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Performance test of coated HSS tool with respect to thrust force, torque and surface integrity on customized EN8 specimen

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Abstract
The scope of this presented work involves the study on effect of cutting speed and feed rate of a customized coated high-speed steel (HSS) tool on thrust force, torque and surface integrity. The standard European norms 8 (EN8) specimen is selected, and its hardness is varied as 15, 20 and 25 Rockwell hardness on the Rockwell C scale (HRC) to make ease of research. Four tools with the composition of R1, R2, R3 and R4 were chosen. Maximum of 67 N thrust force and 8.9 µm surface roughness was obtained at 12.57 m/min cutting speed for 25 HRC specimen. Lower value of thrust force and surface roughness was observed for tool 2. Low as 1.90 µm surface roughness was noticed for 15 HRC specimen when the speed of cut given is 1500 rpm and 1.8µm at a feed rate of 5 mm/rev. A minimum thrust force of 6 and 8 N was observed for feed rate and cutting speed of 5 mm/rev and 62.86 m/min respectively. It was noticed that, thrust force increases gradually when the rate of feed enhanced and is reduced with respect to increase in cutting speed. The tool shows poor performance at the 25 HRC specimen at maximum operating conditions. Tool 2 gives better performance for 15 and 20 HRC of EN8. Thus, tool 2 with R2 composition can be employed till the hardness level of 20 HRC without losing quality of the work.

Keywords
Physical vapour deposition, EN8 (080M40), Thrust force, Torque, Surface integrity.

1.Introduction
The adoption of hard materials dates to 1500 BC during Mesopotamian civilization for the general applications [1]. Wide use of hard materials is spread from domestic to the engineering sector over the last two decades. It is necessary to carve the hard materials to meet the desired application due to increased market demand with respect to quality and technology. Conventional machining of such materials encompasses rough turning, later grinding is employed to achieve higher production rate. In addition, hard turning of such difficult-to-cut alloys reduces the production cost of stable cutting fluids [2]. Despite, modified cutting tools possessing very high red-hot hardness with optimum toughness are highly significant properties to employ dry machining of such alloys.

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Machining of hard engineered alloys is still challenging with the conventional cutting tool materials. It is also evident from available investigations that, machining of hard materials above 20 Rockwell hardness on the Rockwell C scale (HRC) causes the occurrence of failure and very poor performance of the tool. Therefore, rapid developments in the tool design and materials have happened in the recent years to ease the operation during machining of hard materials. Further, developments have welcomed the special technique called coating on the surface of the tool to improve its surface properties comprising hardness, toughness, strength, stabilized its shape and properties at elevated temperature and more.

When a cutting tool fails due to inefficient strength showing inferior performance, the coating is provided to impart enhanced mechanical properties for better performance. Dureja et al. [3] have proved that coated carbide tools are feasible for hard turning and can be potential candidates to substitute costlier tools such as cubic boron nitride tools and ceramic tools, which helps to achieve economic machining. The micro coating techniques employed over tool substrate have led to expeditious improvement in the hardness significantly. Zhang et al. [4] showed by providing a micro coating to improve hardness significantly can improve the hardness at the exterior surface of the tool. Micro hardness is increased by 1935 HV about 11 µm, which is nearly 5 times harder on a steel substrate. Various coating materials utilized extensively over tool materials in the past years were nitride and carbide of titanium, zirconium nitrides, titanium aluminium nitride etc. [5]. The primary reason is their superior stable hardness at elevated temperature, subsequently exhibiting excellent machining performance characteristics. In addition, technical and economic considerations lead to the conclusion that coated tools are one of the most lucrative and extensively used types of tools for machining of hardened steels. The primary reasons governing the coated tools behaviour are resistant to abrasion and diffusion with thermal barrier characteristic [6].

The main objective of current research is to investigate the tool performance characteristics of different types of coating material during machining of hardened steels. Thus, 4 different coatings were considered in the study. The tool performance characteristics were studied through surface integrity was studied as a function of surface roughness and cutting forces. The article is structured further in the following manner. Literature review in section 2. Materials and Methods were explored with workpiece material machined, and characteristics studied in section 3. Results have been elaborated in section 4. Section 5 discussed the analysis. Conclusions have been presented in section 6.

2.Literature review

Many studies reported the challenges encountered during machining of hard materials. Sousa and Silva [7] presented a detailed review report on the machining performance of coated tools. The authors concluded that coated tools help to reduce tool wear, thereby improves tool life and aid to achieve significant economical machining coupled with slightly eco-friendly machining. The reported literatures have also focused on enhancing machining performance in terms of quality and cost reduction of final product. Corrosion remains as the highest point of importance in respect to tool since it can lead to tool failure during the operation. Corrosion inhibiting properties, improved mechanical properties of tools can be enhanced by physical vapour deposition (PVD) and chemical vapour deposition (CVD) techniques. Dobrzañski et al. [8] reports that, PVD method proves as better for TiN+multiTiAlSiN coating which shows improved corrosion resistance properties. Frictional effects produced during operation should be low as possible to avoid any insignificant performance of the tool. A study by Thirumalai et al. [9] reveals the 18 % improvement in the value of the coefficient of friction when diamond like carbon (DLC) coatings were provided on base surface. Also, the PVD method gives significant improvement in tribological and mechanical properties of the tool. Lessiak and Haubner [10] stated that, there are chances where coatings may fail when the tool is operated for heavy duty machining processes. The premature failure of the tool can be prevented through employing by using diamond powder coating preferably thereby imparting additional heavy-duty hours to the tool. Longer the tool life, better will be the economy. Huang et al. [11] reported that when the tool is coated with amorphous carbon, there is an observation in increased tool life of up to 121 hours during cutting of aluminium alloy. In addition, improved surface finish was achieved. Fernández-abia et al. [12] concluded that, optimized geometries have been produced for different tool coating materials. The nACo® coating produces superior performance than AlTiN, perhaps due to its nano crystalline structure. Increased feed rate increases the force required for cutting while reduces as speed of cutting increases. Lower cutting speeds attract built up edge (BUE) and variation in temperature, thereby results in a poor surface finish of machined sample [13–15].

Cutting forces depend upon factors like the time required, hardness of work piece, geometry of the tool. It was found that the radial force is the largest one, produced during the cutting of medium carbon steel [16, 17]. DLC coatings can also be provided since the tool coated with it exhibits very good hardness, wear resistance, lower friction. Even adhesion property can also be altered by doping technique [18, 19]. Lower thrust force and good surface finish are obtained with AlCrN when compared to AlTiN coating. There is an appreciable increase in tool life which is an added advantage [20, 21]. Sahoo and Sahoo [22] reported that good surface finish is a result of high quality of machined product. Inserts are also used in place of coatings to obtain desired surface roughness values. A tool with TiN insert shows better surface finish against uncoated carbide tool during the turning of steel. It also results in lower values of frictional coefficient and better diffusion during the machining process. The comparative assessment of AlTiSiN coating on tool proved to be more lucrative compared to AlTiN owing to the higher hardness of coating material. The BUE formation, edge failure and coating film detachment was more pronounced during machining with AlTiN tool [23]. Thus, coating layer hardness acts as deciding factors for machining characteristics of any coated tools. Thrust force and surface integrity resulted in an operation defines the quality of the finished product. Whether it is coated or uncoated, feed rate plays predominant role in the magnitude of the thrust force produced. While, cutting speed is important in maintaining the good surface roughness. Das et al. [24] stated that, TiN coating provided on tool acts in inhibiting the frictional resistance produced during operation. Lower surface roughness as desired can be obtained. Comparison of properties and microstructure of coatings are necessary by means of X-ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM) etc., to suggest the best coating for specific applications. Presence of amorphous phase cane refines the grain structure. A refinement of 8.7 and 5.2 nm is observed for CrBN and AlCrBN coating. Fine grain can strengthen and increase the hardness of 37.2 GPa [25]. Wan et al. [26] investigated and reported that, the high bias voltage for base material after evaporation increases the rate of phase transformation from amorphous to solid. Coatings produced in the bias voltage of -110 to -50 V produce a single-phase solid layer in case of nano structure with multilayer. Chromium present during coating is the main reason to form an amorphous layer initially which is converted to solid later after high bias voltage. Tillmann et al. [27] investigated how roughness and residual stress influences the wear resistance of PVD coated surfaces. Chandru et al. [28] evaluated machining characteristics of carbon nano-tube (CNT), coated high speed steel (HSS) tool and found that speed and thickness of cut is major affecting parameters during the machining. A study by Ikumapayi et al. [29] shown the possibility of enhancing the tool properties with the help of heat treatment. For lower frictional force production, high adhesion multilayer coating is provided as there is a lower coefficient of friction (COF) and higher adhesion is observed in multilayer coatings. Some of the major drawbacks like, poor performance of the tool, adhering of oxides on work material, inferior machined quality obtained was noticed in some of the literature. Upon considering the weak points from the previous studies, an effort is made to overcome these problems by investigating the effect of different coating materials in machining of hard materials. Rao et al. [30] explained that Taguchi technique can be used to optimize machining parameters during hard turning with TiAlN nano-structured coated tools. The study attempted to obtain parameter combination levels for minimum surface roughness and maximum removal rate during the turning of American iron and steel institute (AISI 304) hardened steel. Manoharan et al. [5] successfully employed grey Taguchi based response surface methodology to model the machinability characteristics of coated carbide tools and effect of process parameters on machinability. Thus, attained with optimum process parameter levels to achieve minimum cutting force with maximum material removal rate. Sahu et al. [31] utilized Taguchi technique to optimize machining parameters to obtain minimum cutting force and surface roughness during cutting of EN31 steel with TiAlN coated tool with help of signal to noise ratio (S/N) analysis. Das et al. [32] presented an optimization technique based on the desirability approach of Taguchi's technique for attaining optimum machining parameter values for multi-objective optimization task during machining with the AlTiSiN coated tool. The technique helped to reduce the search space of optimal values. The approach considered both sustainability and economic aspects of hard turning. Thus, it is evident that the Taguchi technique can be utilized in the multi-objective optimization during hard machining using coated carbide tools. Further, it helps to minimize the number of trials and the search space for optimization of input parameters.

The literature review reveals that, sufficient research reports have paid attention on the coated carbide tools to enhance prime tool's characteristics such as tribological and thermal behaviour. Substantiate information of studies reported on coated tool behaviour during hard turning is presented. Though a large number of works are available, limited attempts are made to develop novel coating materials. It also depicts that, there is a large scope for the novel developments in the coating material to improve their machining properties with the primary consideration of hard machining. Further, multi-objective optimization of hard turning characteristics with coated tool needs special emphasis. The current research deliberates on the effect of different coating materials and its performance during machining of hard materials. Effect of coated tool performance on varying cutting speed and feed rate is discussed. In addition, tool performance evaluation considering thrust force, torque and surface integrity produced as speed and feed changes is also discussed. Better tool coating material in the machining of EN8 hard material is suggested for efficient and quality output. HSS tool with high carbon proportion was selected which has a hardness level up to 75 HRC. TiSiNO, ALCRONA PRO (AP) and FUTURA (FTR) were chosen as coating materials since they possess a high process reliability and increased tool life. HSS tool selected can withstand 500ºC and produced by powder metallurgical process, which poses high content of alloying elements to impart unique properties like hardness, hot hardness, toughness, wear resistance.

3.Materials and methods

3.1Physical vapour deposition (PVD)

3.1.1Coating procedure

Sputtering coating technique type of PVD coating process is used to coat on HSS tool. Vacuum coating is carried out in four stages viz. evaporation, transportation, reaction and finally followed by deposition. *Figure 1 (a)* shows sputtering coating machine where the tool with coating materials is placed inside in a vacuum chamber. Pressure and temperature maintained in the range of 6-10 bar and 200-500ºC during coating. The temperature is held higher in the top layer of the tool to make sure that coating fits permanently on the surface of the tool which gives strength. Impingement on a substrate with highly charged positive ions are done to promote strong adhesive bonding between base material and coating alloy. Reacting gas like nitrogen with 99.9% concentration is introduced during the deposition process to achieve coating with varying compositions. *Table 1* shows the process parameters maintained during this film deposition. Coating thickness of 1 to 4 µm is obtained under these control conditions. Coating of four different layers on tools is done under different controlled conditions as discussed earlier. *Figure 1* (b) shows coating of four different layers on the selected HSS tool.

(a) (b)

Figure 1 (a) PVD-sputtering coating machine, (b) HSS drill i) TiSiN (R1) ii) TiSiN +AlCrN (R2) iii) TiAlN (R3) iv) TiAlN+ AlCrN (R4)

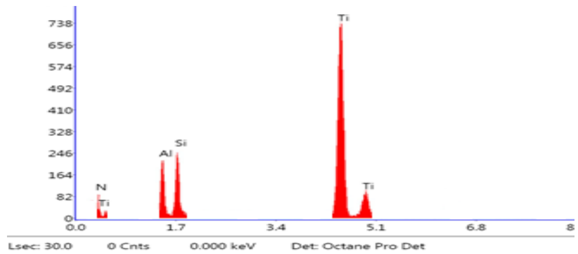
Table 1 Process variables used during the deposition

Electric current (A)	Pressure (Pa)	N_2 flow (scc/m)	Time of deposition (h)	Temp. of deposition (F)	Bias voltage (V)
100	3	300	2	932	-55

3.2Energy dispersive X-Ray analysis (EDAX) analysis of coated tools

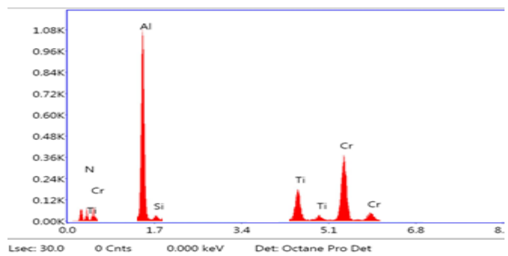
Figure 2 shows elemental composition of coated tools using energy dispersive X-ray analysis (EDAX). The tool 1 has the atomic and weight percent of the element Ti of 38.52 and 56.32% respectively which constitutes for the maximum share compare to Al and silicon. Tool 2 has 37.37% by weight of aluminum. The higher percentage of aluminum presence improves yield strength of the base material. It is observed that, along with desired composition estimated to be produced, there are some other elements which are present in small percentage, it may be due to interaction of coating materials during the process of coating. Tool 3 has weight percentage of Ti of maximum contributing to 65.65% and that of N is 11.73% being the minimum. Titanium being the strong material, it increases the strength of the base material and also helps in preventing target surface from corrosion. Similarly, Tool 4 has chromium with maximum percentage having weight percentage of 38.38% and Ti being the minimum composition. The presence chromium in majority helps in fighting against corrosion and wear resistance.

Element	Weight %	Atomic %
N	13.23	30.94
Al	10.31	12.52
Si	10.70	12.48
Ti	56.32	38.52



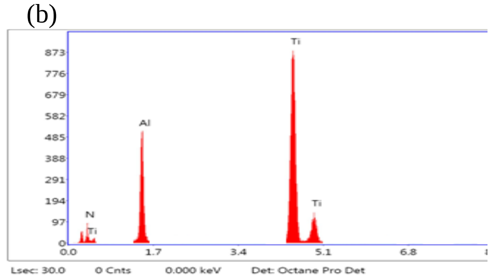
(a)

Element	Weight %	Atomic %
N	20.84	40.08
Al	37.37	37.31
Si	1.18	1.13
Ti	9.85	5.54
Cr	30.76	15.94



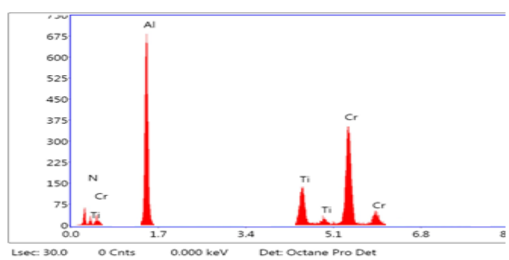
(b)

Element	Weight %	Atomic %
N	11.73	27.50
Al	22.62	27.51
Ti	65.65	44.99



(c)

Element	Weight %	Atomic %
N	14.42	30.64
Al	37.46	41.34
Ti	9.74	6.05
Cr	38.38	21.97



(d)

Figure 2 Elemental composition of tools (a) R1, (b) R2, (c) R3 and (d) R4

3.3Testing methods and procedure

A drill tool dynamometer and surface roughness tester are used for estimation of thrust force, torque and surface integrity respectively. Drilling is carried out with four bits of 8 mm diameter with R1 to R4 compositions. Speed, feed and hardness of work piece (15 to 25 in the interval of 5 HRC) are varied to investigate the tool performance. Hardness of the EN8 work piece is varied by using the heat treatment process in the temperature of 600ºC, 580ºC and 550ºC for 15, 20 and 25 HRC respectively. The treatment time required to get each hardness level is Two hours. The operation is done with speed of 12.57 to 62.86 m/min and feed 5 to 25 mm/rev with an interval of 5 mm/rev. The tool maker dynamometer is connected to machine in *Figure 3 (a)* to measure thrust force and torque. *Figure 3 (b)* shows surface roughness testing procedure. *Figure 4* shows a block diagram of testing procedure followed in carrying out the present research work.

(a) (b)

Figure 3 (a) Tool testing machine, (b) Surface roughness tester

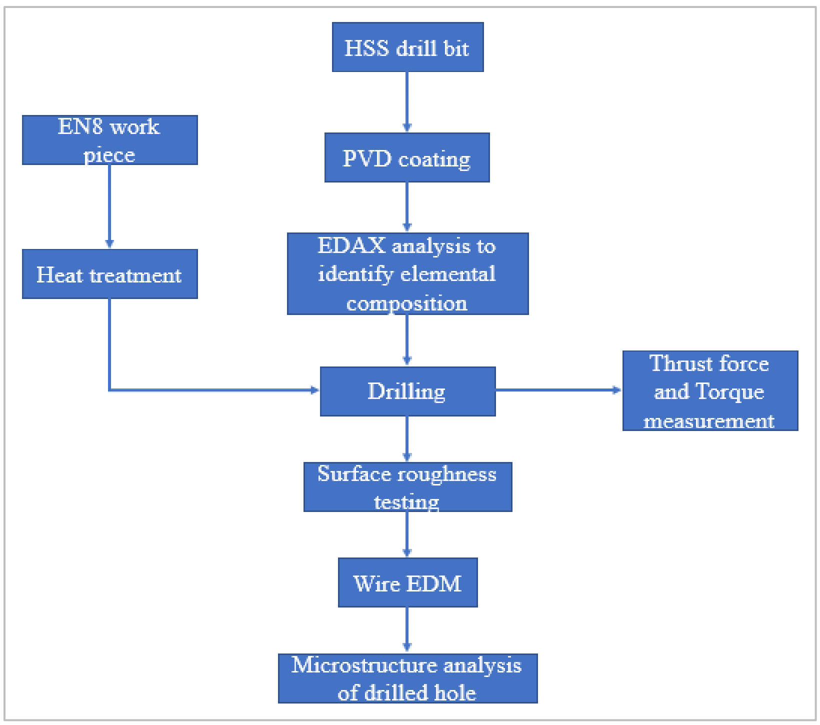


Figure 4 Block diagram showing the complete performance test of coated specimen

4.Results

Un-alloyed steel with a medium percentage of carbon is selected as a specimen for the experimental investigation. EN8 (080M40) an engineering steel with good tensile capacity is chosen and its hardness is varied at 15, 20 and 25 HRC respectively for this study. HSS drill bit with the composition of chromium 4%, tungsten 6%, molybdenum <10%, vanadium 2%, cobalt <9%, carbon 1% is selected and are coated with R1 (TiSiNo [AlTiN/TiSiN]), R2 (TiSiNo [AlTiN/TiSiN] + AP [AlCrN]), R3 (FTR [TiAlN multilayer]), and R4 (FTR [TiAlN multilayer], +AP [AlCrN]).

4.1Cutting force analysis

4.1.1The effect of cutting parameters on thrust force

Thrust force comparison between four tools during drilling is shown in *Figure 5*. Alterations of cutting speed and feed rate is studied to select best among them. Changes in composition of tools influences the frictional resistance developed during drilling. Radial cutting force mainly affects the quality of the work produced than the tangential cutting force. The average values of cutting forces are lower for tool 2 with 14.6 N and higher for tool 3 with 34 N and the remaining tools values falls in between tool 2 and 3. Also, cutting speed and feed rate plays a major role deciding the tool for specific applications. As it is clear, as cutting speed increases from 12.57 to 62.86 m/min, thrust force produced decreases gradually. This is because of lower friction at higher speeds. For tool 1 thrust force developed in descending order of 26 to 11 N. Similarly, trend can be seen for tool 2, 3 and 4 respectively. Better is the tool if it produces very low levels of thrust forces. Here tool 2 with R2 composition has a thrust force of 22 N at 12.57 m/min, and 8 N at 62.86 m/min which is lower than tool 1, 3 and 4 at every selected speed. Also, when feed rate is varied from 5 to 25 mm/rev, again tool 2 shows a similar trend of lower thrust force of 6 N at 5 mm/rev and 22 N at 25 mm/rev among other tools. Thus, with provided higher cutting speed and lower feed rate thrust forced produced will be minimum [11, 15]. This shows that tool 2 with R2 composition is better and can be safely used and preferred for practical applications. The reason behind the lower values of thrust force at higher cutting speed and lower feed rate is due to the frictional resistance produced during the operation.

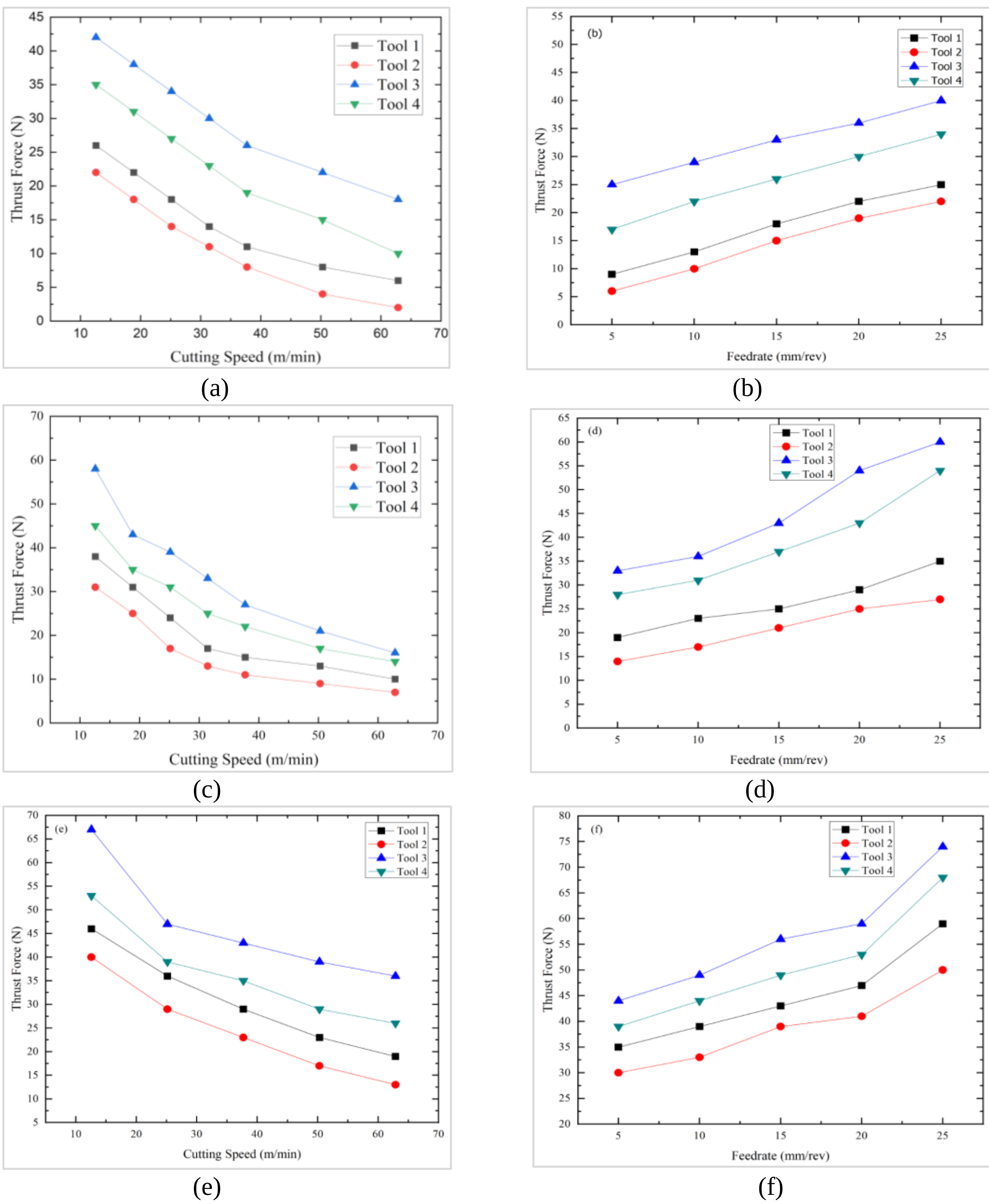


Figure 5 Effect of cutting speed and Feed rate on thrust force using different tools on work piece with different hardness of 15HRC (a & b), 20HRC (c & d) and 25HRC (e & f)

EN8 specimen hardness is varied to 20 and 25 HRC. Drilling is done on both these hardness specimens. *Figure 5* shows the variation in thrust force against speed and feed for EN8 work having a hardness of 20 and 25 HRC respectively.

Tool with different coatings is used to perform the drilling operation as in the case of 15 HRC sample. There is an observation of lower thrust force when cutting speed ascends and also as in the case of decrease of feed rate. Here, tool 3 gives maximum values of thrust force of 58 N and 27 N at 12.57 and 62.86 m/min respectively. Also, there is a thrust force of 33 N and 60 N at 5 and 25 mm/rev of feed given during machining. The obtained result in not desired, since higher thrust force may result in poor quality operation [17, 20]. Tool 2 gives the better results of 31, 11 and 14, 27 N at the same speeds and feed rates respectively among the selected tools which is preferable. Similarly, tool 2 comes out as the best among all four coated HSS tools even for 25 HRC specimens giving the lower thrust value of 13 N as shown in *Figure 5*.

Tool 2 of R2 chemistry had showed minimum values in thrust force for a given speed and feed with respect to 20 and 25 HRC. The reason behinds this is that, the presence of silicon, tin and chromium share exhibits better frictional resistance and mechanical properties.

4.1.2The effect of cutting parameters on torque

The performance of all four tools when (a) cutting speed and (b) feed rate is varied is shown in *Figure 6 (a)* and *(b)* with respect to the torque against 15 HRC specimen. This study results in selecting the most suitable tool by considering the torque as a selection parameter. As it can be seen in the below graph, we can observe notable changes in resulted torque for different tool composition under varied speed and feed. As cutting speed increased from 12.57 to 62.86 m/min, there is a notable decrease in torque can be observed the main reason behind this is the reduced frictional force at high cutting speeds. Also, the magnitude of torque increases as feed rate is increased as shown. The torque developed for t tool 3 is being the highest to 4.15 and 4.17 N-m at 12.57 m/min, 25 mm/rev, cutting speed and feed rate respectively. The lower torque observed for the tool 2 of R2 chemistry, the lowest torque being the 1.12 N-m at 5 mm/rev. After tool 2, the acceptable results are observed for tool 1 followed by tool 4. It is noticed that the resulting torque will be in the acceptable range of the tool in the order of 2, 1, 4 and 3. Additionally, it was seen that higher torque will be resulted as cutting feed is increased and there have a reduction in torque observed as speed of cut increases.

The variation of torque when all the four tools are examined against the 20 and 25 HRC specimen is shown in *Figure 6(c)*, *(d)* and *6 (e)*, *(f)* respectively. As discussed earlier in case of 15 HRC specimen, the similar trend is followed here too, as cutting speed increased, there is a decrease in magnitude of the torque and as feed rate increases, the value of torque also increases which is because of the frictional barrier between the tool and the specimen.

Figure 6(c) and *(d)* shows the variations in torque magnitude as cutting speed 12.57 to 62.86 m/min and feed rate 5 to 25 mm/rev is varied. Here, the highest torque was released by the tool 3 which counts about 4.25 N-m at 12.57 m/min and lowest is observed for the tool 2 which is 2.15 N-m for the same speed for 20 HRC specimen. As feed rate is changed, tool 2 had given lowest and tool 3 had given highest torque magnitude at 1.7 and 4.25 N-m at 5 and 25 mm/rev respectively.

Other tools fall in between these tools first being the tool 1 after tool 2 and next being tool 4 followed by tool 3. Similarly, as examination conducted for 25 HRC specimen as shown in *Figure 6 (e),* and *(f),* the similar pattern of torque variation was observed lowest being tool 2 and that of the highest being the tool 3 which had 1.92 N-m at 62.86 m/min and 4.35 N-m at 25 mm/rev. Out of 20 and 25 HRC specimen used to test the tools performed better in 20 compared to 25 HRC specimen. It may be due to the higher hardness of the test material, which tends to induce higher friction and heat at the tool-work interface.

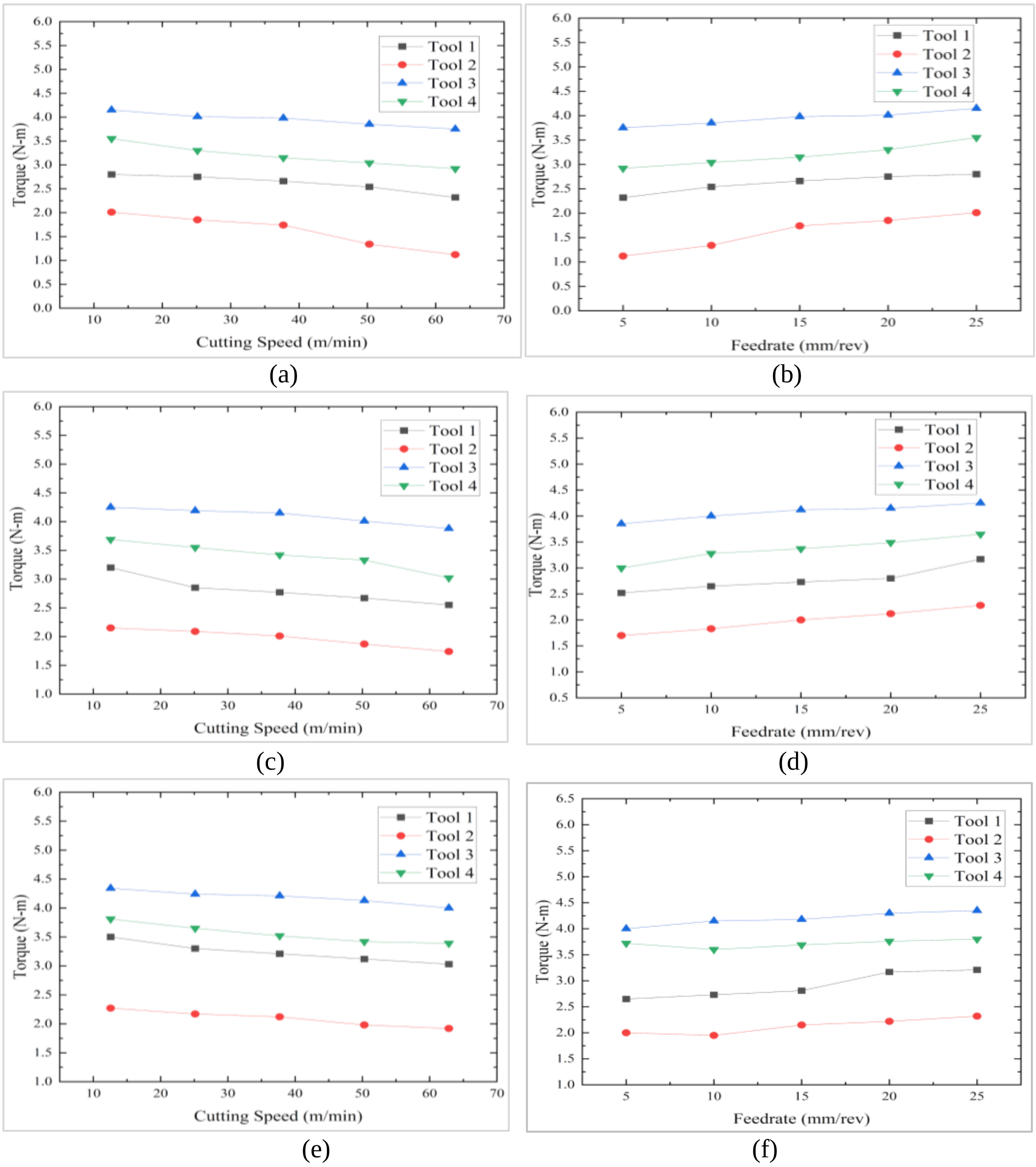
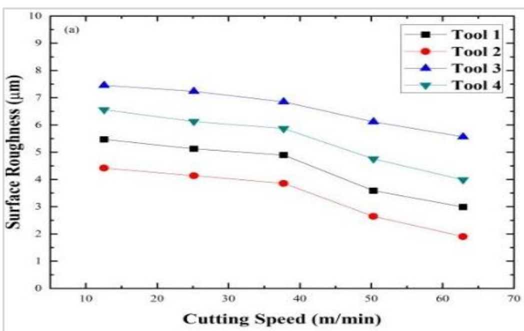


Figure 6 Effect of cutting speed and Feed rate with torque using different tools on work piece with different hardness of 15HRC (a & b), 20HRC (c & d) and 25HRC (e & f).

4.2Surface integrity analysis

4.2.1Surface roughness

Good surface finish is a result of better performance of the tool. Comparison of four different composition tools (R1, R2, R3 and R4) is shown in *Figure 7*. Surface roughness is greatly influenced by the speed and feed. A surface roughness of 7.4 µm and 5.5 µm is seen when the speed of cut is 12.57 and 62.86 m/min respectively in case of tool 3. Also, it is between 5.3 and 7.5 for 5 and 25 rev/mm feed rates respectively for tool 3 which is higher among other tools. Here, tool 2 has the lower values of 4.4 and 1.9 µm at the same speeds as said earlier. Again, it is 1.8 and 4.2 µm for same feed rate as before which is preferable. Tool 2 with R2 composition shows better performance which can be chosen for realistic application for 15 HRC work. From this analysis it is clear that, surface roughness will be minimum for higher speed of cut and minimum for lower feed rate values [7, 10, 11, 16, 18]. This gives a base in selecting the tool upon requirement. The performance of the tools is checked with different composition EN8 specimen. The EN8 work with an HRC value of 20 and 25 is compared against varied feed and speed, which is depicted in *Figure 7*. A similar trend of surface roughness is followed as of 15 HRC for same speed and feed. Here, the highest roughness value 8.2 µm from tool 3 which is followed by 6.9 µm from tool 4 for 12.57 m/min cutting speed and becomes minimum as speed rises. Also, when feed rate is 5 mm/rev, roughness of 6.7 µm and next precedes 4.6 µm from tool 4. Tool 2 has a roughness value of 5.4, 1.9 µm at 12.57 & 62.86 m/min and 2.31 & 4.45 µm for 5 & 25 mm/rev feed respectively in case of 20 HRC work. Similar fashion in surface roughness is seen against varied speed of cut and feed during machining of 25 HRC EN8. As seen in previous cases, tool 2 again shows better operating characteristics for producing better roughness values for practical applications. The major problem in 25 HRC specimens is the poor performance of the tool. From this analysis, it is clear that surface roughness will be lower for higher cutting speeds and lower for lower feed rate value. This is because; at higher cutting speeds lower, frictional resistance will be induced by tool and work which gives an idea in selecting the tool upon requirement.



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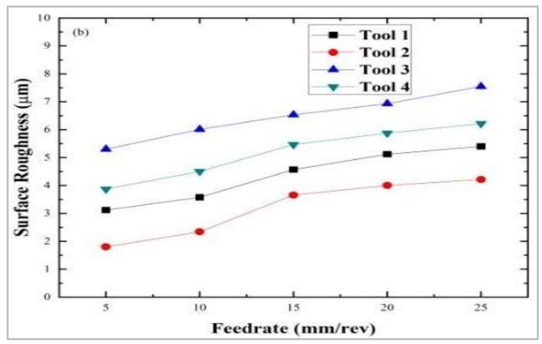

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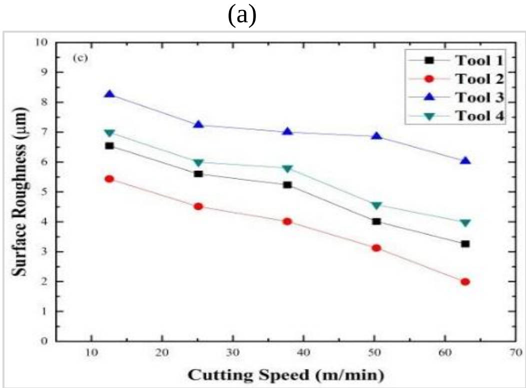

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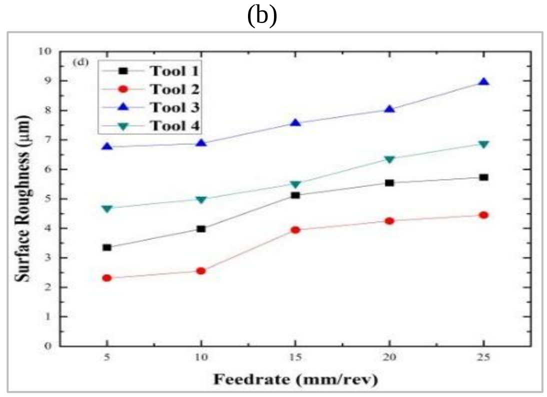

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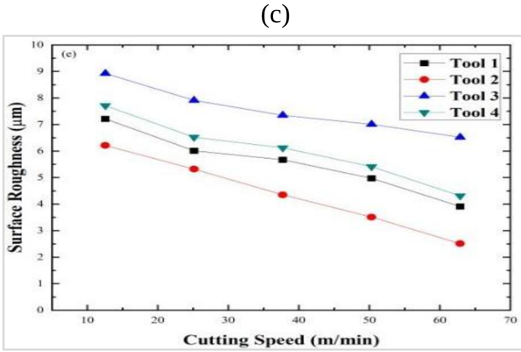

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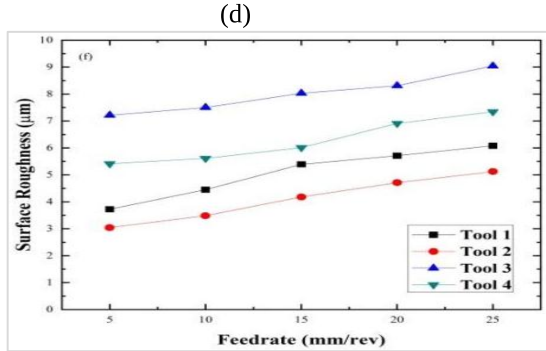
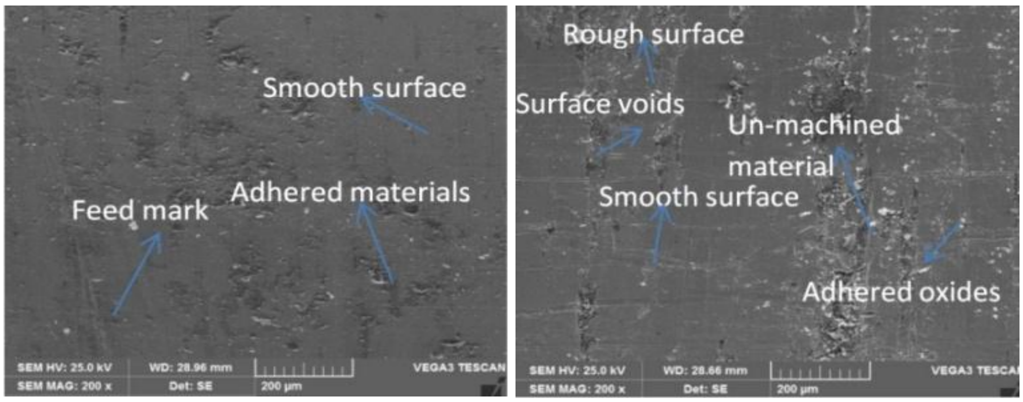


(f)

Figure 7 Effect of Cutting speed and Feed rate on torque using different tools on work piece with different hardness of 15HRC (a & b), 20HRC (c & d) and 25HRC (e & f)

4.3Microstructure analysis of drilled surface

SEM images showing the surface quality of the drilled work piece are considered in evaluating the performance of the tool as shown in *Figure 8.* Medium carbon steel without any alloying element is chosen as the work. The operation is done by maintaining peed of cut at 12.57 m/min along with feed of 5 mm/rev. Varied coated HSS tools were tested to decide the better performing one. As discussed earlier it is evident in *Figure 8* that, good surface finish is observed at higher speeds. Work having 20 and 25HRC is selected for testing. *Figure 8 (a)* shows good surface quality compared to *Figure 8 (b).* As hardness increased, the resistance force between tool and work increased [11]. Here, as hardness of the work increases there are higher surface voids, adhered oxides, rough surface and it can be seen in the images. This shows that, better surface quality is observed at maximum speed and minimum feed for lower hardness of the work.



(a) (b)

Figure 8 SEM view of drilled EN8 steel showing (a) Good surface quality with 20 HRC, (b) Poor surface quality with 25 HRC

5.Discussion

The experimental investigations carried out to evaluate the performance of different coating materials on HSS tool substrates which resulted in distinct outcomes for all four coating materials selected for this study. It was observed that, the magnitude of thrust force is higher at low speed of cut and reduced gradually as cutting speed increases. In addition, the lower the magnitude of thrust force resulted in minimum feed rate and increases as feed increases. A similar trend is noticed for surface roughness obtained during the study. The magnitude of surface roughness is higher at low speed of cut and at higher feed rate and vice versa. A tool with coating material R2 composition showed better performance with respect to thrust force and surface roughness. Further succeeding significance compositions are R1, R4 and finally the tool with R3 composition. For smooth and efficient machining of hard EN8 material the HSS tool with R2 composition is suggested which results in good quality in machined specimen with improved tool life.

5.1Limitations

Experimental investigations are carried out on a varied hardness EN8 specimen. During machining it was found that, the coated tool performed better for 15 and 20 HRC sample compared to 25 HRC sample. The coating provided is gradually rubbed off while machining at maximum operating conditions and resulted in increased surface roughness. On the other hand, very good machined quality is obtained for sample having a hardness less than 20 HRC. Thus, it is suggested to use these coating compositions developed for machining work up to 20 HRC efficiently.

A complete list of abbreviations is shown in *Appendix I.*

6.Conclusion and future work

Performance investigation of PVD coated HSS tool against the varied hardness EN8 work has been conducted. Four different coating compositions were used for the study resulted in requirement of distinct operating conditions for producing better surface integrity, torque and thrust force. Some of the major concluding remarks are listed below.

- Tool performance with varying composition of R1, R2, R3 & R4 and hardness of 15, 20 & 25 HRC specimen is studied. Out of all these, tool with coating R2 proves very efficient and can be used for laboratories and practical applications.

- Lower thrust force as speed of cut and feed rate varied, influences in quality work produced directly. Here, maximum and minimum thrust force observed is 6 & 67 N for 15 & 25 HRC specimen respectively.
- Lower torque as observed with an R2 composition tool with lower torque value is 1.12N at 5mm/rev.
- The lowest and highest surface roughness is 1.8 & 9.04 µm for 15 & 25 HRC. Out of all these, tool 2 gives lower thrust force and lower surface roughness & better performance when a feed is altered along with speed of cut comparatively.
- For 15 & 20 HRC specimen, the performance is quite good and it is practically feasible. When EN8 with 25 HRC is used, the drilling operation is poor which produces burr, uneven surface roughness and thrust force and drill bit is failing in producing the required results. Thus, the chosen tool 2 can be used for materials having a hardness lower or equal to 20 HRC.

Due to poor performance of the tool during machining of sample above 20 HRC, it is recommended to optimize the process using optimization techniques like Taguchi, RSM, numerical and mathematical models which may result in better performance of the tool. Investigative study on coating composition is to be studied to develop best coating composition which retains its properties during machining of high hard work at high feed and speed.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Author's contribution statement

Roopa D: Conducted the research work and drafted the article. **Vardhaman S Mudakappanavar:** Designed and planned the experimentation and parameters with their levels. Also helped to prepared first draft through technical inputs. **R. Suresh:** Conceptualized the current work and revisions were made to draft the article. **Tataram K Chavan:** The important revisions and final draft of the manuscript was done.

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Appendix I

S. No.	Abbreviation	Description
1	AISI	American Iron and Steel Institute
2	BUE	Built Up Edge
3	CNT	Carbon Nano-Tube
4	COF	Coefficient of Friction
5	CVD	Chemical Vapour Deposition
6	DLC	Diamond Like Carbon
7	EDAX	Energy Dispersive X-Ray Analysis
8	EN	European Norms
9	EN8	Unalloyed Medium Carbon Steel (080M40)
10	HRC	Rockwell Hardness on Rockwell C Scale
11	HSS	High Speed Steel
12	PVD	Physical Vapour Deposition
13	S/N	Signal-to-Noise Ratio
14	SEM	Scanning Electron Microscopy
15	XPS	X-Ray Photoelectron Spectroscopy