Analysis of Flank Wear and Chip Morphology when Machining Super Duplex Stainless Steel in a Gas Cooled Environment

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Abstract: The aim of this paper is to analyse the influence of turning parameters on the flank wear and chip morphology during a turning process. Here, the work piece material, Super duplex stainless steel SAF 2507 was turned with uncoated carbide tool. Liquid CO_2 which acts as a coolant, forms a gas cooled environment. The gas cooled machining in turn was compared with the dry and wet machining. Totally 18 experiments were conducted in order to measure the flank wear (Vb) with a tool makers microscope. The experiments were performed with the same cutting conditions and tool characteristics on the three methods of cooling. During the experimental procedure the removed chips were collected and evaluated together with the various cutting conditions. Using MINITAB 15 software, the optimized values of machining parameters were predicted using response surface methodology. Confirmation tests were carried out to compare the results of predicted values with the experimental value. The flank wear and the chips produced at the optimized values are analysed by scanning electron microscope (JOEL Model 6390). From the experimental results, it was found that flank wear gets reduced in case of gas cooled machining.

Keywords: Gas Cooling Machining; Super Duplex Stainless Steel, Tool wear; Optimization; RSM; Chip morphology.

I. INTRODUCTION

Duplex stainless steels (DSSs), meaning those with a mixed microstructure of about equal proportions of austenite and ferrite, have existed for more than 70 years. The early grades were alloys of chromium, nickel and molybdenum [1]. Modern duplex stainless steels emerged in the early 1980s, developed from cast alloys. Their popularity stems from an attractive combination of properties, including high strength and excellent resistance to chloride stress corrosion cracking. Like the austenite stainless steel, duplex stainless steels are a family of grades, which range in corrosion performance depending upon the alloy content [2]. Super Duplex Stainless Steels are used in a variety of applications such as (a) Oil and gas industry equipment (b) Offshore platforms, heat exchangers, process and service water systems, fire-fighting systems, injection and ballast water systems (c) Chemical process industries, heat exchangers, vessels, and piping (d) Desalination plants, high pressure RO-plant and seawater piping (e) Mechanical and structural components, high strength, corrosion-resistant parts (f) Power industry FGD systems, utility and industrial scrubber systems, absorber towers, ducting, and piping. The austenitic phase to be stabilized requires quite high nickel and chromium additions. Ferrite grades have almost no Nickel and the Chromium content can be kept as low as 12%. The level of Chromium additions is, of course, one of the major players when considering corrosion resistance properties. Duplex grades are designed to have a 50% α / 50% γ microstructure. Their chemistry is characterized by significant contents of Cr+Mo% while the Nickel content remains at about 50% of the austenitic grades having similar corrosion resistance properties [3].

Super duplex stainless steel is considered as a difficult-to-machine material due to high cutting temperatures and rapid tool wear. Machining of super duplex stainless steel is difficult due to its inherent material properties such as low thermal conductivity increasing the tool temperature at tool/work piece interface which affects the tool life adversely; high dynamic shear strength during cutting resulting in localization of shear stress and the production of abrasive saw-tooth edges; and chemical reactivity with most tool materials at elevated temperatures resulting in accelerated tool wear [4]. Flank wear was caused by friction between the flank face of the tool and the machined surfaces. Tool wear depends on the tool, work piece material (physical, mechanical and chemical properties), tool geometry, cutting parameters, cutting fluid, etc [5]. Flank wear generally attributed to rubbing of the tool with work piece at the interface, causing abrasive and/or adhesive wear and at high temperatures. Abrasion is the main wear mechanism in flank wear. BUE and irregular wear are often faced in machining stainless steels. At low cutting speed, the contact between work piece and flank of the tool was more and rubbing action continued for more time. The cutting zone temperature increases, this softens and decreases the strength of the BUE [6].

Tool flank wear was strongly influenced by the interactions between cutting tool and work piece in the form of contact stress and cutting temperature. As the cutting speeds and feed rates are increased, the rubbing action also faster and more heat produced even though less contact time exist.. The generation of heat at flank side softens the edge and more wear occurred. The increase in cutting speeds wears the tool faster and reduces the life of the tool [7]. When the contact time was more at low speeds, the BUE formed which in turn act as another cutting edge. Dutta investigated the influence of the cutting parameters on the various types of composites used in tool materials, and how they affect the quality of the machined surface and the tool-wear mechanism during machining. Among other parameters, he analyzed the macroscopic and microscopic chip structure formed under the influence of various machining regimes. The results were presented in a diagram of cutting-force components and cutting speed dependence, tool-wear degree, and their influence on the quality of the machined surface and the tool life [8].

Chip forming mechanism and chip morphology are characteristics which provide key information on the machining process and machined surface quality. Chip forming mechanism and type of chip segmentation exert primary influence on tool life and machined surface quality. Proper identification and understanding of chip forming mechanism can help us detect tool wear in machining of harder materials and special steels. Chip forming mechanism, as well as its form and flow over tool rake surface, significantly impact the tool wear and machined surface quality [9]. Two of the most common chip morphologies are the continuous and the discontinuous or serrated chip. Serrated chip formation is related to the localization of plastic flow by shear, which occurs periodically along the length of the chips. Traditionally, most investigations of metal cutting have focussed on continuous chip which is relatively stable, and hence simple to analyze. Continuous chip can interface with the machining process causing some flaws and damage on the machined surface, cutting or machine tool, or even injuries to the operator, thus production efficiency may have to be reduced. A serrated chip is easier to break and dispose during automated machining. Therefore, predicting the cutting conditions that lead to a serrated chip and associated shear band widths and spacing under such cutting conditions is critical for the purpose of chip control and disposal [10].

Shaw summarised that the two main functions of cutting fluids are lubrication and cooling. Lubrication is effective when cutting fluid is introduced to the tool–chip interface through either penetration or diffusion, which is more likely to happen at low cutting speeds [11]. However, the lubrication action diminishes at normal cutting speeds used in turning and milling as considered in this study. Therefore, the main function of cutting fluid changes to cooling and the cooling effectiveness reduces as cutting speed increases because the time allowed for cooling becomes extremely short (on the order of milliseconds). Most cutting fluids are formulated from mineral oils, which are extracted from crude oil, primarily for economic reasons. Although alternative, naturally derived cutting fluids are available (vegetable oils), there has been limited use of these cutting fluids. This is partly due to higher costs and partly due to a reduced performance [12]. In cryogenic machining a cryogenic cutting fluid (non-oil-based) is delivered to the cutting region of the cutting tool, which is exposed to the highest temperature during the machining process. Coolant is usually nitrogen fluid which is liquefied by cooling to -196^0 C. It evaporates harmlessly into the air requiring no disposal. Chip generated have no residual oil on them and can be recycled as scrap metal [13].

The earliest application of gas coolant goes back to 1930s, when nitrogen gas was applied as a coolant. Nitrogen gas formed a film on tool surface, chip easily moved away from tool face, and lower friction occurred in tool-work piece chip interface. With nitrogen gas the tool life increased considerably [14]. Ying lin et al. found that the use of nitrogen gas in high speed milling of Ti 6Al-4V enhanced the machining performance .Other gases that have been used are carbon dioxide, argon, water vapour, and air [15]. Some researchers have observed that cooling by oxygen can enhance tool life, whereas in some cases it reduced tool life due to oxidation effect. It has been observed that use of oxygen reduces the chip–tool contact length. In many cases, oxygen prevents the formation of built-up edge by oxidizing the chip surface [16]. In the turning of AISI 1040, oxygen has more lubricating effect than nitrogen and CO_2 has more lubricating effect than oxygen. Hollis carried out turning using CO_2 and CO_2 along with argon gas. Argon provides an inert atmosphere and provides more enhanced tool life and less hardening at the machined surface. Particularly, in the machining of titanium, argon prevents the absorption of CO2 on the machined surface [17]. Podgorkov and Godlevski proposed a new and pollution free cutting technique with water vapours coolant and lubricant during cutting process. They used water vapour with temperature less than 100^{0}C. The coolant was a mixture of water in gas and liquid form. Water vapour is cheap and pollution free, thus an ideal coolant. It has been observed that water vapour lubrication causes more uniform cooling and increases the tool life of cemented carbide tools by about 1.5 times in turning of stainless steel [18]. Williams and Tabor have suggested a model for the lubricating action of gas or vapour during orthogonal machining based on their experimental study. According to their model, a number of capillaries get formed at the interface of chip and rake face of the tool. The lubricant in gas or liquid form is drawn in these capillaries and creates a boundary lubrication layer [19]. U.S. Dixit et al., observed that air cooling always provides better machining performance. It is particularly needed in the high speed machining and hard turning [20]. Sarma has carried out the air cooling at fixed temperature and velocity of the air. The effect of lowering the air temperature and changing the jet velocity was not studied. It may be possible to obtain the better machining performance by optimizing the parameters of the air [21].

Reviewed in the introductory section of this paper are the investigations focused on the tool wear, chip morphology and the alternate methods of cooling. The experiment was setup based on an analysis of previous investigations. The remaining sections review the experimental results of tool wear obtained. The final part presents some conclusions and recommendations for future investigations. The design of experiments was made using Taguchi’s technique and for the same set of machining parameters, the experiments were repeated for all the three methods. Taguchi method consist of a plan of experiment with the objective of acquiring data in a controlled way, executing these experiments and analyzing data, in order to obtain information about the behaviour of the given process. It uses the orthogonal arrays to define the experimental plans and the treatment of the experimental results is based on the analysis of variance (ANOVA).

II. DESIGN OF EXPERIMENTS

Design of experiments is a powerful tool for modelling and analysis of process variables. Taguchi design of experiments is a simple robust technique for analyzing and optimizing the process parameters. In this method, main parameters which are assumed to have influence on process results are located at different columns in a designed orthogonal array. In general surface roughness and flank wear are mainly depends on the manufacturing conditions employed, such as cutting speed, feed, depth of cut machine tool, cutting tool rigidity and geometry etc. Among these parameters cutting speed, feed and depth of cut are controlled by the operator at the time of machining process. In the Taguchi design of experiments the signal to noise ratio (η) representing quality characteristics for the observed data [22]. Depending on the experimental response, there are several quality characteristics. In the case of surface roughness and flank wear, lower values of them are desirable. There are three S/N ratios that are available, which will be selected based on the response function and its characteristics. In turning operation, desired responses are minimum surface roughness and minimum tool wear so, smaller the better “SB” ratio were selected. The S/N ratio for minimum responses type of characteristic can be calculated as follows:

$$\eta = -10 \log\left(\frac{1}{n}\sum_{i=1}^{n} Yi^2\right)$$

Where Yi is the observed data at ith trial and n is the number of trails. From the S/N ratio, the effective parameters having influence on process results can be seen and the optimal sets of process parameters can be determined [23].

III. EXPERIMENTAL CONDITIONS AND PROCEDURE

The work material used as test specimen was super duplex stainless steel SAF 2507. A cylindrical bar of test specimen 65mm diameter and 450mm length were used for the turning tests. Initially, it is plain turned in a rigid and powerful Kirloskar Turnmaster all geared type lathe machine by using uncoated carbide insert at industrial speed feed combinations. Uncoated Cemented carbide cutting tool inserts(CNMG 120408-QM, grade H13A) were used for turning tests. The inserts were rigidly attached to a tool holder (PCLNR25M12).

The cutting speed was derived from the measured spindle speed and the diameter of the work material. In dry machining, turning operation is carried out without any coolant or cutting oil. In wet machining, in order to obtain a good surface finish, the cutting oil is used during turning. The cutting oil named MAK Sherol B is mixed with water in the ratio 1:8. The cutting oil provides the function of coolant as well as lubricant during turning. The cutting oil is applied during turning at the tool work interface by means of coolant supply arrangement. For Gas cooled machining, liquid CO_2 in the form of thin but high speed jet is impinged from a specially designed nozzle towards the cutting zone almost parallel to the cutting edges. The parameter levels were chosen within the intervals recommended by the tool manufacturer and investigation of the present study. Three process parameters at two and three levels led to a total of 18 tests for turning operation. After each test, the flank wear is measured by tool maker’s microscope. The factors and levels used in the experiment and the chemical composition of the work material in percentage by weight are given in Table 1&2.

TABLE 1
FACTORS (PARAMETERS) AND LEVELS FOR DESIGN OF EXPERIMENTS

Machining Parameters	**Unit**	**Levels**		
		1	**2**	**3**
Cutting Speed	m/min	100	120	-
Feed	mm/rev	0.06	0.08	0.1
Depth of cut	mm	0.50	0.75	1.0

TABLE II
THE CHEMICAL COMPOSITION OF WORK MATERIAL IN PERCENTAGE BY WEIGHT

Elements	**Percentage by weight**
Carbon (max)	0.03
Manganese(max)	1.0
Silicon(max)	0.80
Chromium	24.00/26.00
Molybdenum	3.0/5.0
Nickel	6.0/8.0
Copper (max)	0.50
Nitrogen	0.24/0.32
Iron	Balance
Sulphur (max)	0.02
Phosphorous (max)	0.035

IV. RESULTS AND DISCUSSIONS

The turning operation is carried out and the flank wear measured for all the three methods, i.e. Dry, Wet and Gas Cooled machining after 18 experiments were given in table 3.

TABLE III
FLANK WEAR MEASURED WHEN TURNING

Trial	**Cutting Speed (m/min)**	**Feed (mm/rev)**	**Depth of Cut (mm)**	**Flank Wear (mm)**		
				Dry	**Wet**	**Gas cooled**
1	100	0.06	0.5	0.10	0.09	0.07
2	100	0.06	0.75	0.07	0.06	0.06
3	100	0.06	1.0	0.20	0.12	0.09
4	100	0.08	0.5	0.10	0.09	0.07
5	100	0.08	0.75	0.08	0.08	0.06
6	100	0.08	1.0	0.15	0.10	0.09
7	100	0.1	0.5	0.08	0.09	0.07
8	100	0.1	0.75	0.07	0.08	0.05
9	100	0.1	1.0	0.10	0.09	0.06
10	120	0.06	0.5	0.08	0.10	0.08

11	120	0.06	0.75	0.10	0.06	0.06
12	120	0.06	1.0	0.09	0.11	0.09
13	120	0.08	0.5	0.14	0.16	0.11
14	120	0.08	0.75	0.12	0.14	0.12
15	120	0.08	1.0	0.13	0.11	0.07
16	120	0.1	0.5	0.09	0.13	0.08
17	120	0.1	0.75	0.07	0.10	0.05
18	120	0.1	1.0	0.18	0.14	0.09

V. ANALYSIS OF FLANK WEAR

Regression analysis is performed to find out the relationship between factors and the average tool Wear (Vb). With MINITAB software Statistical model based on linear equation were developed for Tool Wear. The regression equation is

$$Vb\ (\text{Dry}) = 0.029 + 0.000278\, v - 0.208\, f + 0.0867\, a$$

$$Vb\ (\text{Wet}) = -\,0.0825 + 0.00139\, v + 0.375\, f + 0.0033\, a$$

$$Vb\ (\text{Gas cooled}) = 0.0108 + 0.000722\, v - 0.208\, f + 0.0033\, a$$

(Where, v=cutting speed, f=feed rate and a=depth of cut)

5.1 Analysis of flank wear in dry machining

Table 4 shows that test results are valid. Predicted machining factors performance was compared with the actual machining performance and, subsequently, a good agreement was made. Since the amount of errors was proved to be acceptable, so these models same as previous model can be selected as the best ones and use them in optimization level.

TABLE IV
RESULTS FOR CONFIRMATION TEST FOR FLANK WEAR (DRY)

Run	**v**	**f**	**d**	**Results of Model**	**Results of Experiment**	**Error (%)**
7	100	0.10	0.50	0.07935	0.08	0.8
14	120	0.08	0.75	0.11075	0.12	7.7

The effect of machining parameters on flank wear is presented in Fig 1. It indicates that depth of cut has the most significant effect on Tool Wear (V_b). Tool wear is minimum when the value of depth of cut is 0.75mm. The influence of feed rate in determining the tool wear ranks the second. The feed rate and the cutting speed have less significant effect on Tool wear compared with the depth of cut.

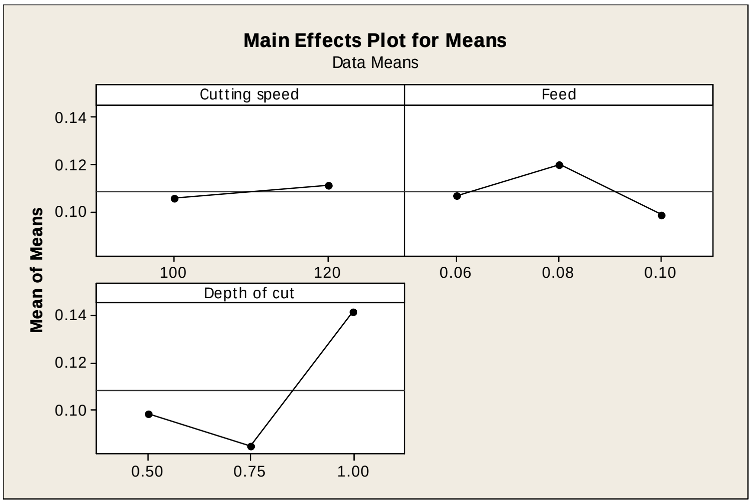


Fig 1: Effect of machining parameters on Flank Wear V_b (Dry)

5.2 Analysis of flank wear in wet machining

Table5 shows that test results are valid. Predicted machining factors performance was compared with the actual machining performance and, subsequently, a good agreement was made. Since the amount of errors was proved to be acceptable, so these models same as previous model can be selected as the best ones and use them in optimization level.

TABLE V
RESULTS FOR CONFIRMATION TEST FOR FLANK WEAR (WET)

Run	**v**	**f**	**d**	**Results of Model**	**Results of Experiment**	**Error (%)**
4	100	0.08	0.50	0.08815	0.09	2.1
12	120	0.06	1.00	0.1101	0.11	0.1

The effect of factors on flank Wear is presented in Fig 2. It indicates that the cutting speed has the most significant effect on Tool Wear (Vb). Next to that, the tool wear is minimum when the value of depth of cut is 0.75mm respectively. The feed rate also has more significant effect on Tool wear next to the cutting speed and depth of cut.

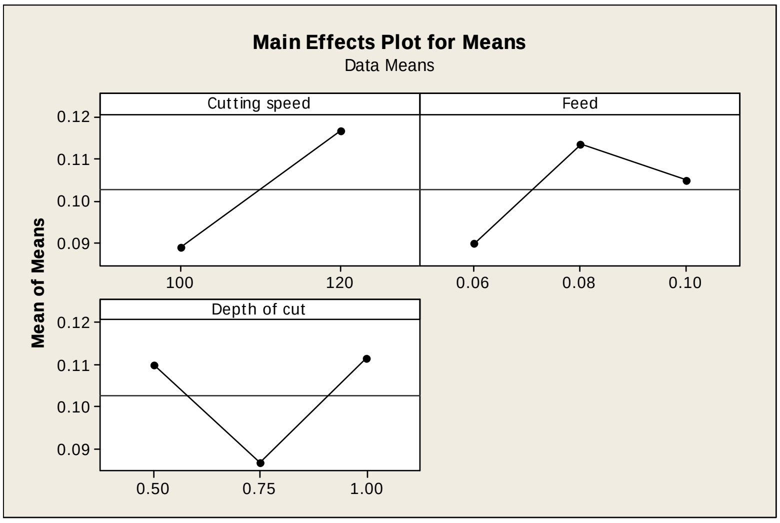


Fig 2: Effect of machining parameters on flank wear Vb(wet)

5.3 Analysis of flank wear in gas cooled machining

Table 6 shows that test results are valid. Predicted machining factors performance was compared with the actual machining performance and, subsequently, a good agreement was made. Since the amount of errors was proved to be acceptable, so these models same as previous model can be selected as the best ones and use them in optimization level.

TABLE VI
RESULTS FOR CONFIRMATION TEST FOR FLANK WEAR (GAS COOLED)

Run	**v**	**f**	**d**	**Results of Model**	**Results of Experiment**	**Error (%)**
1	100	0.06	0.50	0.07217	0.07	3.1
13	120	0.08	0.50	0.08826	0.09	1.9

The effect of factors on flank Wear is presented in Fig 3. It indicates that all the three factors have most significant effect on Tool Wear (Vb). The tool wear is minimum when the cutting speed decreases, feed has the maximum value and the depth of cut has the medium value. In short, the tool wear is minimum when the cutting speed is 100 m/min, feed is 0.10 mm/rev and the depth of cut is 0.75mm respectively.

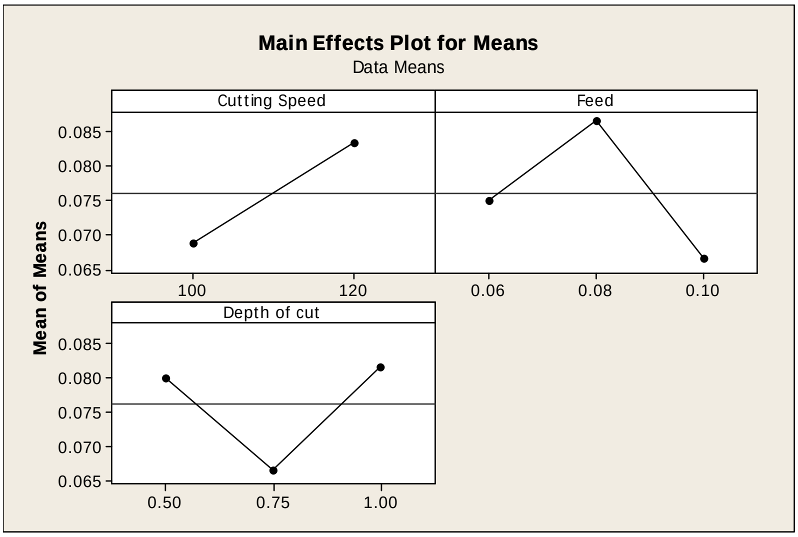


Fig 3: Effect of machining parameters on tool wear (Vb-Gas cooled)

VI. OPTIMIZATION OF MACHINING DATA

The primary objective in machining operations is to produce high-quality products with low cost. In order to minimize the machining cost for machining economics problem, the optimization of cutting parameters is one of the most important issues since these parameters strongly affect the cost, productivity and quality. Various traditional machining optimization techniques like Lagrange’s method, geometric programming, goal programming, dynamic programming etc. have been successfully applied in the past for optimizing the various machining process variables. Fuzzy logic, genetic algorithm, scatter search, Taguchi technique and response surface methodology are the latest optimization techniques that are being applied successfully in industrial applications for optimal selection of process variables in the area of machining. In this paper, RSM was used to optimize the experimental results for both dry and gas cooled machining and optimized values of machining parameters were predicted by RSM.

6.1 Response Surface Methodology (RSM)

Experimentation and making inferences are the twin features of general scientific methodology. Statistics as a scientific discipline is mainly designed to achieve these objectives. Planning of experiments is particularly very useful in deriving clear and accurate conclusions from the experimental observations, on the basis of which inferences can be made in the best possible manner. The methodology for making inferences has three main aspects. First, it establishes methods for drawing inferences from observations when these are not exact but subject to variation, because inferences are not exact but probabilistic in nature. Second, it specifies methods for collection of data appropriately, so that assumptions for the application of appropriate statistical methods to them are satisfied. Lastly, techniques for proper interpretation of results are devised. The advantages of response surface methodology are as follows:

- Numbers of trials are reduced.
- Optimum values of parameters can be determined.
- Assessment of experimental error can be made.

- Qualitative estimation of parameters can be made.
- Inference regarding the effect of parameters on the characteristics of the process can be made

The machining parameters namely the cutting speed, feed and depth of cut for all the three methods namely; dry machining, wet machining and gas cooled machining were optimized by response surface methodology using Minitab 15 software. The optimized values of machining parameters for dry machining are Cutting speed=120 m/min, feed=0.06mm/rev, depth of cut=0.6465 mm. For Dry machining, the predicted value of tool wear is Vb =0.0701. The composite desirability is 0.97490.

The optimized values of machining parameters for wet machining are Cutting speed=116.3636 m/min, feed=0.06 mm/rev, depth of cut=0.7071 mm respectively. For Wet machining, the predicted value of tool wear is Vb=0.0775. The composite desirability is 0.97076.

The optimized values of machining parameters for gas cooled machining are Cutting speed = 100 m/min, feed=0.06mm/rev, depth of cut=0.6162 mm respectively. For Gas cooled machining, the predicted value of tool wear is Vb=0.0602. The composite desirability is 0.97989.

VII. CONFIRMATION TEST (VALIDATION DATA)

The machining parameters were optimized by response surface methodology using Minitab 15 software. The confirmation experiments were conducted for all the three methods namely; dry machining, wet machining and gas cooled machining using the optimized values of machining parameters. For same set of machining parameters three trials were conducted and the average of the three values is taken. The percentage of error was calculated. The error in the predicted and experimental value for the gas cooled machining is lesser than other two methods of cooling. A good agreement between the experimental and predicted value of response was obtained. Because the percentage of error is less, it confirms that the results have excellent reproducibility. The optimal values of machining and response parameters for the dry machining, wet machining and the gas cooled machining were given in table 7, 8 & 9.

TABLE VII
VALIDATION RESULT FOR DRY MACHINING

CP	**OV**	**Vb**	
		POV	**EOV**
CS	120	0.0701	0.08
F	0.06		
D	0.6465		
Error (%)		12.3	

TABLE VIII
VALIDATION RESULT FOR WET MACHINING

CP	**OV**	**Vb**	
		POV	**EOV**
CS	116.3636	0.0775	0.07
F	0.06		
D	0.7071		
Error (%)		10.7	

TABLE IX
VALIDATION RESULT FOR GAS COOLED MACHINING

CP	**OV**	**Vb**	
		POV	**EOV**
CS	100	0.0602	0.06
F	0.06		
D	0.6162		
Error (%)		0.3	

Where,

CP- Cutting Parameters, CS- Cutting speed, F- Feed, D- Depth of cut

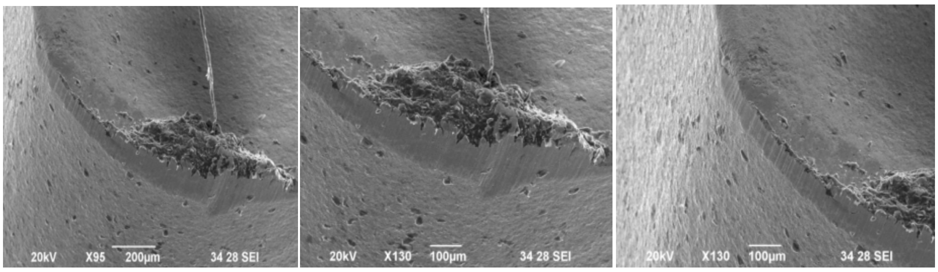
OV- Optimum value of parameters, POV- Predicted optimum value, EOV- Experimental optimum value

VIII. SCANNING ELECTRON MICROSCOPE ANALYSIS

8.1 Analysis of Flank wear:

The turning operation is carried out at the optimization values of machining parameters for all the three methods namely; dry machining, wet machining and gas cooled machining. The experimental values of tool wear was compared with the predicted values generated by response surface methodology. The gas cooled machining was said to exhibit the excellent performance in terms of tool wear while comparing with dry machining and wet machining.

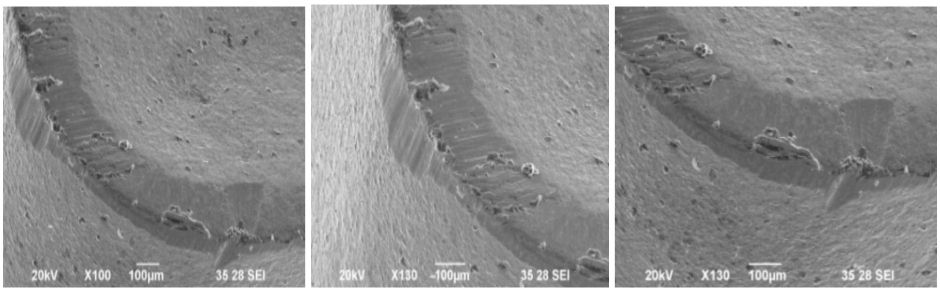
The tool wear at the optimized values for all the three methods were analyzed by scanning electron microscope (JOEL Model 6390). The tool wear is significantly reduced in case of gas cooled machining comparing with the dry machining (without coolant) and wet machining (with cutting oil). The SEM images of tool wear at various magnification levels (95x and 130x) for dry machining were given in figure 4. The images were taken when turning operation is carried out at the cutting speed of 120 m/min, feed rate of 0.06mm/rev and depth of cut of 0.6465 mm.



(95x) (130x) (130x)

Fig 4: SEM images of tool wear when turned at optimized value of machining parameters in dry machining (without coolant) at various magnification levels

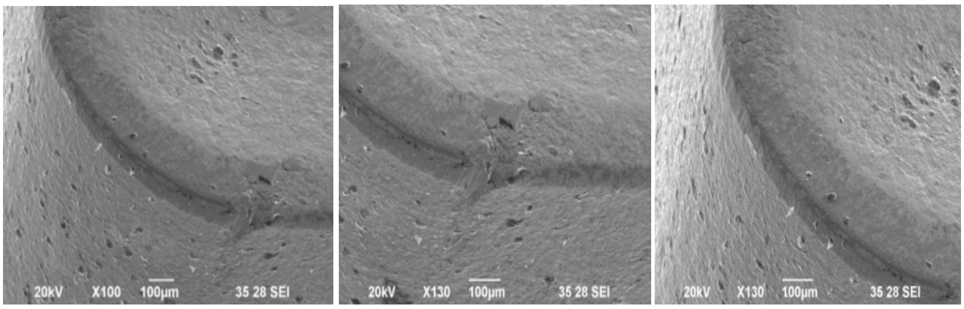
The SEM images of tool wear at various magnification levels (100x and 130x) for wet machining were given in figure 5. The images were taken when turning operation is carried out at the cutting speed of 116.3636 m/min, feed rate of 0.06 mm/rev and depth of cut of 0.7071 mm respectively.



(100x) (130x) (130x)

Fig 5: SEM images of tool wear when turned at optimized value of machining parameters in wet machining (with cutting oil) at various magnification levels

The SEM images of tool wear at various magnification levels (100x and 130x) for gas cooled machining were given in figure 6. The images were taken when turning operation is carried out at the cutting speed of 100 m/min, feed rate of 0.06 mm/rev and depth of cut of 0.6162 mm respectively.

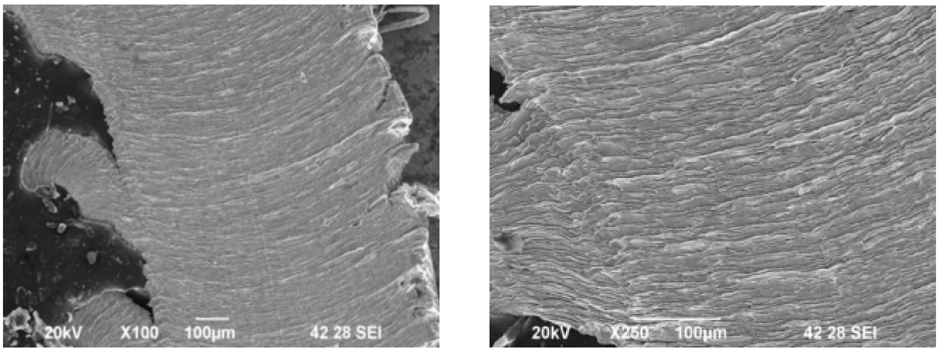


(100x) (130x) (130x)

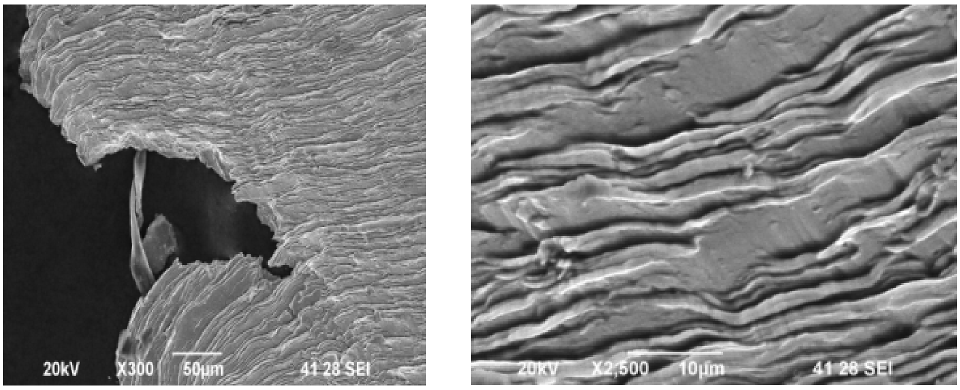
Fig 6: SEM images of tool wear when turned at optimized value of machining parameters in Gas cooled machining (with liquid CO2 as coolant) at various magnification levels

8.2 Analysis of chip produced at optimized value of machining parameters:

The chips produced at the optimized values for all the three methods i.e. dry machining, wet machining and gas cooled machining were analyzed by scanning electron microscope. The sharper edges of the chips produced in gas cooled machining when turned at optimized values were significantly reduced while comparing with the dry machining and wet machining. The continuous and curling chips produced in dry machining gets curled within the tool work interface and needs to be removed at short interval during turning. The tool work interface tends to be less affected by the chips produced in gas cooled machining as they gets break off at regular interval and forms a discontinuous chips. The colour of the chips turns white (silver) when turned at gas cooled environment. The SEM images of chips produced in dry machining when turning operation is carried out at the cutting speed of 120 m/min, feed rate of 0.06mm/rev and depth of cut of 0.6465 mm at various magnification levels (100x, 250x, 300x and 2500x) were given in figure 7.



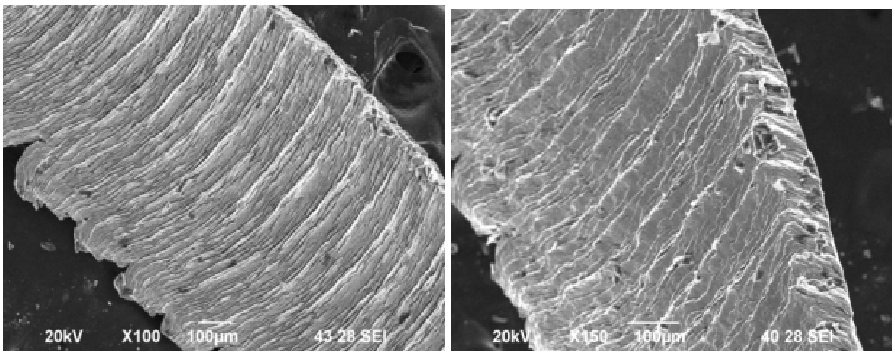
(100x) (250x)



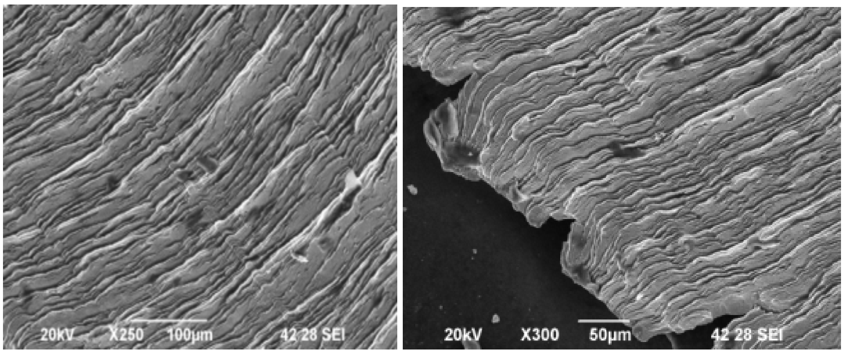
(300x) (2500x)

Fig 7: SEM images of chip produced when turned at optimized value of machining parameters in dry machining (without coolant)

The SEM images of chips produced in wet machining when turning operation is carried out at the cutting speed of 116.3636 m/min, feed rate of 0.06 mm/rev and depth of cut of 0.7071 mm at various magnification levels (100x, 150x, 250x and 300x) were given in figure 8.



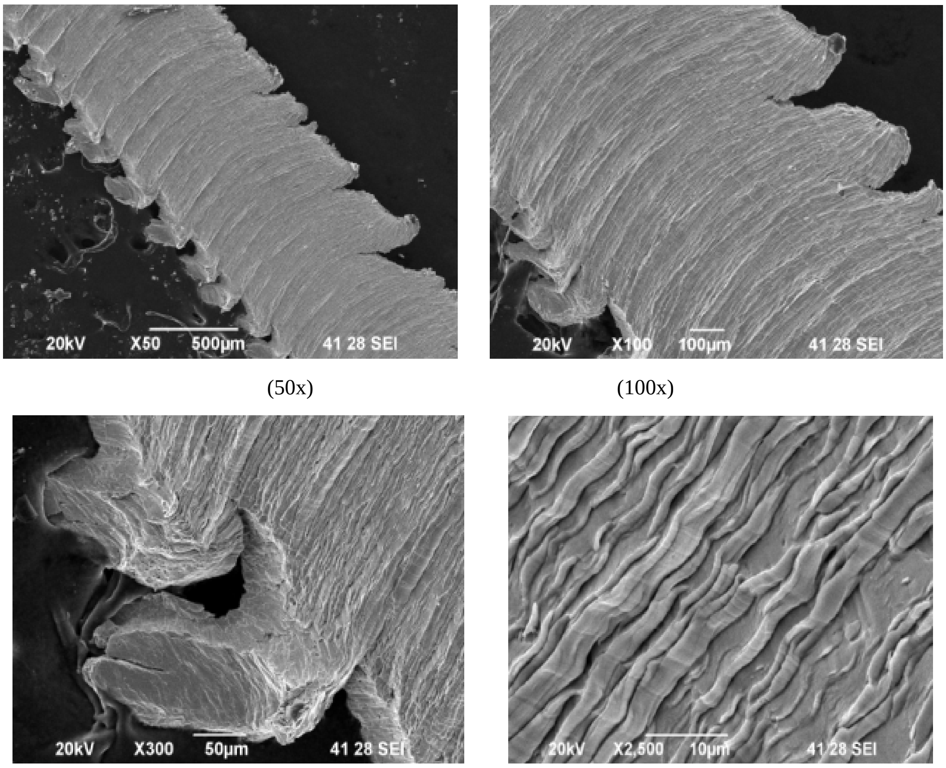
(100x) (150x)



(250x) (300x)

Fig 8: SEM images of chip produced when turned at optimized value of machining parameters in Wet machining (with cutting oil)

The SEM images of chips produced in gas cooled machining when turning operation is carried out at the cutting speed of 100 m/min, feed rate of 0.06 mm/rev and depth of cut of 0.6162 mm at various magnification levels (100x, 250x, 300x and 2500x) were given in figure 9.



(50x) (100x)

(300x) (2500x)

Fig 9: SEM images of chip produced when turned at optimized value of machining parameters in gas cooled machining (liquid CO_2 as coolant)

IX CONCLUSION

- The machining parameters that influence tool wear was found out. While comparing all the three methods, the tool wear gets reduced in gas cooled machining.
- The optimized values of machining parameters for turning super duplex stainless steel are

❖ For dry machining: (i) cutting speed = 120 m/min, feed rate = 0.06 mm/rev and depth of cut = 0.6465 mm

❖ For wet machining (i) cutting speed = 116.3636 m/min, feed rate = 0.06 mm/rev and depth of cut = 0.7071 mm

❖ For gas cooled machining: (i) cutting speed = 100 m/min, feed rate = 0.06 mm/rev and depth of cut = 0.6162 mm

- The cutting zone temperature and force acted during turning operation were also considerably reduced in case of gas cooled machining.
- Gas cooled machining (using liquid CO2 as coolant) was found to be an excellent alternative to conventional dry machining and wet machining (using cutting oil). The problem of disposing conventional cutting fluid is avoided by using liquid CO_2. In cost wise, using liquid CO_2 is also economical (1Kg=11 INR).

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