and coolant utilization. Output parameters are machined surface roughness and tool wear. As shown in Table 3, experiments are performed using an L8 array with two levels for all input parameters, except for feed rate for which four input parameters are considered. In each test, a complete spline with 33 teeth according to DIN 5481 is manufactured using a new insert (Figure 6). The depth of cut is kept constant for all experiment at 2 mm.

Table 3: Details of experiments.

Test no.	Feed rate (mm/min)	Cutting speed (m/min)	Workpiece material	Cutting insert	Coolant utilization
1	28	235	60SiMn5	TCMW	Dry
2	28	330	AISI 1552	TCMT	Coolant
3	40	235	60SiMn5	TCMT	Coolant
4	40	330	AISI 1552	TCMW	Dry
5	56	235	AISI 1552	TCMW	Coolant
6	56	330	60SiMn5	TCMT	Dry
7	80	235	AISI 1552	TCMT	Dry
8	80	330	60SiMn5	TCMW	Coolant

(a)



(b)

(c)

Figure 6: Steps in performing experiments: (a) workpieces prepared for spline milling tests, (b) spline milling using the developed cutter on a horizontal milling machine, (c) 33-tooth spline parts manufactured in the tests.

4. Results and Discussions

Table 4 shows the results of surface roughness and tool wear measurements. The objective of experiments is to study the effects of input parameters on machined surface roughness and tool wear during spline cutting on the hardened workpieces. ANOVA methods are used for this purpose.

Table 4: Results of surface roughness and tool wear measurements.

Test no.	Surface roughness - R_a (µm)	Tool wear – V_B (mm)
1	0.200	1.461
2	0.170	2.398
3	0.166	1.315
4	0.305	0.277
5	0.376	2.592
6	0.161	0.261
7	0.250	1.117
8	0.262	1.795

4.1. *Machined Surface Roughness*

Machined surface roughness is among the most commonly investigated parameters by researchers in the field of hard machining [10]. In this research, surface roughness on spline teeth is measured as a metric for quality of final product. Measurement is performed on the side surface of cut spline tooth using a TR200 surface roughness tester, as shown in Figure 7. Cutoff value for roughness tester is set at 0.8 mm. Roughness values are measured on the 16th and 33rd teeth that were cut and the average value is used for analysis. This was to take into account the effect of wear in the cutting insert since the insert is in its most worn condition when cutting the 33rd tooth.

Figure 7: Measurement of surface roughness on the side surface of a spline tooth.

As shown in Table 4, an increase in feed rate leads to a rise in machined surface roughness. This is in agreement with the available literature on machining hardened steels using tungsten carbide or CBN inserts [11].

Analysis of variance is performed to assess the effect of input parameters on the machined surface roughness and results are shown in Table 5. In this analysis, the error value is taken as $\alpha = 0.1$. In Table 5 with a confidence level of 90%, parameters with a P-value of less than 0.1 are effective inputs and those with P-values of more than 0.1 are not considered effective. Thus, the effective parameters on surface roughness arranged from most effective to least effective are cutting insert, material hardness, cutting speed, feed rate, and coolant utilization.

Table 5: Analysis of regression for assessing the effects of input parameters on machined surface roughness.

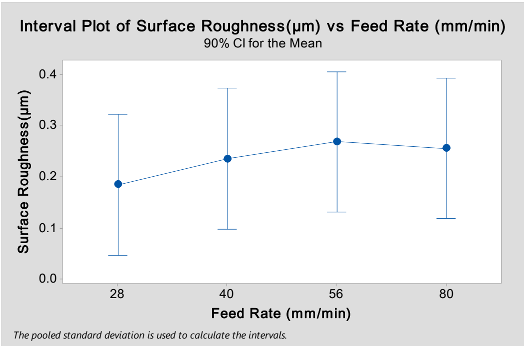
Source	DOF	Sum of squares	Average of squares	F-value	P-value
Regression	5	0.038163	0.007633	4.70	0.185
Feed rate (mm/min)	1	0.004868	0.004868	3.00	0.225
Cutting speed (m/min)	1	0.001105	0.001105	0.68	0.496
Material hardness (HRC)	1	0.012168	0.012168	7.50	0.112
Cutting insert	1	0.019602	0.019602	12.08	0.074
Coolant utilization	1	0.00421	0.000421	0.26	0.661
Error	2	0.003246	0.001623		
Sum	7	0.041410			

Figure 8 shows the effects of each of the five input parameters on machined surface roughness. Figure 8 (a) shows a general trend of rise in surface roughness with increasing feed rate. This matches the observations reported in the literature in the field of hard machining [12]. The only exception in this figure is at the feed rate of 56 mm/min; this exception can be justified by the fact that in this test, the uncoated insert is cutting the harder material with coolant utilization, which causes a very rapid progression of tool wear. As observed by other researchers [10], surface roughness is extensively sensitive to tool wear and increased tool wear can lead to a rapid jump in machined surface roughness.

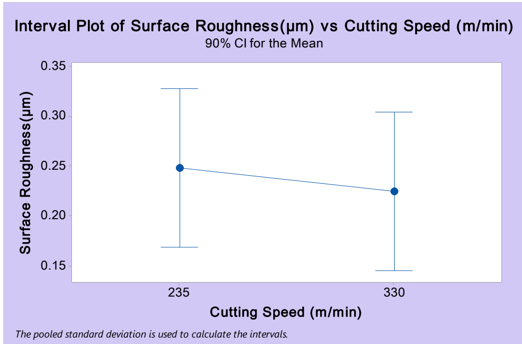
Figure 8 (b) shows a decrease in surface roughness with increasing cutting speed. This proves that high speed milling of hardened spline parts can result in improved quality of spline surface [10]. As shown in Figure 8 (c), increased hardness in workpiece material is a precursor to rise in surface roughness. This is due to the effect of material hardness on progression speed of tool wear; as mentioned earlier in Table 5, the P-value obtained for the effect of material hardness on surface roughness proves that this parameter is more effective than the previous two parameters.

As shown in Figure 8 (d) and discussed earlier in Table 5, cutting insert type is the most effective parameter on spline surface roughness and quality. The CVD-coated TCMT insert is more suitable for high speed milling of hardened steels [13] and can be used for machining splines on hard metals with an excellent surface quality. This can be attributed to the wear-resistant coating on the insert as well as integration of chip breaker.

The P-value for the effect of coolant utilization on surface roughness, as provided in Table 5, is the highest among all input parameters, which is an indication of minimal effect of this parameter. In other words, use of coolant during hard spline milling using the developed disk cutter does not affect the surface quality. Thus, as shown in Figure 8 (e), milling in dry condition is even helpful in achieving better surface quality. Therefore, dry spline cutting on hard steels, which is both cost-efficient and more environmentally friendly, is facilitated using the developed disk cutter.



(a)



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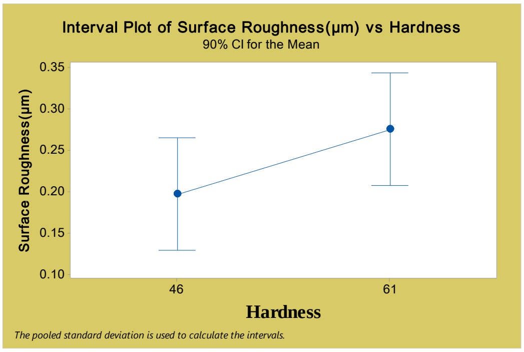

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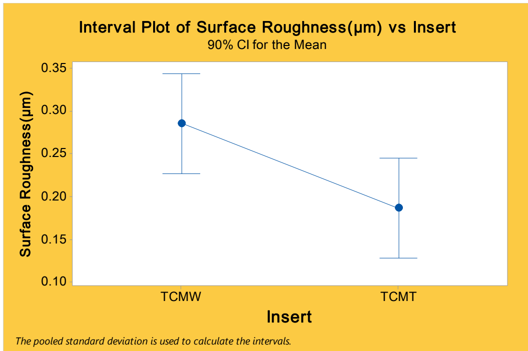
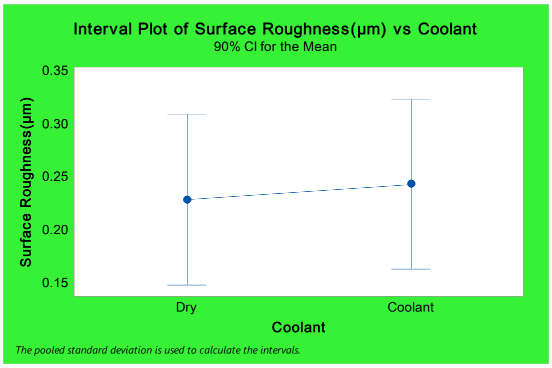


(d)



(e)

Figure 8: Analysis of the effects of input parameters (a) feed rate, (b) cutting speed, (c) workpiece hardness, (d) insert type, and (e) coolant utilization on machined surface roughness.

4.2. *Tool Wear*

A review of the available literature on gear and spline milling demonstrates that wear on the rake face i.e., crater wear, is the dominant wear shape in this process [14]. Therefore, in this paper, the wear length on the rake face is measured and analyzed.

In order to investigate the wear on inserts, all four inserts on the disk cutter are studied under an optical microscope after each test. The captured images are then analyzed using Sandvik Coromant tool wear analyzer software. The maximum wear length on each insert is obtained and the average value is considered in the investigation. Figure 9 and Figure 10 show insert wear after tests no. 1 and no. 6, respectively. Figure 11 shows the software interface for measuring insert wear length.

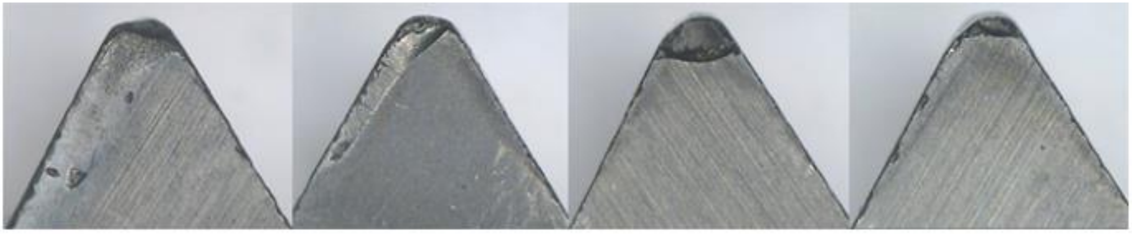


Figure 9: Wear on the four cutting inserts after test no. 1 (Feed rate = 28 mm/min; Cutting speed = 235 m/min; Material hardness = 46 HRC; Dry; TCMW insert).

Figure 10: Wear on the four cutting inserts after test no. 6 (Feed rate = 56 mm/min; Cutting speed = 330 m/min; Material hardness = 46 HRC; Dry; TCMT insert).

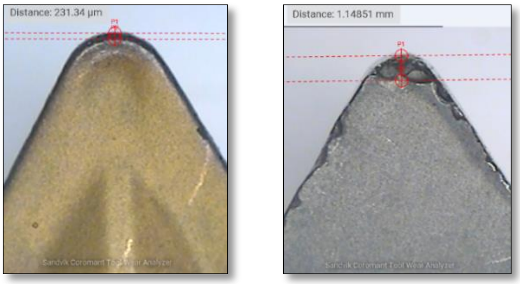


Figure 11: Software interface for measurement of insert wear.

ANOVA is utilized to study the effect of input parameters on the insert wear and results are shown in Table 6. As deduced from this analysis, the effective parameters on tool wear arranged from most effective to least effective are coolant utilization, cutting speed, material hardness, insert type, and feed rate.

Figure 12 shows the effects of each of the five input parameters on insert wear. As depicted in Figure 12 (a), and mentioned above, feed rate does not have a significant effect on tool wear. The only exception is when using a feed rate of 40 mm/min, at which the harder workpiece is cut using the coated insert at a higher cutting speed and without coolant, which led to a reduced insert wear.

Figure 12 (b) proves that tool wear progression is slowed when using a higher cutting speed. This is in line with results reported in the literature [10]. Figure 12 (c) shows that spline milling on the harder workpiece leads to an increased wear rate. As reported by researchers in the field of hard milling, workpiece hardness can significantly affect the wear rate due to the high impact forces on the tool during the process [2].

As presented in Figure 12 (d), insert wear is reduced when using the TCMT insert as compared to the TCMW insert. This is expected due to the wear-resistant coating and chip breaker integration in the TCMT insert. A review of the literature shows that tungsten carbide inserts [13] are more suitable for gear and spline cutting in hardened metals without coolant utilization [4].

Table 6: Analysis of regression for assessing the effects of input parameters on tool wear.

Source	DOF	Sum of squares	Average of squares	F-value	P-value
Regression	5	3.95007	0.79001	1.23	0.506
Feed rate (mm/min)	1	0.01845	0.01845	0.03	0.881
Cutting speed (m/min)	1	0.38764	0.38764	0.60	0.519
Material hardness (HRC)	1	0.29838	0.29838	0.46	0.566
Cutting insert	1	13184/0	0.13184	0.20	0.695
Coolant utilization	1	3.11376	3.11376	4.83	0.159
Error	2	1.28807	0.64404		
Sum	7	5.23814			

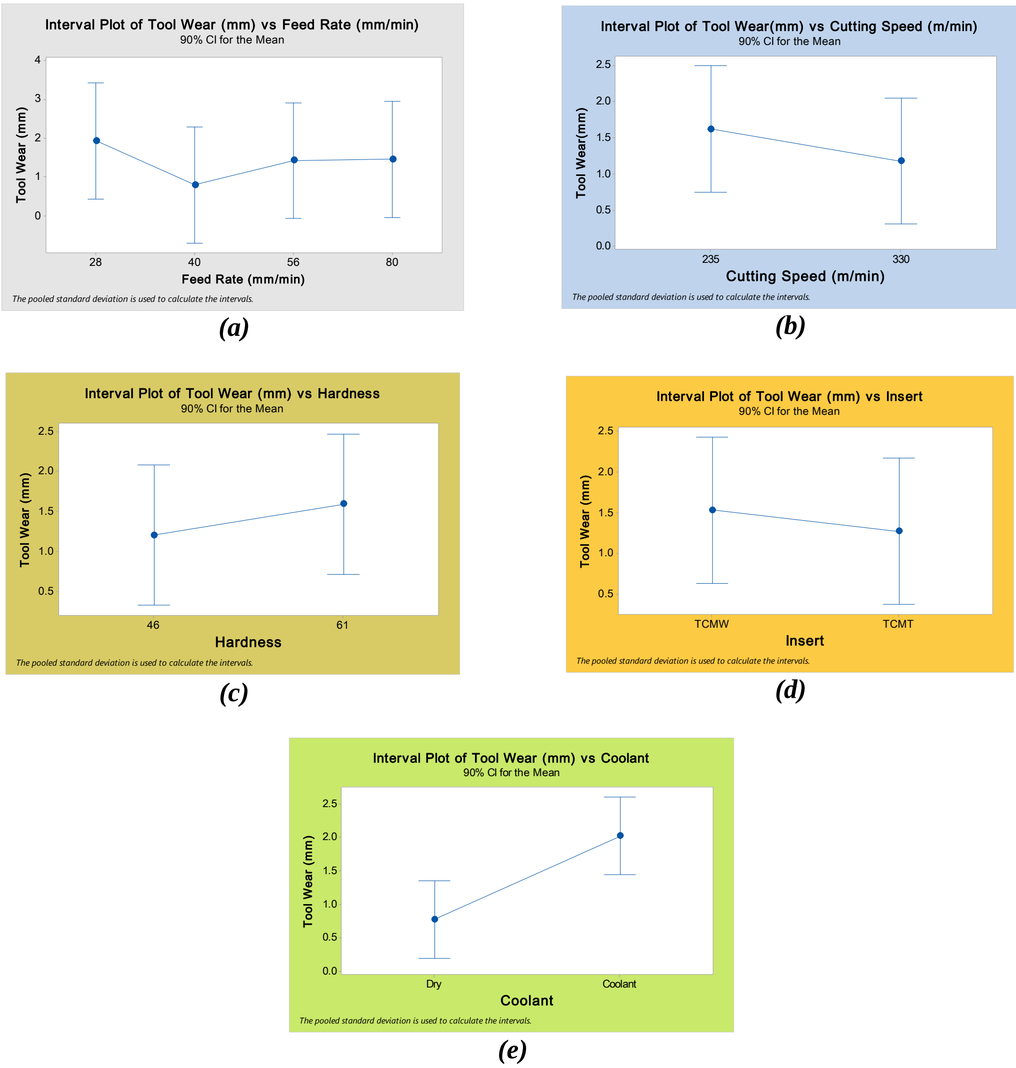


Figure 12: Analysis of effects of input parameters (a) feed rate, (b) cutting speed, (c) workpiece hardness, (d) insert type, and (e) coolant utilization on tool wear

ANOVA results proved that coolant utilization is the most effective parameter on insert wear rate during hard spline milling using the developed disk cutter. As shown in Figure 12 (e), the average insert wear after dry cutting the complete 33-tooth spline using the developed cutter is about one third of insert wear after cutting using coolant. The main factor contributing to this phenomenon is the effect of coolant on inducing thermal shocks in the insert when the tool enters and exits the cutting zone [13]. Spline milling on hard metals generates an extensive amount of heat and leads to very high temperatures. When the tool exits the cutting zone and comes in contact with the coolant, a sudden drop in temperature occurs and thus, thermal shocks are induced. These recurring shocks result in rapid progression of tool wear and reduced tool life [13]. The advantage of using dry conditions in milling hard metals has previously been reported in literature [15]. Therefore, dry spline milling using the developed disk cutter helps increase tool life and is more cost-efficient while also environmentally friendly.

5. Conclusions

- In this research, a new disk cutter for milling spline forms on hard metals is designed and developed. The cutter holds four inserts and facilitates manufacturing spline workpieces on general vertical and horizontal milling centers. The developed cutter is shown to be capable of cutting workpiece materials with hardness values exceeding 60 HRC at high cutting speeds without the need for special equipment.
- In order to assess applicability of the developed tool, milling is performed to produce a 33-tooth spline workpiece on two hard steel alloys. Using two types of tungsten carbide inserts, parts are cut at different feed rates, cutting speeds, and under dry and flood cutting conditions. An investigation of surface roughness on machined spline parts proves that the developed cutter can achieve excellent surface quality, which in some cases exceeds the surface quality achieved in grinding.
- Results show that the insert type is the most effective parameter on surface quality of machined splines. Using CVD coated tungsten carbide inserts with integrated chip breaker leads to a significant decline in surface roughness.
- Wear analysis performed on the inserts after manufacturing complete spline parts reveals the link between use of cutting fluids and tool wear; application of cutting fluids leads to a significant increase in tool wear rate. Therefore, using the developed disk cutter, very good tool life can be achieved under dry cutting condition. This confirms the cutter's capability in achieving a cost-efficient and environmentally friendly spline milling process on hard metals.

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