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TECHNICAL ARTICLE

# Comparative Machinability Aspects of Austenitic and Duplex Stainless Steels During Dry Turning

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Austenitic stainless steel (ASS) and duplex stainless steel (DSS) are referred as "difficult-to-cut" materials in the manufacturing industry because of different machining difficulties including work hardening, high cutting temperatures and formation of built-up layers. DSS is the preferred replacement for ASS but includes a difficult manufacturing environment. Moreover, the wet machining conditions raise several issues related to the human health, environment, disposition and costing. However, turning of these materials in the dry environment is a challenging task. The present research work is a comparison of machinability aspects of ASS 304 and DSS 2205 in a dry environment using AlTiN coating deposited by two advanced coating deposition techniques including direct current magnetron sputtering (DCMS) and high-power impulse magnetron sputtering (HiPIMS). Uncoated tools showed the worst performance at every stage of machining. AlTiN (HiPIMS)-coated tools showed the lowest increase in average surface roughness of 8%, 17% lower cutting force and 1.5-times higher tool life compared to AlTiN (DCMS) tools. DSS 2205 was the most difficult material to machine in dry conditions, exhibiting the lowest average tool life of 3890 mm compared to 4315 mm by ASS 304. Moreover, HiPIMS-coated tools helped in improving the machining performance of DSS 2205 up to some extent.

## INTRODUCTION

Stainless steels are one of the most widely used engineering materials. Compared to other material grades, they are used in considerable quantities (72%). Stainless steels are chemically more complicated than alloy steels. Austenitic stainless steels (ASS) and duplex stainless steels (DSS) are known for their excellent corrosion resistance. Moreover, both materials are termed difficult to cut.[1] ASS grades can be utilized in applications where a single property is required, while DSS is the best option when an amalgamation of characteristics is required. At high temperature machining, both duplex and austenitic stainless steels provide considerable obstacles, DSS is more demanding because of its increased strength and hardness and poorer thermal properties. Although ASS has a tendency to work harden, it provides greater heat dissipation and easier machining under identical circumstances than DSS. When comparing DSS to ASS grades, DSS has a pitting resistance equivalent number (PREN) of 36, but ASS only has 20.[2] DSSs are known for their corrosion resistance in critical environments including salt water applications like in marine settings. However, ASS is known for its better mechanical properties like deep drawability. DSS provides higher strength to weight ratio with corrosion resistance, leading to both cost and weight savings.[3]

The choice of ASS 304 and DSS 2205 for dry machining research is motivated by their pioneering prestige in their respective steel families and various industrial applications but contrasting

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properties. ASS was famous as a marine grade steel, but its vulnerability to stress corrosion cracking (SCC) made DSS a better alternative for marine applications. ASS 304 is used for aircraft components, chemical processing equipment, beverage industries and heat exchangers, whereas DSS 2205 is important in the aggressive corrosion environment, e.g., in desalination plants, offshore structures, chemical storage tanks and pipes carrying corrosive oil and gas, pumps and valves. DSSs are more suitable and used as a preferred alternative in conditions where a highly critical corrosive environment is to be sustained. Stress corrosion cracking accelerates because of the combination of high temperature and tensile stresses, where standard austenitic grades 304 and 316 tend to fail. Duplex stainless steels (DSS) and their grades have a mixed microstructure, featuring equal proportions of austenite and ferrite phases. DSSs have a high chromium content (21% to 26%), which offers good corrosion resistance and high strength. Nitrogen and manganese replacing the nickel (up to some extent) resulted in lower cost compared to ASS, without compromising the mechanical properties. Moreover, the design strength of DSS, which is about twice that of ASS, also contributed to the cost saving.[1]

The family of grades ASS and DSS are termed ‘difficult to cut’ because of their poor thermal conductivity, low ductility, high mechanical strengths, toughness and work hardening tendency.[4,5] Mahdavinejad and Saeedy carried out the machining of AISI 304 stainless steel in dry and wet conditions with cutting speed and feed rate in the range of 100 and 200 m/min and 0.2 to 0.4 mm/rev, respectively. He cited the poor conductivity of AISI 304 steel as the primary cause of the cutting tool wear.[6] Akasawa et al.[7] investigated the AISI 304 and 316 materials with cutting speed and feed rate in the range of 0.05 to 0.1 mm/rev, respectively. They found the BUE formation to be more dominant. Selinder et al.[8] also noted the BUE issues and work hardening tendency of the machined surface, which made the SS 304 machining problematic. DSS, when machined with PVD-coated tools, showed the BUL, which accelerated surface roughness.[9] The heat induction resulted in plastic deformation and wear craters and severe fragmentation, making DSS more complicated to machine.[10] However, exact comparison with evaluation of response parameters is not published by researchers.

Although ASS and DSS are relatively similar because of its higher strength and high alloy content, DSS requires some special changes in the machining practice. DSS hardness (35 HRC) does not indicate machining difficulties, but other features such as high work hardening, low thermal conductivity and high toughness add to machining issues. Therefore, duplex grades are more difficult to cut than the 300-series austenitic stainless steels.[1] Ran et al.[11] compared AISI316L stainless steel with the DSS for mechanical and corrosion resistance and found the DSS to be better and more economical. Higher nitrogen (N) and molybdenum (Mo) contents make the DSS machining difficult even when coated carbide tools are used. Nitrogen enhances the strength and hardness of the austenite phase within DSS, since it is a potential austenite stabilizer. It also makes a contribution to work hardening tendency of the material which is difficult to cut through. At high temperatures, the increased hardness and strength lead to higher cutting forces and accelerated wear on carbide-coated tools. On the other hand, molybdenum helps to stabilize a ferrite possessing higher hardness, which leads to a microstructure that confronts the machining. Mo also contributes to the high temperature strength of DSS by solid solution strengthening. Moreover, during DSS machining, chip control becomes difficult because of excessive mechanical and thermal loads on the tool point. This results in a strong adhesive interaction between the tools and the chip, forming the Built-up Edge (BUE).[12] The DSS has a strong affinity for BUE formation compared to the ASS. This occurs as the workpiece material sticks to the substrate during cutting.[13] BUE formation is a big concern resulting in higher cutting forces, poor dimensional tolerance control, faster tool wear and deterioration of the machined surface in both materials. Higher Mo content of the DSS increases in strength even at higher temperatures, thus requiring higher cutting forces and rendering the DSS very ‘difficult to machine’.[13,14]

Extensive research and development efforts are being devoted globally to optimizing machining techniques to ensure effective and economical machining of stainless steels via adequate knowledge of the ASS and DSS during machining. However, the machining difficulties of these SS grades remained unaltered. Moreover, the focus related to the machining of these materials shifted on the dry turning in the last decade, since wet machining environments caused various environmental issues, damage to ecological factors, health standards as well as operational safety. Authors have also reported the dry turning to be the most economical machining method than wet machining.[15] All these concerns led to the elimination of cutting fluids and the promotion of dry cutting to increase productivity. Dry machining is environmentally preferable and will soon be regarded as a requirement for industrial businesses. The benefits of dry machining include no pollution of the atmosphere and water, no residue on the swarf, which means less disposal, no hazard to health and non-injurious, cost savings and so on.[16,17] When employing a dry machining environment for DSS and ASS, particularly high-performance coatings over cutting tools are used. Dry cutting necessitates better surface topography in cutting tools.

The surface of cutting tools is improved by commonly available surface modification techniques such as chemical vapor deposition (CVD) and physical vapor deposition (PVD).[18] PVD technique has surpassed the CVD because of its low process operating temperature, compressive residual stresses, and eco- and environment-friendly attributes. Furthermore, the PVD technique has the benefit of producing dense columnar structures, which are ideal for sharp cutting edges and play a key role in machining difficult-to-cut materials.[19–21] Krolczyk et al.[22] studied the dry machining of DSS 2205 using a CVD multilayer Ti (C, N)/$Al_2O_3$/TiN-coated carbide tool to predict the surface roughness. They discovered that the dominant factor for surface roughness was the feed rate. Kaladhar et al. claimed a surface roughness of 0.4 $\mu$m is sufficient while dry turning DSS 2205 to eliminate post-finishing operation like grinding.[23] Authors have claimed the feed rate to be the most dominant parameter for surface roughness.[24] Chinchanikar et al.[25] carried out the comparative study of PVD and CVD-coated carbide tools to evaluate their machining performance. Since PVD coatings caused low friction during machining of AISI 4340 steel, lower cutting forces were recorded for PVD over CVD-coated tools. Regarding PVD coating techniques, it has been discovered that cathodic arc evaporation (CAE), pulsed DC magnetron sputtering (DCMS) and high-power impulse magnetron sputtering (HiPIMS) are the most recent breakthroughs.[4] Wagh et al.[26] studied the performance of AlCrN/TiAlN-coated carbide tools using the CAE technique for high-speed turning of AISI 304 steel in the dry environment. The surface roughness rose with increasing cutting feed but reduced with increasing cutting speed. Due to the lower friction coefficient of the coating, AlCrN/TiAlN-coated cutting tools provided lower cutting forces. Since the coating's limited thermal conductivity, the tool-chip interface temperature rose with increasing cutting speed and reached temperatures of up to 1025 °C. Kulkarni et al.[27] used multilayer CAE AlTiN/TiAlN-coated carbide tools to examine the machinability of AISI 304. The greatest measured temperature was 938 °C, and the tool-work zone temperature rose with increasing cutting speed. The dominant parameter of cutting force was found to be feed. Researchers also evaluated the AlTiCrN coatings produced by HiPIMS and CAE techniques individually. It was reported that the HiPIMS methodology delivered better results owing to higher adhesion property as well as generation of a stable $\alpha$ $(Al,Cr)_2O_3$ mixed oxide layer.[28] Kulkarni et al.[27] investigated the machining performance of ASS 304 using HiPIMS AlTiCrN and DCMS AlTiN coatings. They found that the DCMS-coated tools delivered higher cutting forces and cutting temperature because of coating properties such as low adhesion strength and microhardness. Furthermore, nose wear was found to be a dominant wear mode for DCMS-coated tools. Quillin et al.[29] also investigated the comparative microstructural study of DCMS and HiPIMS Cr coatings on the SiC substrates. It was reported that the pulsed DCMS caused coarsening of the columnar grains, resulted into the dense microstructure and induced tensile stresses. Several studies discovered that the HiPIMS deposition generates coatings with superior density, defect-free microstructure, greater hardness, adhesion strength, compressive stresses and smoother surfaces than DCMS coatings.[4,30–32] In recent years, many coating materials have emerged for turning ASS and DSS. Authors have recommended that using a dry environment for machining DSS 2205[33] and SS 304[34] necessitates the use of extremely efficient coatings such as AlTiN, TiAlN possessing exceptional hot hardness, wear resistance, thermal stability, oxidation resistance, etc.

The literature available suggests the importance of ASS and DSS in industry. Moreover, machining these materials in a dry environment is a challenging task which gave a rise to use of advanced PVD coatings and deposition techniques. Most of the researchers[23] have worked on separate investigations of either ASS or DSS or have used only empirical and simulation models to predict the response parameters.[35] However, these two materials have some different aspects related to the properties and accordingly used for different applications. Selecting one of ASS and DSS requires a clear comparative understanding about the machining aspects, which is missing in the literature. Leading to this, in the present investigation, comparison of machining aspects of ASS and DSS is done. Moreover, PVD DCMS and HiPIMS coating deposition techniques have been used for depositing AlTiN coatings individually on carbide inserts since they have not been investigated for comparison of dry turning of DSS2205 and ASS 304 steels. Dry turning of ASS and DSS was carried out using cutting speeds in the range of 100 m/min to 180 m/min and feed rate from 0.12 mm/rev to 0.18 mm/rev, with a constant depth of cut of 0.8 mm. The response parameters including surface roughness, cutting force and tool life were measured to analyze the machining performance.

## MATERIALS AND METHODS

### Workpiece Material

The current investigation was carried out to analyze the machining performance of ASS304 and DSS2205 grades during dry turning. DSS2205 have higher chromium than ASS304 responsible for good corrosion resistance and strength. However, the nickel is replaced with some nitrogen and manganese, which lowers the cost without adjusting the material properties. The chemical composition of ASS304 and DSS2205 indicating the major alloying elements is shown in Table I.

The cost saving for DSS is due to the double design strength compared to ASS. In many aspects, though, DSS and ASS are similar; the lower machinability index of DSS needs some special changes during machining.

The properties of ASS 304 and DSS 2205 are given in Table II. Due to these distinct properties of austenitic and duplex stainless steels, it will be interesting to see how these two materials perform in dry turning for machining productivity.

## Cutting Tool, Coatings and Characterization

Indexable carbide inserts (ISO: CNMG120408) with positive chip breaker geometry MF4 were used for straight dry turning of ASS 304 and DSS 2205 materials. The tool geometry was selected as per the suggestions from DSS manufacturers, International Molybdenum Association, and the literature survey. AlTiN coating deposition on tungsten carbide indexable inserts was carried out using the advanced and recently developed PVD high-power impulse magnetron sputtering (HiPIMS) and high-rate vacuum DC magnetron sputtering (DCMS). Characterization was carried out to analyze the properties of workpiece materials, uncoated WC tool and PVD AlTiN coatings.

Uncoated WC tool and ASS304 and DSS2205 workpiece materials were investigated for the microstructures. Moreover, the AlTiN coating was evaluated in terms of microhardness, microstructure, thickness, adhesion strength and surface roughness. The microstructures of tool, workpiece and coating materials were observed using the JEOL (JSM-7600F) field emission gun-scanning electron microscope (FEG-SEM). The fractograph of coatings taken through FEG-SEM helped to measure the thickness of the coatings used. The coating thickness was also confirmed using the scratch test. However, energy-dispersive X-ray spectroscopy (EDS) was used for confirming the chemical composition of the PVD coatings. The adhesion strength of the coating was measured using the scratch test based on the 'critical load phenomenon.' Using a scratch speed of 0.2 mm/s with a diamond stylus having a 0.4-mm-tip and loading rate of 5 N/mm, adhesion strength was measured. The microhardness was measured using a HMV-2 Series Vickers microhardness tester, using a load of 50 g for a time of 20 s. The surface roughness of coatings was also measured with the SJ 301 contact roughness tester. For accurate results, microhardness, surface roughness and adhesion tests were carried out for three readings, and the average of the three readings measured is reported in this investigation.

## Machining Performance

To study the comparative machinability aspects of ASS 304 and DSS 2205, tungsten carbide tools coated with AlTiN coating deposited using DCMS and HiPIMS techniques were used. In the current investigation, two advanced coating deposition techniques including DCMS and HIPIMS are used. Moreover, the coating service was provided by renowned and leading coating service providers. DCMS coatings are provided by Guhring, India, and HiPIMS by CemeCon, Germany. The process parameters for DCMS and HiPIMS techniques are as depicted in Table III.

The performance of coated tools was compared with uncoated tools during dry turning for the performance measures including tool life, cutting force and surface roughness. For dry turning, a CNC lathe (AC Jobber XL) was used. The

**Table I. Alloying elements (wt.%) of ASS304 and DSS2205 steels**

| | Cr | Ni | Mo | Si | C | N | Mn | Fe |
|---|---|---|---|---|---|---|---|---|
| ASS | 18 | 9 | 2.5 | 0.5 | 0.04 | 0.10 | 2 | Balanced |
| DSS | 22 | 6 | 3.70 | 0.67 | 0.030 | 0.15 | 1.73 | Balanced |

**Table II. Mechanical-physical properties of investigated ASS304 and DSS2205 steels**

| Mechanical properties | ASS 304 | DSS 2205 |
|---|---|---|
| Tensile strength (MPa) | 520 | 621 |
| Yield strength 0.2% (MPa) | 247 | 448 |
| Compressive strength (MPa) | 210 | 308 |
| Elongation (%) | 45 | 25 |
| Hardness (Rockwell B) | 92 | 108 |
| Modulus of elasticity (kN/mm$^2$) | 200 | 200 |
| Thermal conductivity (W/m K) at 100 °C | 16.7 | 15 |
| Specific heat capacity (J/kg K) | 502 | 418 |

**Table III. Coating deposition parameters**

| Parameter | CAE | HiPIMS |
|---|---|---|
| Vacuum chamber pressure (Pa) | $1.33*10^{-1}$ | $1.33*10^{-8}$ |
| Deposition temperature (°C) | 580 | 450 |
| Deposition rate (A/min) | 750,000 | 10,000 |

**Table IV. Full factorial design of experiments (DoE) for investigated ASS 304 and DSS 2205 steels**

| Expt. No. | Speed (m/min) | Feed (mm/rev) | DoC (mm) |
|---|---|---|---|
| 1 | 100 | 0.12 | 0.8 |
| 2 | 100 | 0.15 | |
| 3 | 100 | 0.18 | |
| 4 | 140 | 0.12 | |
| 5 | 140 | 0.15 | |
| 6 | 140 | 0.18 | |
| 7 | 180 | 0.12 | |
| 8 | 180 | 0.15 | |
| 9 | 180 | 0.18 | |

dimensions of the workpiece (round bars) were 265 mm long and 85 mm diameter. Considering the length of the workpiece, a pass length of 240 mm was chosen for each machining cut. The selected cutting parameters are as depicted in Table IV. Full factorial design of experiments (DoE) was selected by referring to the cutting conditions provided by the researchers through literature, recommendations of the International Molybdenum Association (IMoA) and the manufacturers of ASS and DSS materials. The depth of cut (DoC) was kept constant at 0.8 mm.

The Epi-fluorescence Nikon microscope Eclipse 50i with Nikon's CFI60 optical system was used to measure tool wear. The criterion of 0.6-mm tool wear was used to decide the tool life of all the uncoated and coated tools used. After machining, the average surface roughness (Ra) of the machined surface was checked using the SJ 301 contact roughness tester. A sampling length of 0.8 mm was chosen for surface roughness measurement. The surface roughness was measured at three different points after each machining pass, and the average of the three readings is reported in this investigation. The cutting forces were measured using a Kistler three-component piezo-electric force dynamometer during the dry turning.

## RESULTS AND DISCUSSION

This section elaborates the detail justifications for the results obtained after the characterization followed by the dry turning of ASS 304 and DSS 2205.

### Characterization of Workpiece Materials and Carbide Tool

ASS 304 and DSS 2205 were characterized for the chemical composition using SEM-EDS methodology to confirm the alloying elements and microstructural features. The EDS examination results compared and validated the main alloying elements. The micrographs recorded using the SEM are shown in Fig. 1a and b, revealing the microstructures of ASS 304 and DSS 2205, respectively. The microstructure of ASS 304 shows a single phase of austenite whereas the duplex 2205 steel depicted alternate layers of austenite and ferrite situated alternatively. The change in hardness encountered after turning is caused by these alternate layers of austenite and ferrite present in DSS 2205.

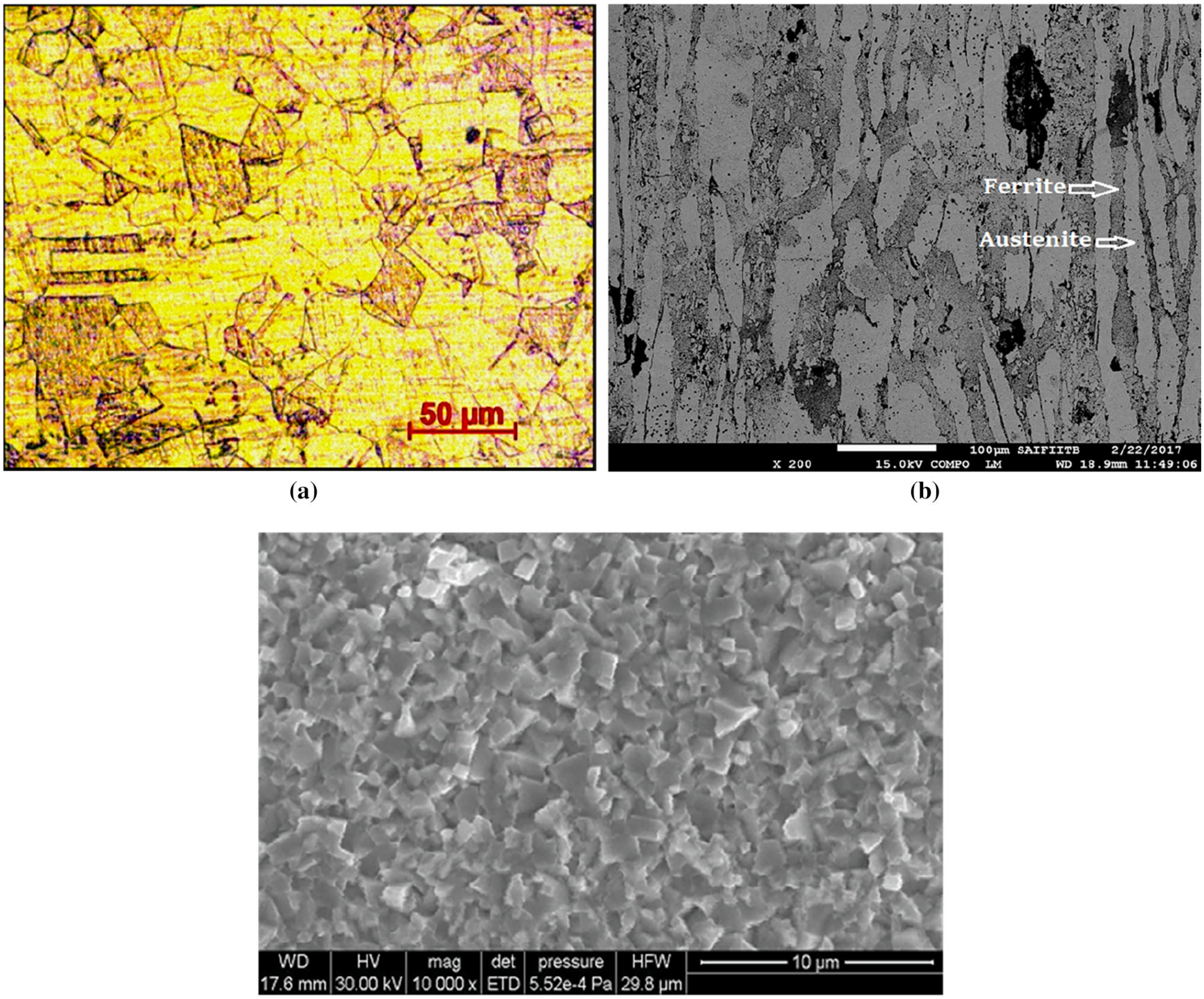
The microstructure of a carbide (WC) tool is shown in Fig. 1c. The WC tools manufactured by SECO showed good control over the grain size with uniform and compact grain structure. It represents the homogeneous and fine grains of the WC tool with an average grain size in the range of 0.3–0.5 $\mu$m. The grain structure is almost void free because of the perfect binding of WC grains with cobalt binder (9–11%).

### Characterization of PVD Coatings

In this investigation AlTiN coating was deposited using two advanced PVD deposition techniques including DCMS and HiPIMS. For ease of discussion and better clarity, hereafter these two coatings will be termed AlTiN (DCMS) and AlTiN (HiPIMS). Moreover, it is necessary to assign specific nomenclature to the uncoated and AlTiN-coated tools deposited using different coating techniques for machining ASS 304 and DSS 2205. Hereafter, the nomenclature for the tools used in this investigation is as depicted in Table V.

Characterization of AlTiN (DCMS) and AlTiN (HiPIMS) coatings was done for microstructure, coating thickness, adhesion strength, microhardness and surface roughness. SEM analysis was used to reveal the microstructures of single-layer AlTiN (DCMS) and AlTiN (HiPIMS) coatings. Figure 2a and b depicts fractographs of both coatings measuring the coating thickness. Coating thicknesses of 3.2 $\mu$m and 4 $\mu$m were recorded for AlTiN (DCMS) and AlTiN (HiPIMS) coatings, respectively. In addition, the SEM fractographs also revealed the dense-columnar structure of AlTiN coating deposited by DCMS technique. Moreover, the micrograph (Fig. 2b) of AlTiN coating showed a very compact structure when deposited using HiPIMS technique.

Figure 2a and b shows the SEM micrographs indicating the microstructure of both coatings used. AlTiN (DCMS) technique showed columnar microstructure with microparticles of varying size on the surface, whereas the AlTiN (HiPIMS) coating showed non-porous, defect-free, smooth and compact microstructure.



(a)

(b)

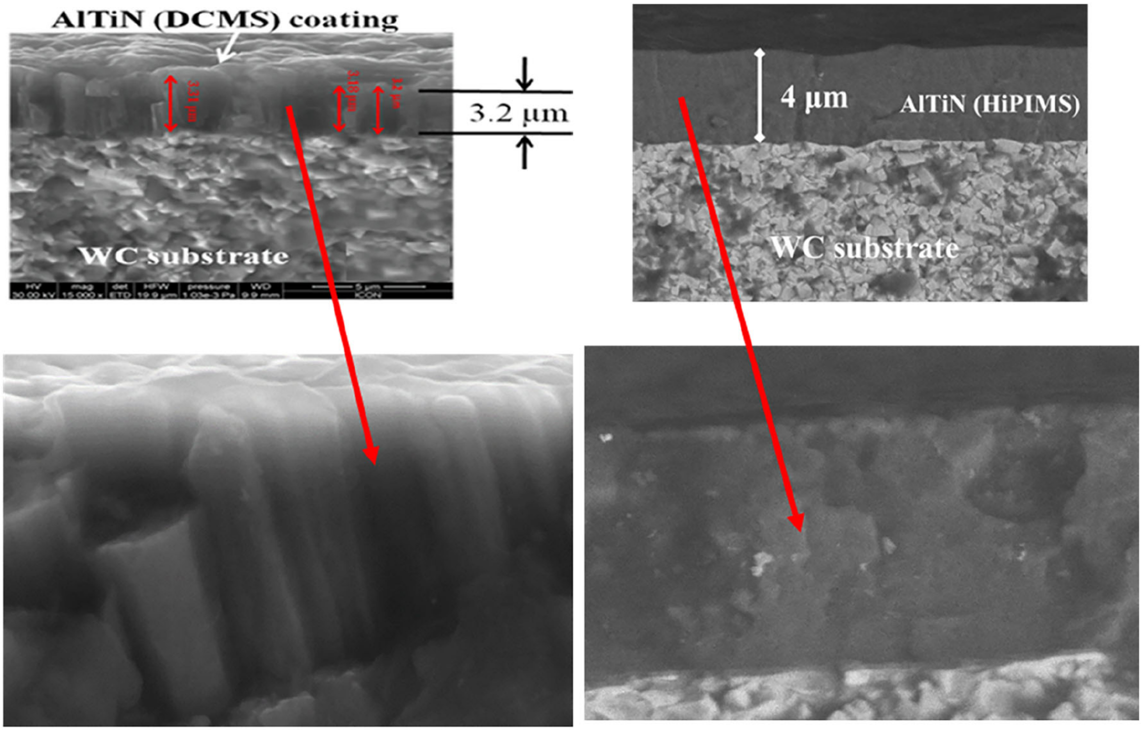
(c)

Fig. 1. SEM micrographs showing the microstructures of (a) ASS 304 and (b) DSS2205, (c) cemented carbide (WC) insert.

**Table V. Tool nomenclature**

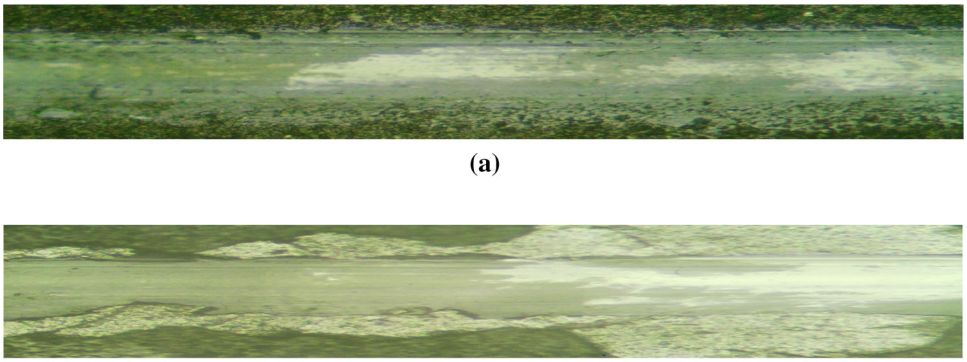
| Sr. no. | Tool coating and deposition method | Workpiece | Tool nomenclature |
|---|---|---|---|
| 1 | Uncoated | ASS 304 | T1 |
| 2 | Uncoated | DSS 2205 | T2 |
| 3 | AlTiN (DCMS) | ASS 304 | T3 |
| 4 | AlTiN (DCMS) | DSS 2205 | T4 |
| 5 | AlTiN (HiPIMS) | ASS 304 | T5 |
| 6 | AlTiN (HiPIMS) | DSS 2205 | T6 |

The scratch path images for both the coatings used are as shown in Fig. 3a and b. AlTiN (HiPIMS) coating showed a good adhesion bond between the coating and the substrate exhibiting higher adhesion strength of 101 N compared to 93 N of AlTiN (DCMS) coating. The conventionally deposited AlTiN coating using DCMS technique delaminated early resulting in poor adhesion strength. The white portion in the scratch path indicated the tool surface exposure due to delamination of the coating. Figure 3a shows earlier delamination of the coating and tool surface exposure, which resulted in lower



(a) (b)

Fig. 2. SEM fractographs and microstructure of AlTiN coating coated using (a) DCMS and (b) HiPIMS deposition techniques.



(a)

(b)

Fig. 3. Scratch path of AlTiN coating deposited using (a) DCMS and (b) HiPIMS techniques.

adhesion strength of an AlTiN (DCMS) coating. Moreover, advanced properties of AlTiN (HiPIMS) kept it intact, and the delayed delamination is clearly depicted in Fig. 3b, exhibiting higher adhesion strength of 101 N.

The Vickers microhardness test with 50 g load was performed on the investigated coated carbide tools with AlTiN coating. The microhardness of 35 GPa for AlTiN (DCMS) coating was recorded, whereas it was found to be 37 GPa for the AlTiN (HiPIMS) coating. A similar range of microhardness for AlTiN coating is reported in previous literature. Microhardness is a correlating factor with the grain size. The compact structure of AlTiN (HiPIMS) coating is the reason for higher microhardness compared to AlTiN (DCMS) coating. HiPIMS technique has a slow deposition rate causing lower grain size of deposited particles, i.e., fine grain structure. As the grain size decreases, the grain boundaries increase, increasing the obstacles and as a result the microhardness.

The surface roughness measurement was carried out on the coating surface. AlTiN (DCMS) coating exhibited a surface roughness of 0.21 $\mu$m whereas AlTiN (HiPIMS) coating showed a surface roughness of 0.19 $\mu$m. No substantial difference was observed between the investigated coatings. However, the difference in surface roughness is minor as

**Table VI. Characterization results with mean values and standard deviation of PVD-coated tools**

| | AlTiN (DCMS) | | | AlTiN (HiPIMS) | | |
|---|---|---|---|---|---|---|
| **Properties** | **Reading** | **Mean** | **SD** | **Reading** | **Mean** | **SD** |
| Coating thickness ($\mu$m) | 3.2 | 3.23 | 0.20 | 4 | 3.96 | 0.20 |
| | 3.5 | | | 4.2 | | |
| | 3 | | | 3.7 | | |
| Adhesion strength (N) | 93 | 93.3 | 1.24 | 101 | 100.83 | 0.23 |
| | 92 | | | 101 | | |
| | 95 | | | 100.5 | | |
| Microhardness (GPa) ($HV_{0.05}$) | 35 | 34.8 | 0.23 | 37 | 36.83 | 0.24 |
| | 35 | | | 36.5 | | |
| | 34.5 | | | 37 | | |
| Surface roughness ($\mu$m) | 0.21 | 0.21 | 0.005 | 0.19 | 0.19 | 0.002 |
| | 0.22 | | | 0.19 | | |
| | 0.21 | | | 0.195 | | |

tool wear takes place, the friction increases, and the tool life decreases. The results obtained through the characterization of coated tools is as depicted in Table VI.

## Effect of Cutting Parameters on Surface Roughness

In this section, the effect of cutting speed and feed rate on surface roughness is discussed.

### *Effect of Cutting Speed on Surface Roughness*

Figure 4a, b and c illustrates the influence of cutting speed on surface roughness at a feed rate of 0.12 mm/rev to 0.18 mm/rev, respectively. Surface roughness reduced when the cutting speed was raised from 100 m/min to 180 m/min at every feed rate used for both uncoated and coated tools. Lower cutting speeds have a higher susceptibility to BUL formation. At lower cutting speeds, friction between the tool and workpiece rises, leading to greater surface roughness exhibiting BUL formation. BUL formation decreases as the cutting speed increases. Lower BUL reduces friction between the tool and the chips generated, reducing surface roughness.[36,37]

Uncoated tools reported the highest surface roughness among all cutting tools used in this investigation. The protective hard PVD coatings helped coated tools for retaining sharp cutting edges for longer machining distances. Another reason for this one is the Al layer on top of the coated tools.[38] When Al is mixed with oxygen at higher temperatures, it forms an $Al_2O_3$ protective layer. On the other hand, the uncoated tools were unable to sustain dry machining and experienced faster tool wear and friction. Hence, higher surface roughness was observed for uncoated tools compared to coated tools.

T3 and T4 tools exhibited higher surface roughness than T5- and T6-coated tools. T5 and T6 tools contain the AlTiN coating deposited by HiPIMS technique, which exhibited the lowest surface roughness. This is due to a low coefficient of friction, high thermal stability as well as adhesion strength produced by HiPIMS deposition technique. Moreover, these enhanced properties of the coatings as well as higher thermal stability protects the cutting edge even at high temperatures, lowering the tool wear rate, which as a result contributed to lower the surface roughness of the machined surface.[20,39,40] Since DSS 2205 has higher hardness and yield strength, it is more difficult to machine even with PVD-coated tools. This exhibits higher surface roughness values for DSS 2205 compared to ASS 304 at every cutting condition and coating used. Moreover, the tendency of formation of BUE for DSS 2205 is more than for ASS 304 because of higher mechanical and thermal loads while machining. This contributes to increasing surface roughness. The average rate of increase in surface roughness for DSS 2205 compared to ASS 304 was 13% and 19% for uncoated and AlTiN (DCMS)-coated tools respectively. Moreover, when AlTiN (HiPIMS)-coated tools were used, the rate of increase for DSS 2205 was only 8%. This clearly suggests the importance of enhanced properties of HiPIMS deposition technique for dry machining of DSS 2205. On the other hand, the DCMS coatings were only suitable for machining ASS 304 material and were unable to sustain a critical environment during dry machining of DSS 2205.

### *Effect of Feed Rate on Surface Roughness*

Figure 5a, b and c depicts the influence of feed on the surface roughness. An increase in feed values from 0.12 mm/rev to 0.18 mm/rev resulted in an increase in the surface roughness. This occurred because of an increase in material removal rate (MRR) upon increasing the feed rate. Uncoated tools have a larger coefficient of friction and so provide more resistance to chip movement over the rake

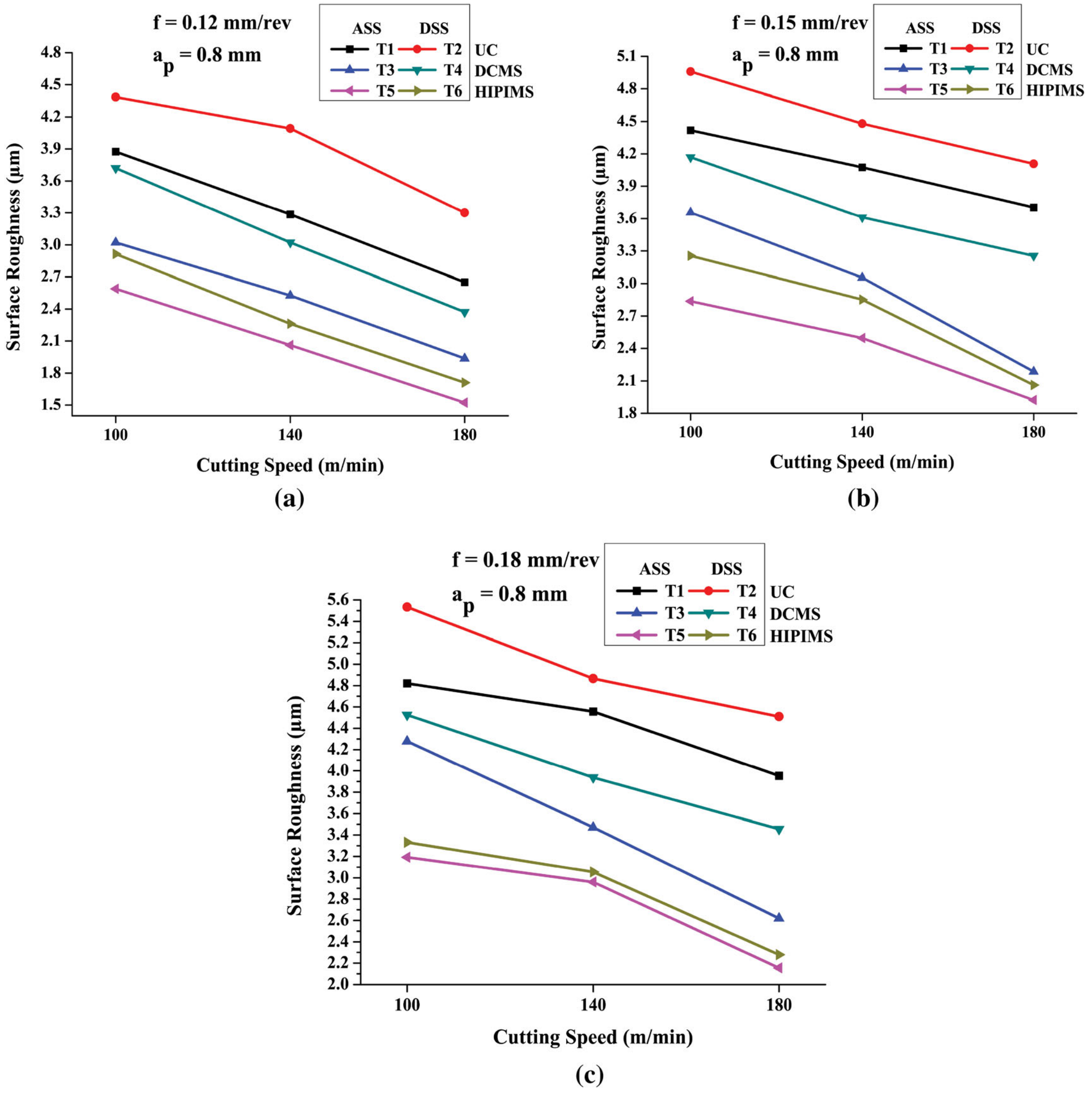


Fig 4. Effect of cutting speed on average surface roughness (Ra) at (a) *f* = 0.12 mm/rev, (b) *f* = 0.15 mm/rev and (c) *f* = 0.18 mm/rev.

surface. Increased friction causes BUL generation as temperature rises, increasing surface roughness.[41] Therefore, uncoated tools provided the worst performance regarding the surface roughness.

Coated tools, on the other hand, have a lower coefficient of friction. As a result, the coated tools facilitated less friction force and delivered low surface roughness. Moreover, in case of coated tools, due to the high Al content, AlTiN coatings have higher microhardness.[42] This happens because smaller crystals promote grain boundary hardening. The coated tools provided better stability during dry turning exhibiting lower surface roughness.

The least surface roughness in the range of 1.7 $\mu$m and 3.1 $\mu$m was observed for AlTiN (HiPIMS)-coated tools. Moreover, AlTiN (DCMS) tools and uncoated tools exhibited surface roughness in the range of 1.20–4.2 $\mu$m and from 2.65 $\mu$m to 4.8 $\mu$m, respectively. The performance of the DCMS-based coating was intermediate to the uncoated and the HiPIMS-based coating. This can be attributed to the lower adhesion strength (93 N) of DCMS coatings compared to that of HiPIMS coatings (101 N). Moreover, as higher feed rates cause an increase in temperature in the cutting zone, the thermal stability of coatings plays an important role in controlling the surface roughness of the material as it provides the wear resistance to the coatings. Since AlTiN (HiPIMS) coating has a thermal stability up to 850°C, it outperformed the AlTiN (DCMS) coating. Compared with the ASS 304, DSS 2205 exhibited the highest surface roughness at all the cutting conditions. When the feed rate increased from 0.12 mm/rev to 0.18 mm/rev at a cutting speed of 100 m/min, the surface roughness increase observed was by 24%, 41% and 20% for T1, T3 and T5 tools, respectively. DSS 2205 has poor thermal conductivity (15 W/m K). Hence, during dry turning the heat produced is transferred to the tool instead of the workpiece. Moreover, due to the rise

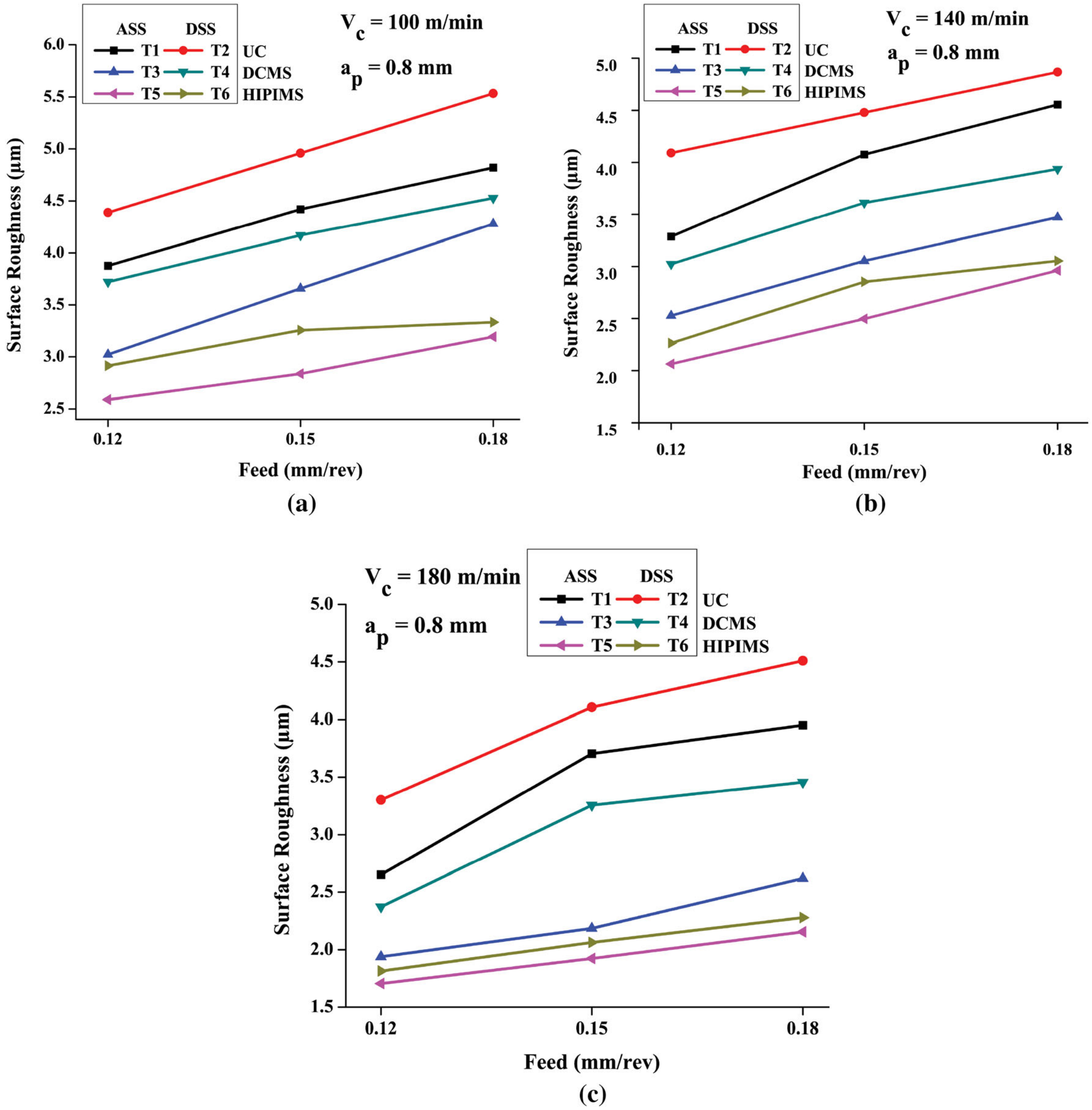


Fig. 5. Effect of feed rate on average surface roughness (Ra) at (a) $V_c$ = 100 m/min, (b) $V_c$ = 140 m/min and (c) $V_c$ = 180 m/min.

in temperature, the tool wear rate and friction between the tool and workpiece are accelerated, resulting in higher surface roughness than that of ASS 304.

## Effect of Cutting Parameters on Cutting force

### *Effect of Cutting Speed on Cutting Force*

Figure 6a, b, and c depicts the influence of cutting speed on cutting force during dry turning of ASS 304 and DSS 2205 at a feed rate of 0.12 mm/rev, 0.15 mm/rev and 0.18 mm/rev, respectively. The cutting force decreased as the cutting speed increased from 100 m/min to 180 m/min at all the feed rates used. This indicated higher cutting forces at lower cutting speeds. Machining at lower cutting speeds caused higher tool-chip contact for an elongated time. Hence, the tool rake face experienced higher contact of chip at initial stages of machining, producing higher cutting forces. Moreover, as the cutting speed is increased, this contact of the tool and chip is for less time, and subsequently lower cutting forces are observed.[43] Selvaraj et al.[44] claimed a rise in cutting forces for the increase in cutting speed over 120 m/min was used when coating with a top layer of Ti was used. However, in this investigation, even after the cutting speed was increased beyond 120 m/min, the surface roughness decreased with cutting speed. This is because the top layer of Al, which at higher cutting speeds due to higher temperatures produces $Al_2O_3$ hard layer, protecting the sharp cutting edge and exhibiting reduction, is cutting force.

Uncoated tools generated greater cutting forces than coated tools. The uncoated tools wear out at faster rates causing higher friction and cutting

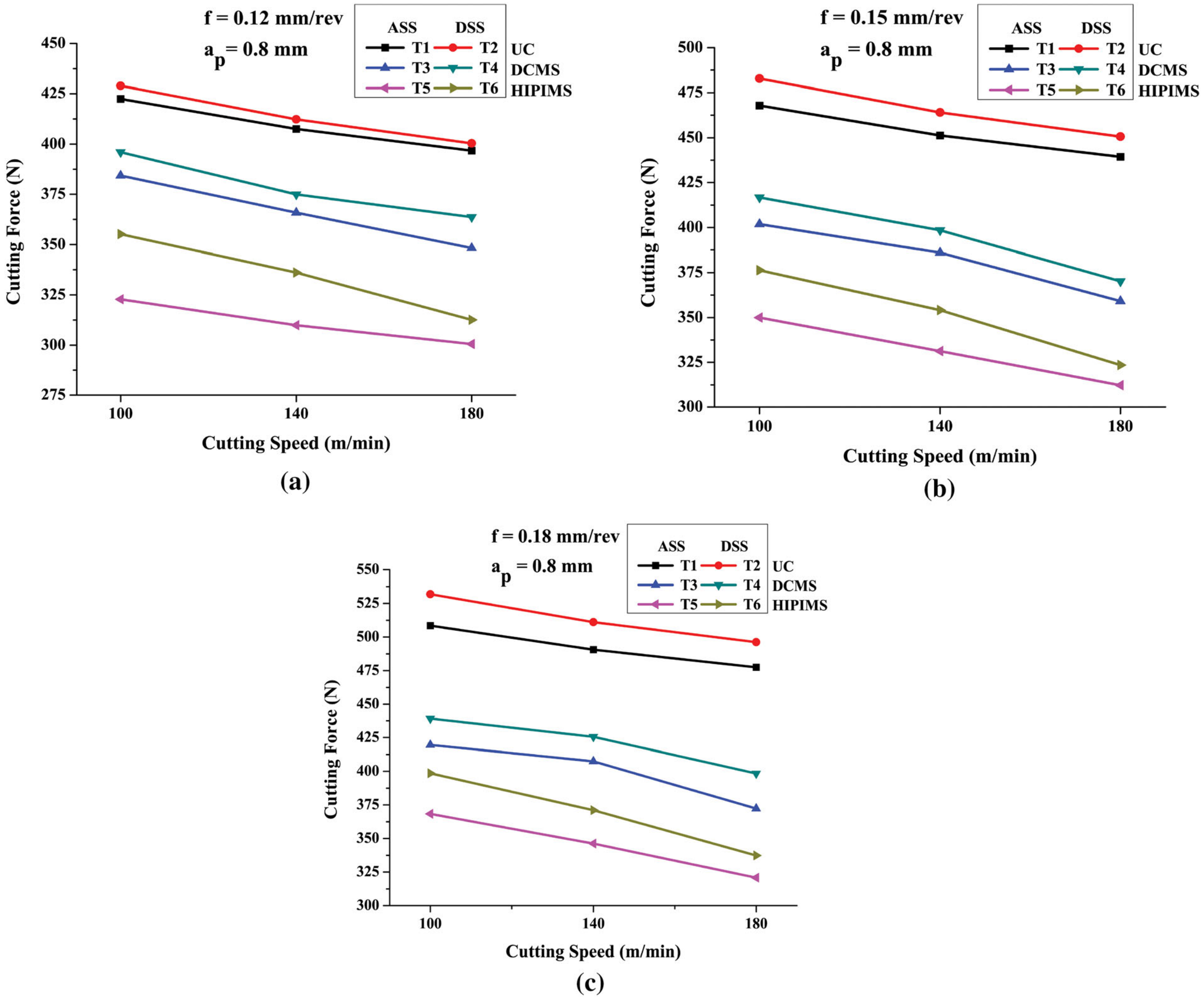


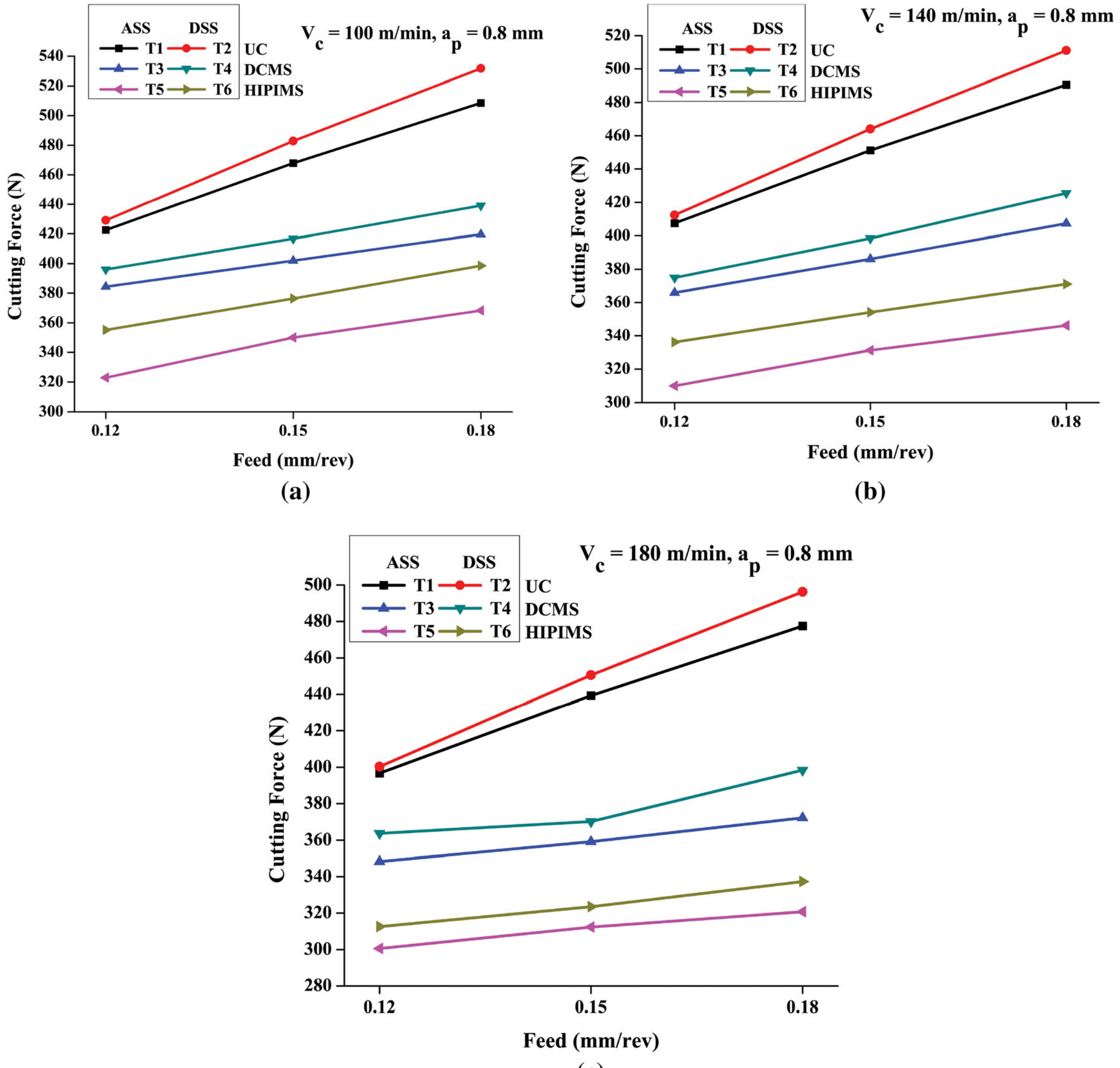
Fig. 6. Effect of cutting speed on cutting force at (a) $f$ = 0.12 mm/rev, (b) $f$ = 0.15 mm/rev and (c) $f$ = 0.18 mm/rev.

temperatures. Moreover, due to increased thermal conductivity of uncoated tools, a rise in temperature affects the strength and hardness of uncoated tool material. The amount of force required for plastic deformation of the work material rises as the hardness of the tool decreases.[45] As a result, a higher amount of cutting forces for the uncoated tools were reported. On the other hand, for coated tools, AlTiN (DCMS) and AlTiN (HiPIMS) coatings contains a nitride phase, which is hard in nature, and the thermal conductivity of these coated tools remains intact even at high cutting temperatures. This also retains the hardness of the tools, requiring less force for material deformation.[46] Hence, coated tools exhibited fewer cutting forces than uncoated tools.

It is important to emphasize that HiPIMS coatings have outperformed DCMS coatings at every cutting condition. The coated tools with AlTiN (DCMS) coating, i.e., T3 and T4, exhibited 17% higher cutting forces than the tools T5 and T6 with AlTiN (HiPIMS) coating. This is since the HiPIMS coating properties such as adhesion strength and thermal stability were discovered to be superior to DCMS coating as well as to uncoated tools. The increase in cutting force for DSS 2205 was found to be 4% to 6% more compared to ASS 304 at the initial cutting conditions. Moreover, this rise increased up to 10% when higher cutting conditions were used. Higher amount of Mo, Ni and Cr in DSS 2205 gives higher hardness and strength.[44] Moreover, work hardening tendency and lower thermal conductivity of DSS 2205 as compared to ASS 304 are the reasons for higher cutting forces during dry turning of DSS 2205. On the other hand, PVD coatings do not alter their thermal conductivity even at high cutting temperatures. This clearly suggests the machining difficulty of DSS 2205, even when coated tools are used for dry turning.

### *Effect of Feed Rate on Cutting Force*

Figure 7a, b, and c demonstrates the effect of feed on the cutting forces. The cutting force was observed to rise as the feed rate increased from 0.12 mm/rev to 0.18 mm/rev for uncoated and coated tools. The



(a)

(b)

(c)

Fig. 7. Effect of feed on cutting force at (a) $V_c$ = 100 m/min, (b) (a) $V_c$ = 140 m/min and (c) (a) $V_c$ = 180 m/min.

amount of material removed per unit time and the 'cross section' of the cut rose as the feed rate increased, so the shear plane area, chip-tool friction and temperature increased. This phenomenon affects the shear strength of the material which enables it to behave in a ductile capacity. As a result, a significant rise in cutting force was noted upon increasing the feed rate.[2,47,48] When the feed rate increased from 0.12 mm/rev to 0.18 mm/rev at a cutting speed of 100 m/min, the cutting forces, while machining ASS 304 for uncoated, AlTiN (DCMS) and AlTiN (HiPIMS), were 3-, 1.6- and 1.1-times lower compared to machining of DSS 2205. This indicates that the HiPIMS-coated tools, because of their excellent properties, remain intact for their hardness and lower wear, even when the highest feed rate of 0.18 mm/rev is used.

Uncoated tools have delivered the highest cutting forces followed by AlTiN (DCMS)- and AlTiN (HiPIMS)-coated tools. The microhardness of 37 GPa for the AlTiN (HiPIMS) coating was reported, which was found to be superior, and this triggered better performance of AlTiN (HiPIMS)-coated tools in the context of the cutting forces. Moreover, higher feed rates demand high material removal, which requires high cutting forces due to high plastic deformation. In this case, low thermal stability of AlTiN (DCMS) coating could not provide enough wear resistance in the deformation zone and hence produced higher cutting forces than AlTiN (HiPIMS)-coated tools. Since the DSS 2205 has a work hardening tendency and higher hardness of 108 HRB compared to 92 HRB of ASS 304, cutting forces for DSS 2205 were on the higher side, proving poor machinability than ASS 304. Moreover, poor thermal conductivity and lower ductility make DSS 2205 more difficult to deform. This creates a requirement of higher cutting forces for DSS 2205 than ASS 304.

At a cutting speed of 100 m/min, when the feed rate was increased from 0.12 to 0.18 mm/rev, the rate of increase of cutting force for DSS 2205 using AlTiN (HiPIMS) coating, i.e., T6 tool, was 9%. However, at similar conditions, AlTiN (DCMS) coating, i.e., T4 tools showed the 14% rate of increase of cutting force. This clearly reveals the poor machinability index of DSS 2205 and suggests incompetency of AlTiN (DCMS) coatings to sustain the difficult environment while dry turning DSS 2205.

## Effect of Cutting Speed and Feed Rate on Tool Life

Figure 8 depicts the effect of cutting speed and feed rate on the tool life when DSS 2205 and ASS 304 were turn dry. Experiment number is plotted on X-axis, which indicates the combination of cutting speed and feed rate, referring to Table II. Figure 8 shows that the tool life decrements with either cutting speed (100–180 m/min) or feed rate (0.12–0.18 mm/rev) rate increase. The increase in cutting parameters results in cutting temperature increment because the shear area of cutting zone causes higher strain rates. This creates high heat energy and results into higher cutting temperatures at the interface of the chip and tool. Furthermore, tool wear rate accelerates because of high cutting temperatures, and decreased strength results in reduction in tool life. Researchers have reported similar results of decreasing the tool life with cutting parameters.[2,49] This effect was more severe for uncoated than coated tools. Due to higher thermal conductivity, uncoated tools experienced the effect of reduced strength due to high temperatures, resulting in poor performance regarding tool life. Contradictorily, coated tools exhibited higher tool life than uncoated tools due to higher thermal conductivity and thermal stability.

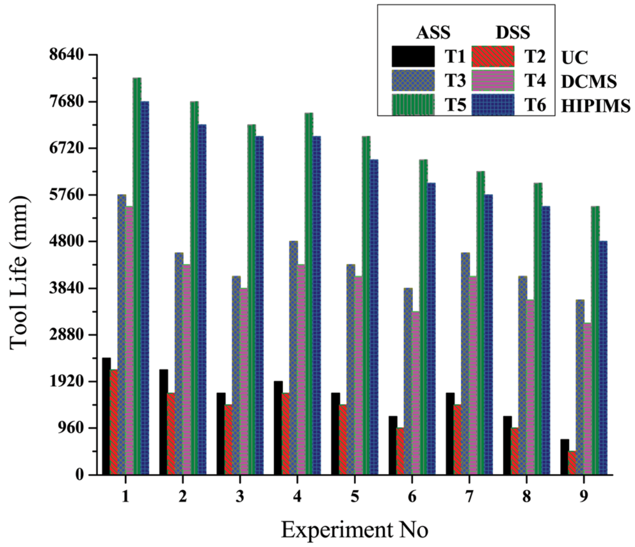


Fig. 8. Effect of cutting speed and feed rate on the tool life.

Among the coated tools, the tool life exhibited by T3 and T4 tools, coated by DCMS technique, was in the range of 3120 mm to 5760 mm. Moreover, T5 and T6 tools, coated using HiPIMS technique, showed higher tool life in the range from 4800 mm to 8160 mm. The average tool life exhibited by AlTiN (HiPIMS) tools was 1.5-times higher than for AlTiN (DCMS), combining all the cutting conditions used in this investigation. The reasons behind the excellency of HiPIMS compared to DCMS technique are explained in the previous sections.

The current investigation focuses on the comparison of machinability of DSS 2205 and ASS 304, which is distinctly understood by observing the tool life exhibited while dry turning. DSS 2205 exhibited a lower tool life compared to ASS 304 for all the cutting conditions. The average tool life exhibited combined for all the tools while machining ASS 304 was 4315 mm. However, during machining of DSS 2205, average tool life was reduced to 3890 mm. This is due to the difficult machining environment of DSS 2205 in dry conditions, which is due to its lower thermal conductivity, work hardening and higher BUL formation tendency. Moreover, the microstructure of DSS2205 exhibits alternate layers of austenite and ferrite. The hardness of these two distinct phases is different, which causes the tool to face alternate soft and hard layer cutting, making the process of machining more difficult. On the other hand, ASS304 contains only austenite phase, making it easy to machine. There was an interesting observation during this investigation related to DSS 2205 machining using DCMS and HiPIMS coatings. The average tool life exhibited by DCMS tools for DSS 2205 was 3996 mm. Moreover, this value increased to 6410 mm when HiPIMS-coated tools were used. This means the HiPIMS-coated tools exhibited 1.6-times higher tool life than DCMS-coated tools for DSS 2205 dry turning. In conclusion, though DSS 2205 is very difficult to machine, using advanced coating deposition techniques including HIPMS can improve the machining performance.

## CONCLUSION

The current comparative research is an attempt to investigate the comparative machinability of ASS 304 and DSS 2205 in a dry environment. For the turning process, HiPIMS and DCMS-based PVD AlTiN-coated carbide tools were used. Both coatings were evaluated based on their performance in terms of surface roughness, cutting force and tool life. As a result of the studies, the following thorough findings were reached:

### Characterization

- The microstructure of ASS 304 revealed a single phase of austenite, whereas the microstructure of duplex 2205 steel showed several alternatively placed austenite-ferrite layers.
- SEM fractographs of DCMS-coated tools revealed a dense columnar structure, whereas the microstructure of the HiPIMS AlTiN-coated tool was more compact and defect-free.
- The properties such as adhesion strength of 101 N and microhardness of 37 GPa were superior for the AlTiN (HiPIMS) coating compared to 93 N and 35.4 GPa of AlTiN (DCMS) coating.

### Machining Performance

- Uncoated tools delivered the worst performance in the context of surface roughness, cutting force and tool life during dry machining of ASS 304 and DSS 2205.
- The average rate of increase in surface roughness for DSS 2205 machining was lowest at 8% when AlTiN (HiPIMS)-coated tools were used compared to 13% and 9% for AlTiN (DCMS) and uncoated tools, respectively.
- The HiPIMS coatings outperformed the DCMS coatings. The cutting force exhibited by AlTiN (DCMS) tools were 17% higher than for AlTiN (HiPIMS)-coated tools.
- Tool life for all the tools decreased with the increment in cutting parameters. The average tool life exhibited by AlTiN (HiPIMS) tools was 1.5-times higher than for AlTiN (DCMS) when combining all the cutting conditions used.
- DSS 2205 was more difficult to machine with an average tool life of 3890 mm compared to 4315 mm of ASS 304.
- The average tool life exhibited by DCMS tools for DSS 2205 was 3996 mm, which increased to 6410 mm, when HiPIMS-coated tools were used. This suggests that although DSS 2205 is very difficult to machine, the machining productivity can be improved using advanced coating techniques.

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## DATA AVAILABILITY

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also form part of an ongoing study. Moreover, the data can be made available as and when requested.

## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest, have full control of all the data included in manuscript and agree to allow the journal to review their data, if required.

## ETHICAL STANDARD

The manuscript does not contain any clinical studies or patient data.

## REFERENCES

1. International Molybdenum Association: Article in press. 3rd ed., IMoA, London, 1 (2014).
2. G.D. Sonawane and V.G. Sargade, *J. Braz. Soc. Mech. Sci. Eng.* 41, 1 https://doi.org/10.1007/s40430-019-2057-4 (2019).
3. R.D. Koyee, U. Heisel, R. Eisseler and S. Schmauder, *J. Manuf. Process.* 16, 451 https://doi.org/10.1016/j.jmapro.2014.05.004 (2014).
4. A.P. Kulkarni and V.G. Sargade, *Mater. Manuf. Process.* 30, 748 https://doi.org/10.1080/10426914.2014.984217 (2015).
5. G. Sonawane, V. Sargade, *Proceedings of 10th International Conference on Precision*, Meso, Micro Nano Enginerring (COPEN 10), 460 (2017).
6. R.A. Mahdavinejad and S. Saeedy, *Sadhna.* 36, 963 (2011).
7. T. Akasawa, H. Sakurai, M. Nakamura, T. Tanaka and K. Takano, *J. Mater. Process. Technol.* 143, 66 https://doi.org/10.1016/S0924-0136(03)00321-2 (2003).
8. T. Selinder, M. Sjöstrand, M. Nordin, M. Larsson and S. Hogmark, *Surf. Coatings Technol.* 105, 51 https://doi.org/10.1016/S0257-8972(98)00446-0 (1998).
9. S. Kadam, R. Khake, S. Mudigonda, *Proceedings of ASME 2017 12th International Manufacturing Science Enginerring Conference MSEC2017*, ASME, 1 (2017).
10. M. Gopal and E.M. Gutema, *J. Eng. Sci. Technol. Rev.* 14, 119 https://doi.org/10.25103/jestr.142.16 (2021).
11. Q. Ran, J. Li, Y. Xu, X. Xiao, H. Yu and L. Jiang, *Mater. Des.* 46, 758 https://doi.org/10.1016/J.MATDES.2012.11.017 (2013).
12. G. Królczyk, M. Gajek and S. Legutko, *Tech. Gaz.* 20, 587 (2013).
13. J. Nomani and A. Pramanik, *Metall. Mater. Trans. A* 47, 3165 (2016).
14. R.D. Koyee, S. Schmauder, R. Eisseler, *Proc. 3rd Int. Conf. Adv. Manuf. Eng. Technol.* 53 (2013).
15. B.D. Bedada, G.K. Woyesssa, M.G. Jiru and B. Negash, *J. Mod. Mech. Eng.* 8, 12 https://doi.org/10.31875/2409-9848.2021.08.2 (2021).
16. G. Krolczyk, A.P. Nieslony and R.W. Maruda, *J. Clean. Prod.* 30, 1 (2016).
17. D.P. Selvaraj and P. Chandramohan, *Sci. Res. Eng.* 2, 453 https://doi.org/10.4236/eng.2010.26059 (2010).
18. P. Taylor, V.G. Sargade, S. Gangopadhyay, S. Paul and A.K. Chattopadhyay, *Mater. Manuf. Process.* 26, 1028 https://doi.org/10.1080/10426914.2010.526978 (2011).
19. A. Jawaid and K. Olajire, *Mater. Manuf. Process.* 14, 559 (1999).
20. R. Bunshah, *Handbook of Hard Coatings*, (William Andrew Publishing, NY, 2002, pp. 108–144).

21. H.B. He, W.Q. Han, H.Y. Li, D.Y. Li, J. Yang, T. Gu and T. Deng, *Int. J. Precis. Eng. Manuf.* 15, 655 https://doi.org/10.1007/s12541-014-0384-z (2014).
22. G. Krolczyk, S. Legutko and M. Gajek, *Metalurgija.* 52, 259 (2013).
23. M.K. Ganesh, S.S. Manoj, K. Bhupendar, K. Nag, V.S. Aditya and G.S. Kaushik, *J. Vib. Eng. Technol.* 11, 3135 https://doi.org/10.1007/s42417-022-00736-0 (2025).
24. S. Masoudi, M.J. Esfahani, F. Jafarian and S.A. Mirsoleimani, *Int. J. Precis. Eng. Manuf. Green Technol.* https://doi.org/10.1007/s40684-019-00042-3 (2019).
25. S. Chinchanikar and S.K. Choudhury, *Int. J. Mach. Mach. Mater.* 18, 466 https://doi.org/10.1504/ijmmm.2016.078991 (2016).
26. S.S. Wagh, A.P. Kulkarni and V.G. Sargade, *Procedia Eng.* 64, 907 https://doi.org/10.1016/J.PROENG.2013.09.167 (2013).
27. A. Kulkarni, V. Sargade and C. More, *Procedia Manuf.* 20, 548 https://doi.org/10.1016/J.PROMFG.2018.02.082 (2018).
28. A.P. Kulkarni, G.G. Joshi and V.G. Sargade, *Surf. Eng.* 29, 402 https://doi.org/10.1179/1743294413Y.0000000130 (2013).
29. K. Quillin, H. Yeom, T. Dabney, E. Willing and K. Sridharan, *Surf. Coatings Technol.* 441, 128 https://doi.org/10.1016/j.surfcoat.2022.128577 (2022).
30. M. Samuelsson, D. Lundin, J. Jensen, M.A. Raadu, J.T. Gudmundsson and U. Helmersson, *Surf. Coatings Technol.* 205, 591 https://doi.org/10.1016/j.surfcoat.2010.07.041 (2010).
31. K. Sarakinos, J. Alami and S. Konstantinidis, *Surf. Coatings Technol.* 204, 1661 https://doi.org/10.1016/j.surfcoat.2009.11.013 (2010).
32. J. Alami, K. Sarakinos, F. Uslu and M. Wuttig, *J. Phys. D Appl. Phys.* 42, 1 https://doi.org/10.1088/0022-3727/42/1/015304 (2009).
33. S. Veprek, *Thin Solid Films* 317, 449 https://doi.org/10.1016/S0040-6090(97)00665-2 (1998).
34. W. Kalss, A. Reiter, V. Derflinger, C. Gey and J.L. Endrino, *Int. J. Refract. Met. Hard Mater.* 24, 399 https://doi.org/10.1016/J.IJRMHM.2005.11.005 (2006).
35. H. Daraghma, M.A. Samad, H. Toor and F.M. Abdallah, *Metals* 10, 339 https://doi.org/10.3390/met10030339 (2020).
36. A. Vinoth Jebaraj, L. Ajaykumar, C.R. Deepak and K.V.V. Aditya, *J. Adv. Res.* 8, 183 https://doi.org/10.1016/j.jare.2017.01.002 (2017).
37. E.C. Bordinassi, M.F. Stipkovic, G.F. Batalha, S. Delijaicov and N.B. De Lima, *J. Achiev. Mater. Manuf. Eng.* 18, 335 (2006).
38. B. Gui, H. Zhou, J. Zheng, X. Liu, X. Feng, Y. Zhang and L. Yang, *Ceram. Int.* 47, 8175 https://doi.org/10.1016/j.ceramint.2020.11.175 (2021).
39. P.I. Hovsepian and A.P. Ehiasarian, *Surf. Eng.* 26, 610 (2010).
40. K.V. Chauhan and S.K. Rawal, *Procedia Technol.* 14, 430 https://doi.org/10.1016/j.protcy.2014.08.055 (2014).
41. G.D. Sonawane, R. Bachhav and A. Barnwal, *JOM* 76, 313 https://doi.org/10.1007/s11837-023-05991-4 (2023).
42. Y.Y. Chang, S.J. Yang and D.Y. Wang, *Surf. Coatings Technol.* 201, 4209 https://doi.org/10.1016/j.surfcoat.2006.08.062 (2006).
43. G. Boothroyd, *Fundamentals of Machining and Machine Tools*: 3rd ed., (CRC Press, Taylor and Francis, UK, 2017, pp 129–150).
44. D.P. Selvaraj, P. Chandramohan and P.K. Rajesh, *J. Eng. Sci. Technol.* 17, 171 (2022).
45. M. Kondo, C. Pinheiro, M. Paula, T. de Souza, J. Souza, M. Ribeiro and M. Alves, *Mater. Res Express.* 6, 1 https://doi.org/10.1088/2053-1591/ab0da8 (2019).
46. G.D. Sonawane and V.G. Sargade, *Int. J. Precis. Eng. Manuf.* https://doi.org/10.1007/s12541-019-00305-8 (2020).
47. G.F. Batalha, S. Delijaicov, J.B. Aguiar, E.C. Bordinassi and M.S. Filho, *J. Achiev. Mater. Manuf. Eng.* 24, 350 (2007).
48. S. Chinchanikar and S.K. Choudhury, *Int. J. Refract. Met. Hard Mater.* 38, 124 https://doi.org/10.1016/j.ijrmhm.2013.01.013 (2013).
49. X.L. Liu, D.H. Wen, Z.J. Li, L. Xiao and F.G. Yan, *J. Mater. Process. Technol.* 129, 200 https://doi.org/10.1016/S0924-0136(02)00651-9 (2002).