Optimization of Cutting Parameters and Grinding Process for Surface Roughness using Taguchi Method and CFD Analysis

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Abstract- Grinding is one of the important metal cutting processes used extensively in the finishing operations. During an abrasive material removal process a lot of heat developed because of high friction. The conventional method of cooling consumes high amount of coolant but still insufficient to control thermal related problems. The proper penetration of coolant is not possible and most of the fluid goes in waste form. This is harmful to environment and workers health. Surface finish is dependent output response in the production process with respect to quantity and quality. This is mainly depends on different input parameters like cutting fluid, wheel speed, work piece speed, depth of cut, grinding wheel grades, material hardness etc. The main objective is to achieve good surface finish by optimizing parameters and analyze the process using CFD by constructing the 3-D model which gives simulation of grinding process. Distribution of temperatures, pressures, velocities and flow pattern in and around the grinding region are obtained in more detail. Such results are helpful to obtain optimized grinding process. In this study the Taguchi method that is a powerful tool to design optimization for quality is used to find the optimum surface roughness in grinding operation. An orthogonal array, a signal-to-noise (S/N) ratio and an analysis of variance (ANOVA) are employed to investigate the surface roughness characteristic for grinding operations. The material hardness and microstructure are examined and optimum grinding parameters are found out for better surface roughness. The experimental results of this study shows that coolant flow rate and table speed have significant effects on the surface roughness while depth of cut has a lower effect on it.

Index Terms- Analysis of Variance (ANOVA), Computational Fluid Dynamics (CFD), Coolant, Grinding, Surface Roughness (Ra).

1. INTRODUCTION

Grinding machines are generally used for achieving of high dimensional accuracy surfaces and good surface finish. In most cases, the grinding is the final processing operation [1], [2]. The grinding wheel is formed by aggregate of cutting edges with negative rake angles, creates comparatively large amount of heat over the cutting operation. A large amount of coolant is needed to achieve the grinding performance in terms of grinding forces, metal removal rate; temperature developed in grinding zone, Specific energy and better work piece surface finish [3]. The traditional function of coolant may be cooling, lubrication, corrosion inhibition, chip removal. It may vary for machining operations. In case of Grinding, the cooling is more preferable than lubricity as high amount of heat develops due to high speed rotation of grinding wheel. These functions of coolant give improvement in tool life and surface finish. Generally the coolants are categorized into Straight type, Soluble, Synthetic and Semi-synthetic type. A large use of coolants requires high amount of cost which is approximately 15 % of total production cost [4]. The major problem is dispose of it after use since it contains toxic contaminants which pollute the land.

Different institute and agency has introduced several health and safety norms due to harmful emission from coolant to worker [5]. Thus from cost, health and environmental point of view, two alternatives are important either to make eco-friendly coolant or use less coolant for grinding operation.

2. LITERATURE REVIEW

The literature review focuses on the literature study done on the review of related journal- papers, articles available as open literature. This literature covers the grinding process related to input parameter such as cutting fluids, machining parameters on output parameters with the different optimization method.

Suresh Thakor et al. [6] explain that, surface finish and metal removal rate are the important output response in production with respect to quality and quality. The material for experimentation is EN8. The cutting fluids, workpiece speed, and depth of cut are input parameters. These are design by full factorial method. Statistical software package MINITAB 17 is used to derive the model between input and output parameters. The experimentation is carried by

cylindrical grinding with Al_2O_3 type grinding wheel. They found that, the water soluble oil as cutting fluid is the most influential parameter followed by depth of cut and work piece speed. The optimum results of parameters are seen for water soluble oil when highest work piece speed of 120 rpm and high depth of cut of 500 µm. Confirmation test gives surface roughness of 0.4246 µm and material removal rate of 0.0974 gm/sec.

Halil Demir et al. [7] has studied the effect of grain size of grinding wheel and depth of cut on surface roughness of AISI 1050 steel material using a Surface Grinder. The machining related parameters like grinding wheel revolution, wheel dressing rate and coolant flow rate are considered constant during experimentation. The result gives lowest surface roughness value when grind by wheel of 80 grain size compare to grinding wheel of 36 and 46 grain size. Generally low grain number wheel used for large volume of chip removal operation. It is also observed that during all stages of experimentation study, surface roughness value significantly increases with increase in depth of cut.

M. Aravind, Dr. S. Periyasamy [8] performed the experimentation on horizontal spindle hydraulic surface grinding machine for selected process parameters namely abrasive grain size, depth of cut and feed on AISI 1035 steel material. The minimum surface roughness value found by Taguchi method at grain size of 60 meshes, depth of cut of 0.05 mm and feed of 0.2 mm. The surface roughness value obtained by Response Surface Methodology gives more good result compare to Taguchi technique for same input process parameters. They concluded that feed of the surface grinding has minimum effect on the surface roughness of material.

Mustafa Kemal Kulekc [9] analyzed the process parameters for AISI 1040 steel plate material using L9 orthogonal array for optimum surface roughness. The work is carried on surface grinding machine using EKR46K type grinding wheel. The grinding parameters considered are wheel speed, feed rate and depth of cut. They concluded that the optimum grinding parameter combination using Taguchi method includes wheel speed of 1500 r/min and depth of cut of 0.05 mm. The contribution order by ANOVA technique found as 50%, 40% and 10% for depth of cut, wheel speed and feed rate respectively.

Ebbrell et al. [10] analyzed the velocity direction of air that can split into two streams when fluid approaches the grinding zone i.e. the boundary layer along the grinding wheel and the reversed air flow along the workpiece. The effect of the boundary layer especially near the grinding zone shows the grinding fluid of low velocity. Thus proper penetration of coolant is not possible.

Stefan D. Mihic et al. [11] explain CFD models used to simulate the fluid flow and heat transfer in a grinding process. The main characteristic of grinding is high precision and high surface finish. The relatively large contact area between tool and workpiece surface creates difficulties in supplying coolant to grinding arc thus resulting thermal damage to workpiece as well as overloading and wear of the grinding wheel. Thus, simulation of grinding process using CFD by creating 3-D model gives the accurate picture and information regarding distribution of temperatures, pressures, fluid flow pattern in and around the grinding region. These results of information are not possible by using experimental work.

Stefan Mihic, Sorin Cioc et al. [12] presents the significance of Computational Fluid Dynamics (CFD) models used to simulate the fluid flow and heat transfer in a grinding process. They explains the importance of correct fluid flow which enhanced process stability, better workpiece quality and tool life. The replacements of numerous experiments which are expensive, time-consuming and have limited capabilities are overcome by CFD technique. The author stated the 3-D model for detailed distributions of temperatures, pressures and flow rates in and around the grinding region.

3. WORKPIECE MATERIAL

The sample size selected for experimentation is 150 mm x 50mm x 20 mm. The black type mild steel plate is taken for experimentation as a sample. Total specimen for experimentation is 15. The sample material is purchased from the local market. The different chemical composition of material tested in lab is given in Table 1.

Table 1: Chemical Composition

Alloying Elements	Composition (%)	Alloying Elements	Composition (%)
C	0.175	S	0.075
Si	0.186	Co	0.026
Mn	0.502	Al	0.017
P	0.050	Ni	0.01

4. EXPERIMENTATION

The experiments are carried out by surface grinding machine on 150 mm x 50 mm x 20 mm under wet condition mainly in respect of surface roughness. The experimental setup is shown in fig 1. The coolant is used to reduce the heat and wash away the grinded metal powder produced during contact of work material and grinding wheel. The type of coolant is soluble cutting oil (AQUA CUT125).

The related parameters like hardness, microstructure, material and coolant properties are measured. The position of nozzle is positioned at nozzle tip of 25-35 mm from grinding zone with 15° - 20° from horizontal position of workpiece. A sump tank of capacity 100 liters is used, from where pump sucks the coolant and after performing the cooling action it again gets collected in it after filtering. Before

conducting every experiment the grinding wheel was dressed at 20 µm down feed using a silicon carbide stone. The speed of the workpiece table is varied by adjusting the knob of the hydraulic system. The wheel used for experimentation is of type 90A46/54K6V31 made by aluminum oxide (Al_2O_3) abrasives with vitrified bond. The size of wheel is 200 mm OD x 20 mm width x 31.75 mm ID with speed of 3000 rpm. The surface roughness is measured by surface roughness tester of model Surftest 211/212. The values of the input process parameters are changed as per design of experiment for the grinding.

Fig 1: Experiment setup

4.1. *Taguchi Method*

Taguchi methods of experimental design provide a simple, effective and systematic approach for the optimization of experimental design for performance quality and expected economic production. This method is a unique and powerful statically experimental design technique which greatly improves the engineering productivity. For present study, table speed, depth of cut and coolant flow rate has been identified as input parameters whereas surface finish is the dependent variable to improve performance characteristics of work piece. The levels of input parameters are shown in Table 2.

Table 2: Grinding parameters and their levels

Level	Table Speed (mm/min)	Depth of cut (microns)	Coolant Flow Rate (ml/min)	Coding
Low	6000	30	600	1
Medium	6500	40	1200	2
High	7000	50	1800	3

Nature and the economic consequences of quality engineering in the world of manufacturing process parameters are computed based on the signal to noise (S/N) analysis. Regardless of the category of the performance characteristic, the larger S/N ratio corresponds to the better performance characteristic. Hence the optimal level of the process parameters is the level with the highest S/N ratio. In this surface roughness should be lower, thus lower the better

concept with formula is used to calculate S/N ratio shown in equation (1).

$$\frac{S}{N} = -\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right) \qquad (1)$$

Where n = sample size and y_i = surface roughness in that run.

Furthermore, a statistical analysis of variance (ANOVA) is performed to obtain optimum process parameters that are statistically significant and the contribution (%) of each of these in surface roughness result. The optimal combination of the process parameters can also be predicted using Minitab 17 software. The design of experiments is shown Table 3.

Table 3: L9 Orthogonal array

Experiment Number	Grinding Parameter Level		
	Table Speed (mm/min)	Depth of Cut (microns)	Coolant Flow Rate (ml/min)
1	6000	30	600
2	6000	40	1200
3	6000	50	1800
4	6500	30	1200
5	6500	40	1800
6	6500	50	600
7	7000	30	1800
8	7000	40	600
9	7000	50	1200

5. RESULT AND DISCUSSION

After completing the experimental trails using L9 Taguchi orthogonal array, the surface roughness values are measured using surface roughness tester of model Surftest 211/212 and the results are tabulated.

5.1. *Optimization using Taguchi Method*

Using Minitab 17 software, the S/N ratios are calculated and tabulated. The smaller the better phenomenon is selected because surface quality will be high when value of surface roughness is small.

5.2. *Analysis of signal to noise (S/N) ratio*

Regardless of smaller the better as in machining, significance of input factors is find out using S/N ratio method. The high value of S/N ratio corresponds to a better performance. Therefore optimum level of parameters is the highest value of S/N ratio. The S/N ratio for surface roughness for orthogonal array is shown in Table 4. The response table of S/N ratio for surface roughness is shown in Table 5. The influence of each control factor is more clearly shown in response graph shown in Fig. 2. The slope of line

which connects the levels shows the strong influence of each control factor. It is observed that coolant flow rate has a strong effect on surface roughness and its S/N ratios. The depth of cut has a lower effect shown shallow shape of the line.

Table 4: L9 Orthogonal Array with S/N Ratios

| Expt. No. | Grinding Parameter Level | | | Output | |
	Table Speed (mm/min)	Depth of cut (microns)	Coolant Flow Rate (ml/min)	Surface Roughness (microns)	S/N Ratio (dB)
1	6000	30	600	16.9	-24.558
2	6000	40	1200	11.2	-20.984
3	6000	50	1800	12.1	-21.656
4	6500	30	1200	11	-20.828
5	6500	40	1800	15.5	-23.807
6	6500	50	600	16.1	-24.137
7	7000	30	1800	11.6	-21.289
8	7000	40	600	11.5	-21.214
9	7000	50	1200	11.1	-20.906

Table 5: Response Table for S/N Ratio

Level	Table Speed	Depth of Cut	Coolant Flow Rate
1	-22.40	-22.22	-23.30
2	-22.92	-22.00	-20.91
3	-21.14	-22.23	-22.25
Delta	1.79	0.23	2.40
Rank	2	3	1

Table 6 shows the factors and their optimum levels obtained using Minitab software. The Table 7 shows the ANOVA results of surface roughness. It shows that coolant flow rate has a contribution of 45% which shows significant effects on surface roughness. Therefore based on S/N ratio and ANOVA analysis the optimum cutting parameters for surface roughness is found as

Table 6: Factors and their optimum levels using

Minitab

Sr. No	Factors	Level	Optimum Level
1	Table Speed (TS)	3	7000 mm/min
2	Depth of Cut (DOC)	2	40 micron
3	Coolant Flow Rate (CFR)	2	1200 ml/min

Table 7: ANOVA for Surface Roughness

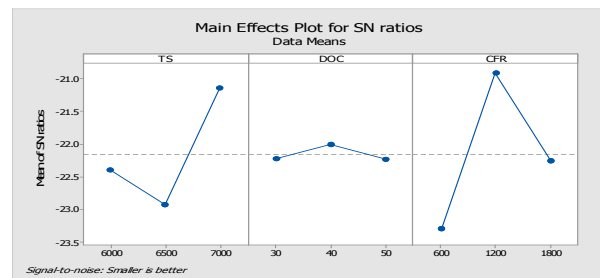| Source	DOF	SS	Mean Square	F value	Contribution (%)
TS	2	12.48	6.24	0.94	26
DOC	2	0.326	0.163	0.02	1 %
CFR	2	20.92	10.46	1.58	45
Error	2	13.20	6.60		28
Total	8	46.94			

Fig. 2: Main effect plot for S/N ratios for Ra

The improvement of S/N ratio and surface roughness are further carried to verify the results obtained using Minitab software considering the optimum parameters. This result is compared with experimentation results. The ratio of S/N ratio is determined by using equation (1) and corresponding surface roughness by experimentation.

Table 8: Results of confirmation experiment

Grinding parameter	Optimal Experiment parameters	Optimum Minitab parameter	Improved Ra (%)	Improved S/N ratio (dB)
Table speed	6500	7000	3.5%	1.4
Depth of cut	30	40		
Coolant flow rate	1200	1200		

Table 8 shows the comparison of S/N ratio and surface roughness obtained considering the experimental grinding optimum parameters with optimum parameters obtained using MINITAB software. The increase in S/N ratios is found as 1.4 dB and corresponding surface roughness improves by 3.5%. A close relation is observed for optimal values of S/N ratio and surface roughness determined in above methods.

5.3. *Microstructure*
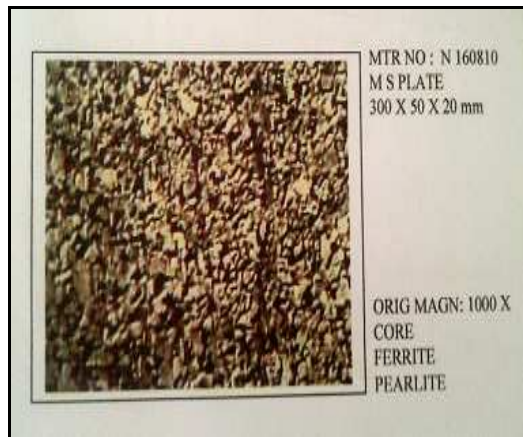
(a) Before Grinding

(b) After Grinding
Fig. 3: Microstructure before and after grinding

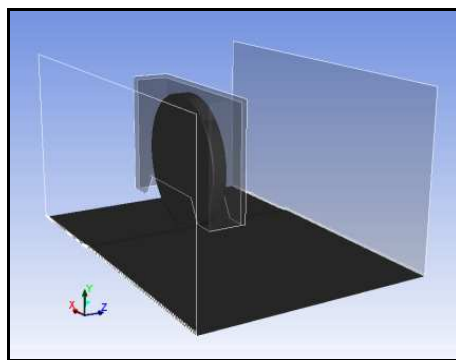Fig. 3 (a) and (b) shows the microstructure of the mild steel sample before grinding process which is of fine pearlite having non-uniform distribution of the structure and have medium and coarse ferrite also has intermediate structure about 8-10 % i.e. it is neither pearlite nor fully ferrite but in between of these. The component after machining process gives a uniform distribution of the structure. The microstructure is determined under the magnification range of 1000X. The nital 3% is used for etching the sample for 30 second.
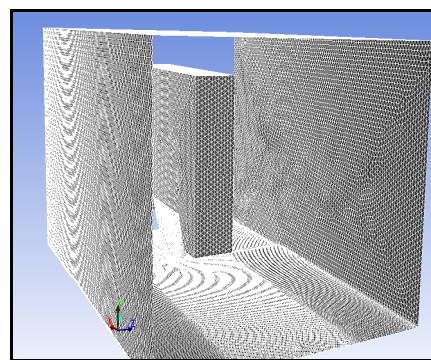
5.4. *Hardness*

The sample of mild steel is tested for hardness before and after the grinding. The hardness is tested on Rockwell hardness with B scale. The ball is used of tungsten denoted by notation 'W'. The hardness of sample before machining is found as 73 HRBW whereas the hardness after machining is 83 HRBW.

5.5. *CFD Results*

The objective of this work is to adapt and apply the approach and methods used in computational fluid dynamics (CFD) to study the fluid flow in grinding and, thus, obtain a detailed and accurate picture of the distribution of quantities such as temperature, pressure, velocity, and liquid volume fraction and coolant flow patterns. The CFD analysis is carried out at constant table speed of 6500 mm/min and depth of cut of 30 micron for coolant flow rate of 600 ml/min, 1200 ml/min and 1800 ml/min.
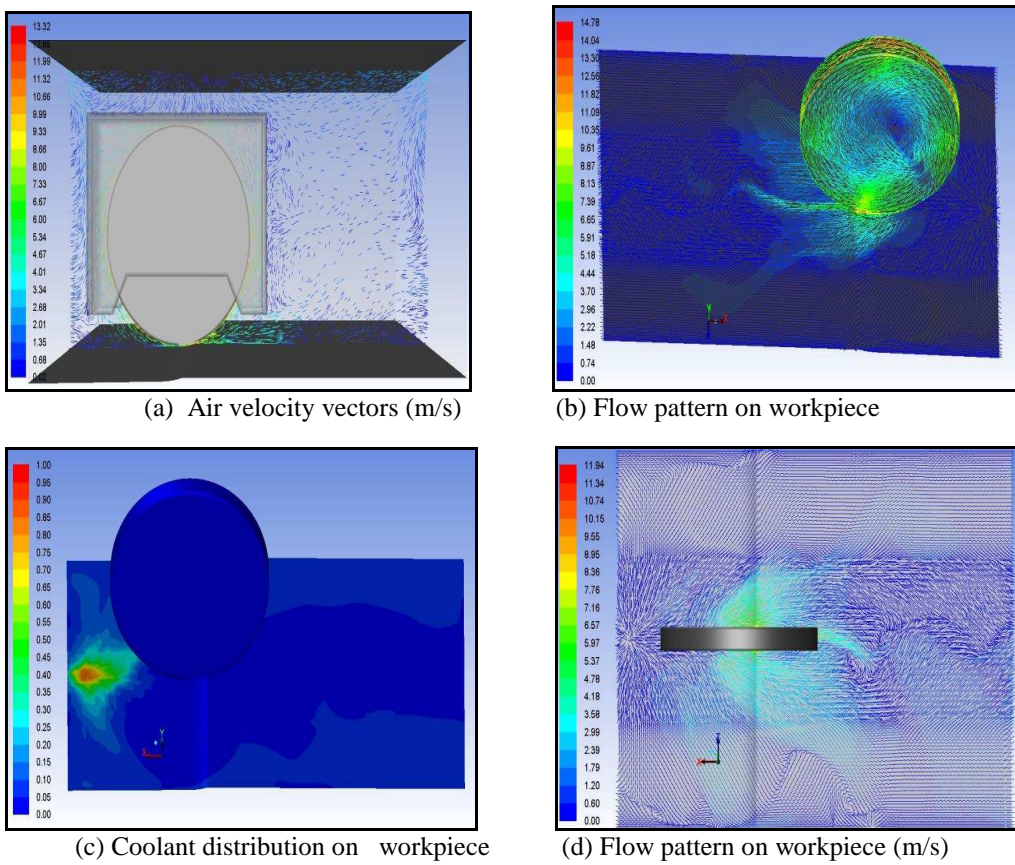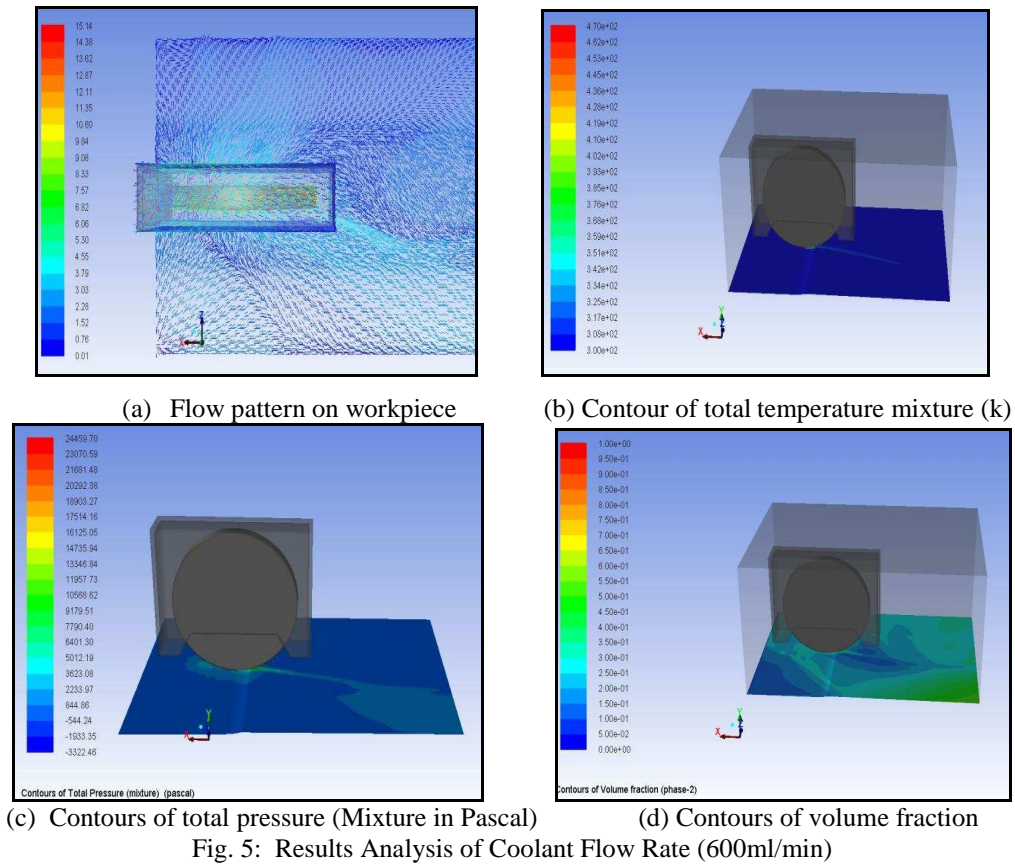

(a) CFD Model and Porous Media   (b) Meshing
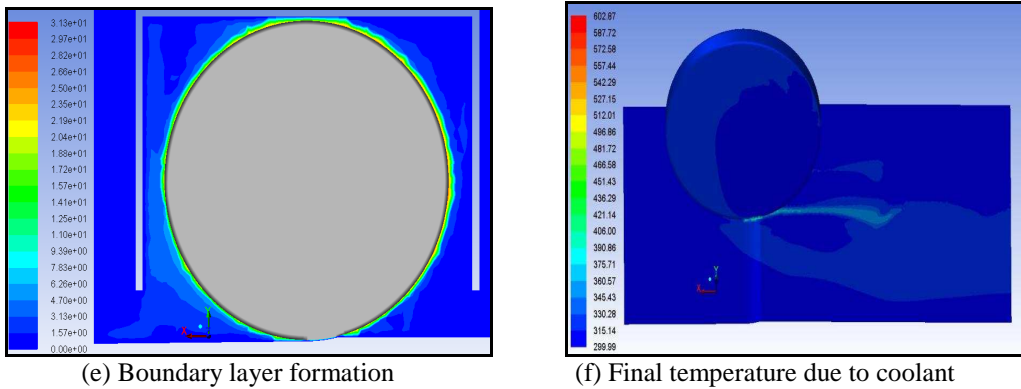Fig. 4: 3-D Model & Grid details

(a)   Flow pattern on workpiece

(b) Contour of total temperature mixture (k)

(c) Contours of total pressure (Mixture in Pascal)

(d) Contours of volume fraction

Fig. 5: Results Analysis of Coolant Flow Rate (600ml/min)

(a)   Air velocity vectors (m/s)

(b) Flow pattern on workpiece

(c) Coolant distribution on   workpiece

(d) Flow pattern on workpiece (m/s)

(e) Boundary layer formation

(f) Final temperature due to coolant

Fig. 6 Results Analysis of Coolant Flow Rate (1200 ml/min)

(a)   Vector distribution

(b) Temperature distribution

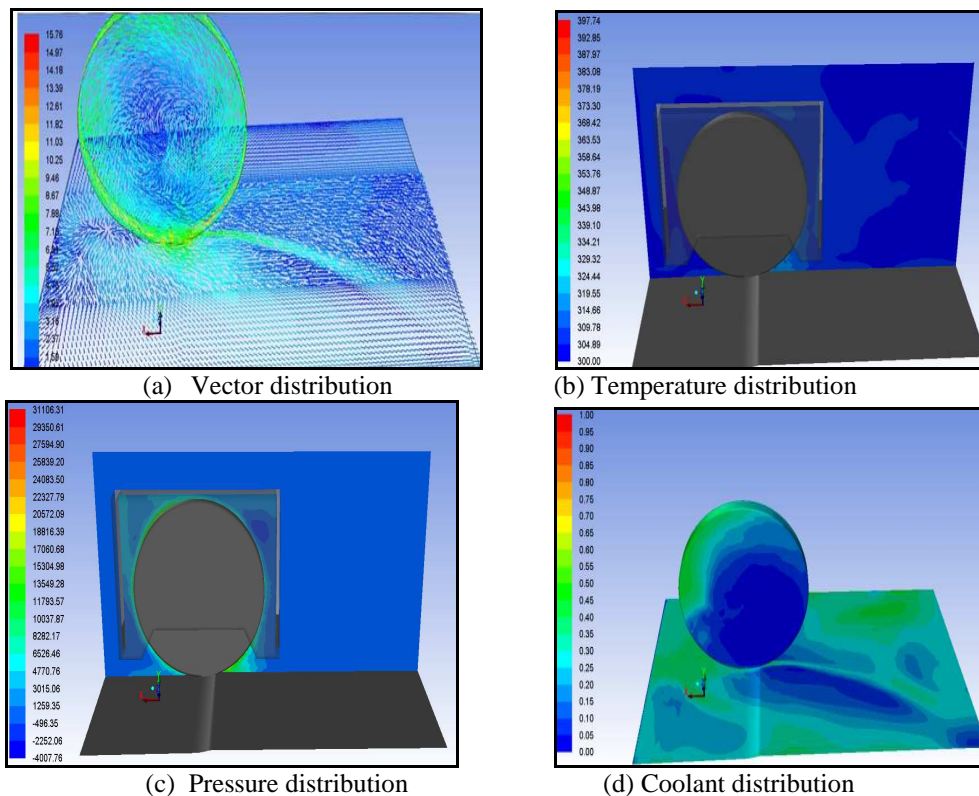(c)   Pressure distribution

(d) Coolant distribution

Fig. 7 Results Analysis of Coolant Flow Rate (1800ml/min)

6. CONCLUSION

In this study, an application and adaption of the Taguchi optimization and quality-control method were established for the optimization of the surface roughness in a grinding process. The objective is to optimized process parameters and grinding process for better surface finish.

1. Three parameters namely table speed, depth of cut and coolant flow rate of each of three levels are used as an input variable whereas the surface finish of job is considered as an output variable. The optimum grinding parameters found from experimentation using L_9 Taguchi orthogonal array are table speed of 6500 mm/min, depth of cut of 30 µm and coolant flow rate of 1200 ml/min.

2. The surface roughness values found from Minitab software for S/N ratio are table speed of 7000 ml/min, depth of cut of 40 µm and coolant flow rate of 1200 ml/min.

3. The order of contribution is determined by Analysis of Variance (ANOVA) method. The result shows that coolant flow rate (45.52%) and table speed (26.65%) are significant effects on the surface roughness compare to depth of cut.

4. The investigation of surface grinding process parameters shows that the selected parameters like table speed, depth of cut and coolant flow rate have affect on the hardness of sample. The value of hardness of grinded sample varies from 73 HRBW to 83 HRBW which affects on improve in surface roughness.

5. The microstructure of grinded sample observed under microstructure gives more uniform distribution of grain structure which helps to improve the results of surface roughness of workpiece.

6. The CFD analysis is studied for three types of coolant flow rates of 600ml/min, 1200 ml/min and 1800ml/min in detail. It is observed that air entrained around a rotating wheel forms a barrier that impedes fluid delivery, thus reducing the useful flow rate. The grinding fluid must first penetrate the air barrier to enter the grinding contact. The air barrier is a sub ambient pressure layer of fast moving air.

7. The reasons for getting better quality results for 1200 ml/min coolant flow rate is explained with CFD as the flow is getting evenly distributed and film formation near wheel.

8. Simulations using the proposed numerical models yielded detailed data and realistic fluid behavior. The distributions of temperatures, pressures and flow rates in and around grinding region were obtained in great detail, which would be difficult or even impossible to obtain using experiments only.

9. The heat transfer coefficient(w/m^2-k) along rim porous and workpiece porous is found as 19130.398 and 10805.339 respectively for coolant flow rate of 1200 ml/min which is highest compared to other two types of coolant flow rate. The highest heat transfer coefficient leads to highest overall cooling also average total temperature along workpiece porous and rim porous is found less for 1200 ml/min.

10. The future development of this work can be in considered in areas like:
   - Nozzle geometry can be considered for coolant flow.
   - Minimum Quantity Lubrication technique for coolant flow.
   - CFD analysis which includes consideration of Minimum Quantity Lubrication and Nozzle geometry for optimizations.

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