World Academy of Science, Engineering and Technology
International Journal of Mechanical and Industrial Engineering
Vol:13, No:5, 2019

Studies on the Characterization and Machinability of Duplex Stainless Steel 2205 during Dry Turning

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Abstract**—**The present investigation is a study of the effect of advanced Physical Vapor Deposition (PVD) coatings on cutting temperature residual stresses and surface roughness during Duplex Stainless Steel (DSS) 2205 turning. Austenite stabilizers like nickel, manganese, and molybdenum reduced the cost of DSS. Surface Integrity (SI) plays an important role in determining corrosion resistance and fatigue life. Resistance to various types of corrosion makes DSS suitable for applications with critical environments like Heat exchangers, Desalination plants, Seawater pipes and Marine components. However, lower thermal conductivity, poor chip control and non-uniform tool wear make DSS very difficult to machine. Cemented carbide tools (M grade) were used to turn DSS in a dry environment. AlTiN and AlTiCrN coatings were deposited using advanced PVD High Pulse Impulse Magnetron Sputtering (HiPIMS) technique. Experiments were conducted with cutting speed of 100 m/min, 140 m/min and 180 m/min. A constant feed and depth of cut of 0.18 mm/rev and 0.8 mm were used, respectively. AlTiCrN coated tools followed by AlTiN coated tools outperformed uncoated tools due to properties like lower thermal conductivity, higher adhesion strength and hardness. Residual stresses were found to be compressive for all the tools used for dry turning, increasing the fatigue life of the machined component. Higher cutting temperatures were observed for coated tools due to its lower thermal conductivity, which results in very less tool wear than uncoated tools. Surface roughness with uncoated tools was found to be three times higher than coated tools due to lower coefficient of friction of coating used.

Keywords**—**Cutting temperatures, DSS2205, dry turning, HiPIMS, surface integrity.

I. Introduction

STAINLESS steel family is having four members as Austenitic (ASS), Ferritic (FSS), Martensitic (MSS) and DSS. Nickel shortage due to the Korean War resulted in more concentration being given to low-nickel duplex alloy steels [1]. The lower percentage of alloying elements like Ni and Mo, which is replaced by austenite stabilizers like nitrogen, makes them a cheaper alternative with more superior mechanical and corrosion resistant properties [2].

Balanced phases of austenite and ferrite in DSS provide better chloride Stress Corrosion Cracking (SCC) resistance than single phase materials like ASS. DSS has served in construction of marine machinery and structures [3]. SS316L was the most famous option for the marine industry. But due to the limitation of poor resistance to SSC and lower strength to weight ratio, DSS are widely used for duplex chemical tankers carrying molasses, fish oil lubricants and methanol. The marine industry also employ DSS for steering propellers, water jet engines, thrusters, propeller shafts and other applications where high mechanical loads are subjected.

Different alloying elements allows DSS to provide versatile properties but on other side makes it more difficult to machine. Higher nitrogen and molybdenum content make DSS machining difficult even when coated carbide tools are used. Uncontrolled flow of chips may cause chipping of coating and tool material on flank face [4], [5]. Nilsson [3] and Voronenko [6] in their reviews reported that though DSS has higher strength, low carbon content and absence of nonmetallic inclusions are the main reasons for poor machinability. Two phase structure results in separate regions with different hardness. Modification in the surface characteristics of tools is proved to be the basic requirement, while machining materials having low machinability. DSS machining with higher cutting speeds results in tool plastic deformation with coating flaking and frittering [1]. If machined at lower speeds, DSS have a basic issue of built-up layer (BUL).

Wet cutting comes with several advantages, but on the other hand, the use of coolants is questioned due to environment issues and operator health in long-term machining. Disposal of the coolant after use is also a big concern as it may lead to the pollution of soil and water [7]. All these issues lead to eliminate the use of cutting fluids and promote dry cutting to improve productivity. Dry cutting demands the improved surface properties of cutting tools. Among the coating techniques used for hard coatings, PVD is preferred over chemical vapour deposition (CVD). This is because of advantages lower deposition temperature, fine grain microstructure of PVD and due to higher deposition temperature, higher stresses and embrittlement in the later. Because of the small grain size, movement of dislocation is restricted and also as the number of grain boundaries are more, the crack development possibility minimal [8], [9]. Hard coatings reduce abrasive wear resulting in improvement in wear resistance. High power impulse magnetron sputtering (HiPIMS) is the recent advancement in PVD technology. Kulkarni et al. [4] reported better performance of HiPIMS over cathodic arc evaporation while dry turning. Researchers have reported almost 60-70% of increase in tool life while machining in dry conditions [10]. Moreover, the use of chip breaker is recommended for machining DSS to avoid BUL formation, which is not found to be advantageous in wet cutting. Researchers have estimated that the cost of use of

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cutting fluids is almost 20% of the total cost of manufacturing [11].

Ran et al. [12] compared AISI 316L stainless Steel with DSS for mechanical strength and corrosion resistance.DSS found to be better with low cost. Krolczyk [13] reported difficulty in controlling the chips during DSS machining. Excessive mechanical and thermal loads are observed on tool point. This results in strong tool workpiece interaction due to BUL formation causing severe tool wear rate. Chen et al. found better wear resistance of CrAlN than TiAlN as higher Al provides better protective oxide films. Selvaraj [14] found increase in surface roughness with higher feed values. Whereas, the effect of cutting speed for surface roughness was found to be significant up to a point and then surface roughness increases. Krolczyk et al. [15] reported decrease in tool life with increase in speed for every feed and no effect of cooling on the metallographic structure. Alauddin et al. [16] found improved productivity and surface roughness when speed is increased. Krolczyk [17] found more hardening depth for dry machining when compared to wet machining because of the high intensity of heat generation at the cutting zone. Austenite, as compared to ferrite, is more prone to strain hardening. Solomon et al. [18] reported martensite formation for austenitic structured materials. DSS applications, like marine components, demand better surface finish with higher fatigue life. Basically DSS is having tensile residual stresses which are not favourable for fatigue life. Compressive residual are reported in the machined surface after dry machining. Higher cutting temperatures during dry machining are favourable as these will reduce the strength of workpiece material, making it more easy to machine.

The literature review reveals that researchers either concentrated on the use of cutting oil or only empirical models for analyzing DSS machining. Moreover, applications of DSS demand optimization of DSS machining with regard to performance measures so as to improve productivity. This paper is an attempt to study cutting temperature, residual stresses and cutting forces during dry turning of DSS2205.

II. Experimental Details

A. Workpiece Material

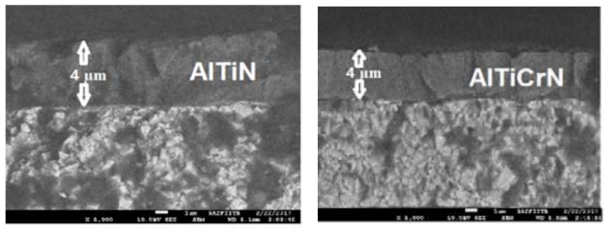
The second most difficult to machine grade from DSS is DSS2205. From the use of DSS, 75-80% of the applications use DSS2205. Major alloying elements confirmed by EDS test of DSS2205 are shown in Table I.

TABLE I
Composition of DSS2205

Cr	Ni	Mo
22.0-23.0	4.50-6.50	3.00-3.50
C	N	S
0.030 Max	0.14-0.20	0.020 Max
Mn	S	P
2.00 Max	1.00 Max	0.030 Max

B. Cutting Tool and Coating Technique

ISO specification of CNMG120408 for M35 grade carbide insert with positive chip breaker geometry MF1 (for BUL prevention) was used. A tool nose radius of 0.8 mm was used on the basis of recommendations from literature survey [1]. PVD HiPIMS from CEMECON, Germany was used for coatings carbide substrates. HiPIMS CC800 was used for coating. Commercially developed coatings, AlTiCrN and AlTiN with 4 µm thickness each were used. SEM microstructure of HiPIMS AlTiCrN and AlTiN coating on carbide tools are as shown in Fig. 1.



(a) (b)

Fig. 1 SEM microstructure of a) AlTiN and b) AlTiCrN coating

The SEM microstructure of the coatings showed non-porous and defect-free coatings. A critical load of 90 N and 110 N measured by a scratch tester and microhardness of 38 GPa and 34 GPa indicate good adhesion and high hardness of AlTiN and AlTiCrN coatings, respectively. This is due to use of advanced PVD HiPIMS technique for coating deposition. Al acts as an oxidizing element responsible to form Al_2O_3 layer. This layer protect sharp cutting edge at high cutting temperature up to 900°C and 1150°C for AlTiN and AlTiCrN coating, respectively. In the present investigation, cutting parameters are selected on the basis of an industrial survey, available literature and recommendations from DSS manufacturers.

Experiments were conducted with cutting speed of 100 mm/min, 140 mm/min and 180 mm/min. A constant feed and depth of cut (DoC) of 0.18 mm/rev and 0.8 mm, respectively, were used. Workpiece with dimensions 250 mm*60 mm were turned dry using CNC Lathe. Every machining cut was of 190 mm so as to measure response parameters. Longer length of cut allows the cutting temperature to achieve stable value. During machining, the cutting forces and cutting temperatures were measured using Kistler Piezo-electric dynamometer and infrared camera, respectively. After machining samples were prepared to measure residual stresses by using x-ray diffraction.

III. Result and Discussion

A. Characterization

Before machining, DSS2205 was tested for chemical composition and microstructure. The EDS test was performed to check the major alloying elements, as shown in Table I.

A sample of DSS2205 was cut and polished. After polishing, etching was done using Carpenter 300 series etchant for an etching time of 2 min. A scanning electron microscope (SEM) was used to observe microstructure, as shown in Fig. 2.

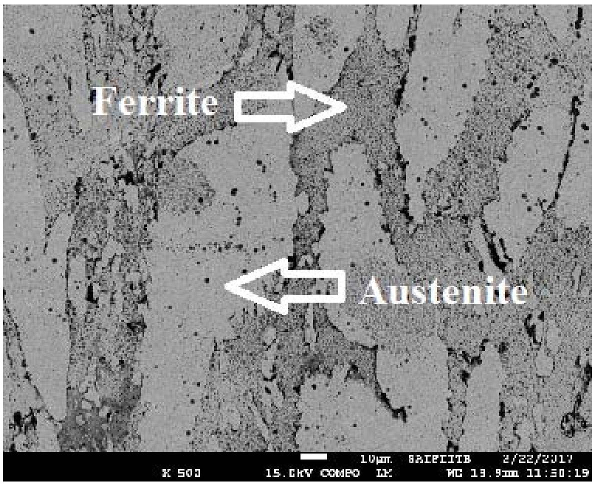


Fig. 2 SEM microstructure of DSS2205

B. Effect of Cutting Speed on Surface Roughness

The effect of cutting speed on surface roughness of the machined surface is shown in Fig. 3. Surface roughness tends to reduce with cutting speed. The initial phase of cutting showed better surface finish but as the machining time increases, the surface roughness also increases. This is due to the fact that initially due to sharp cutting edges, the friction between tool and the workpiece is less resulting in a good finish. But, as the tool wear takes place, the friction coefficient increases and results in higher surface roughness. Also, at lower cutting speeds, the tendency of DSS to form BUL is greater which creates more friction, and as the cutting speed increases, formation of BUL decreases.

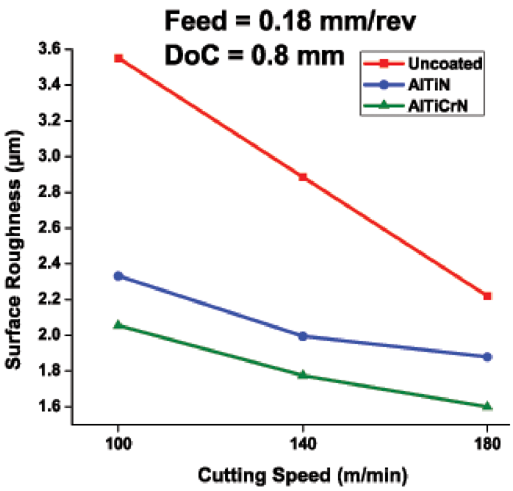


Fig. 3 Effect of cutting speed on surface roughness at feed = 0.18 mm/rev

All three tools used showed the same phenomenon. Uncoated tool wear out in early stages and resulted in higher surface roughness. AlTiN and AlTiCrN coated tools, due to good thermal stability, retained the sharpness of cutting edge resulting in a better finish than the uncoated tool. Researchers have also reported lower cutting forces [4] and cutting pressures [19] for higher cutting speeds used resulting in lower machined surface. The optimum combination of a cutting speed 180 mm/min, feed 0.18 mm/rev, DoC 0.8 with AlTiCrN coated tools exhibited minimum surface roughness. At this cutting condition, surface roughness recorded was 1.402 for AlTiCrN coated tools as compared to 2.78 for uncoated tools i.e. almost two times higher roughness for uncoated tools

C. Effect of Cutting Speed on Cutting Temperature

Cutting temperature during machining plays a vital role in deciding tool wear rate. Higher machining temperature causes the tool to become weak and rapid tool wear takes place reducing the tool life. The effect of cutting speed on cutting temperature is depicted in Fig. 4.

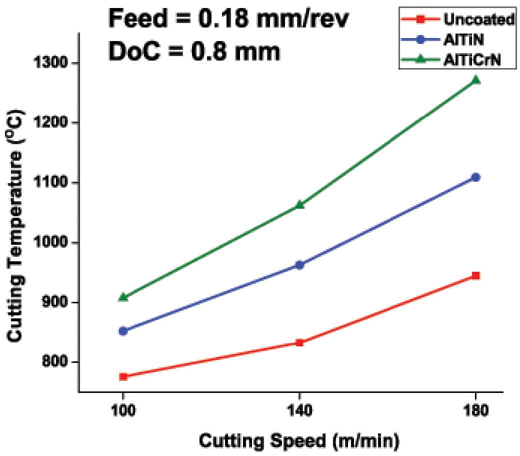


Fig. 4 Effect of cutting speed on cutting temperature at feed = 0.18 mm/rev

Uncoated tools showed lower cutting temperatures as compared to coated tools because of higher thermal conductivity. Higher thermal conductivity causes the temperature to enter into tool and wear it at faster rates reducing its life. However for AlTiN and AlTiCrN coated tools, higher cutting zone temperatures are observed. Lower thermal conductivity of coated tools used does not allow the temperature produced due to machining to go into the tool material, as a result, this temperature is carried away by the chips and remaining goes into to the workpiece material. This reduces the strength of workpiece material, making it easy to machine. As a result, longer tool life is achieved (4-6 times) compared to uncoated tools [7]. The cutting temperature observed for AlTiCrN coated tools during machining is 1271°C compared to 945°C for uncoated tools. This indicates that there is a severe increase in temperature for uncoated tools, causing it to wear out early. Using lower cutting speeds for reducing cutting temperatures might be a solution, but higher productivity demands that higher cutting parameters be used. This can be achieved using high performance coatings for cutting tools.

D. Effect of Cutting Speed on Compressive Residual Stresses

The effect of cutting speed on compressive residual stresses is as shown in Fig. 5. In applications like propeller shafts of marine engines, where components are subjected to fatigue stress, the material becomes more sensitive to induced stresses due to machining.

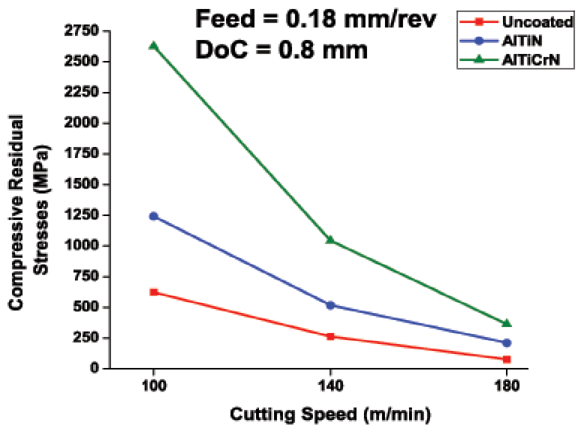


Fig. 5 Effect of cutting speed on compressive residual stresses at feed = 0.18 mm/rev

It was observed that all the stresses measured after machining DSS2205 were compressive. This is due to the use of dry cutting, as researchers have reported tensile stresses after wet cutting. Coated tools showed higher compressive residual stresses than uncoated tools. This is due to faster wear rate of uncoated tools.

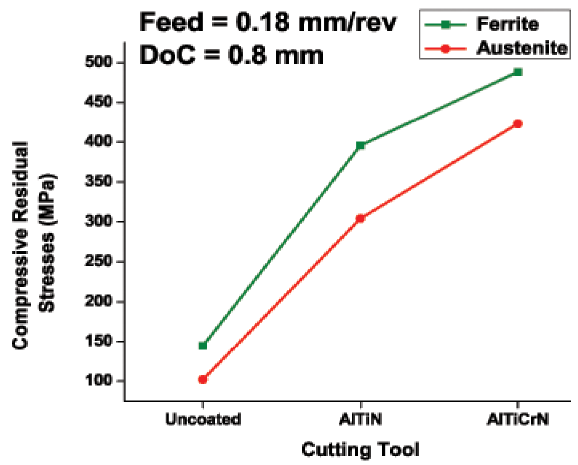


Fig. 6 Residual stresses induced in ferrite and austenite phase

As the cutting speed increases, the surface residual stresses tend to be more tensile due to the increase in cutting temperature with cutting speed. This phenomenon is found to happen only at the machined surface, as the higher cutting temperature induced due to cutting does not penetrate beneath the surface and does not affect the sub-surface. Though cutting temperatures produced during machining with coated tools is on the higher side, the residual stresses are more compressive. This may be due to the lower coefficient of friction of coatings used. The austenite phase exhibited lower compressive residual stresses (Fig. 6) as compared to the ferrite phase. This is because of higher stress relaxation rate (temperature dependant) [20] of ferrite phase.

However there is conflict between researchers about more tensile residual stresses produced due to the increase in cutting speed. But, such a finding is reported for higher cutting speeds used only [21]. This indicates that the trend of inducing residual stresses changes with cutting speeds selected. Also, it is possible to generate ideal residual stresses, as required by selecting and controlling the cutting parameters, resulting in the longer life of the component. There is still a lot of work required to be done for the type and detailed study of residual stresses produced during machining DSS2205.

IV. Conclusions

A. Characterization

- EDS analysis confirmed the alloying elements of material used for experimentation as compared to standard DSS2205.
- SEM microstructure showed alternative layers of austenite and ferrite.

B. Machining

- Increase in cutting speed is found to be beneficial for the surface roughness of a machined surface. Coated tools exhibited very low surface finish than uncoated tools due to rapid tool wear and higher friction.
- Higher cutting temperatures are observed for higher cutting speeds. The use of coated tools resulted in higher cutting temperatures due to the lower thermal conductivity of the coatings.
- Compressive residual stresses tend to change towards tensile as the cutting speed increases due to higher cutting temperatures.
- Coated tools exhibited higher compressive residual stresses which may increase the components fatigue life.
- Higher stress relaxation rate at the ferrite phase resulted in higher compressive residual stress values compared to the austenite phase.
- There is a conflict between the researchers regarding the induced residual stresses with respect to cutting speed variation. So, a detailed study is required to be done.

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