Experimental Analysis and Modelling of Residual Stresses in AISI 304 Shaft During Turning under Dry and Wet Environment

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***Abstract*— AISI 304 is widely used in pharmaceutical industries. Residual stresses induced in the shaft during machining processes. Residual stresses are an effect of thermo-mechanical and micro structural phenomena generated during the machining operation. In this study, the effects of dry and cutting with coolant conditions together with cutting parameters on residual stresses after turning AISI304 steel were investigated. A CNC lathe machine is usedfor machining of AISI304 shaft under different cutting conditions with dry and wet environment. After machining done small pieces are cut from main workpiece by wire cut method for XRD. X-ray diffraction method was used for measuring superficial residualstresses in the feed (axial) directions.While study residual stressesat different cutting speed and depth of cut with constant speed are concluded. As a conclusion we can say that residual stresses vary with variable cutting feed rate and variable cutting speed. It gives that as the cutting feed rate or cutting speed increases values of residual stresses also increases but this phenomena is not constant throughout the analysis. Developed residual stresses under coolant conditions are more than the dry cutting conditions. But these results of residual stresses are not streamlined. Therefore, more up and downs in the graphical comparison and it needs to validate by numerical modelling using ABAQUS/CAE software.**

***Keywords*- ABAQUS, Numerical modelling, Orthogonal cutting, Residual stresses, X-ray diffraction.**

I. INTRODUCTION

Residual stresses are those present in a material or structural component free of external loads or temperature variations. All manufacture process, casting, welding, molding, heat treatment, etc., introduce residual stresses in structures and equipments. Another common cause of the residual stresses introduction are repairs or modification of the in service components. In most cases residual stresses are injurious and there are several documented cases in which these strains were predominant reasons for fatigue failure. A particularly dangerous aspect of the residual stresses is that their presence is generally not noticed. The knowledge of surface residual stresses is important to predict the onset of failure when the component or structure is under loading.

There has been a lot of research devoted to finding residual stresses. Measurement techniques have been developed and simulation techniques have been improved over the years. The reason for the present study is to see if calculations of residual stresses have reached a level where they could be performed on a daily basis or not. Residual stresses in a work piece are merely a function of its material processing and machining history [1].

According to their nature, residual stresses can enhance or impair the functional behaviour of a machined part. In the vicinity of the machined surface, tensile residual stresses have negative effects on fatigue, fracture resistance and stress corrosion. The result often is a substantial reduction in the component's life [2].

Residual stresses in the machined surface layers are controlled by choices of cutting tool, work material and cutting parameters (for example: cutting speed, depth of cut and feed).

This paper introduces anexperimental analysis of residual stresses in AISI304 shaft by using X-ray diffraction method. The aim of this paper is to investigation of residual stresses in AISI 304 at variable cutting parameters and under dry & wet conditions. Firstly, experimental procedure is described. Finally overall conclusions are pointed out and future research direction is discussed.

II. EXPERIMENTAL ANALYSIS OF MACHINING

Henriksen [1] presented the effect of machining on residual stress was done experimentally around 1950. The study was conducted on low carbon steel orthogonally machined. Henriksen established that both mechanical and thermal effects played a role in the development of residual stresses, but that mechanical influence dominated.

Liu and Barash [2] focused on different aspects of the machining process affect the residual stress produced. They found that for orthogonal cutting, the length of the shear plane, tool flank wear, the shape of the cutting edge, and the depth of cut uniquely determine the pattern of the residual stress on a machined surface.

Sadat[3] looked at the residual stress distribution into the surface of the work piece for turned AISI 4340 steel. The residual stress distribution was measured using a deflection etching technique. It was found that the absolute value of the residual stresses at the machined surface were low, but increased with increasing depth into the work piece to a maximum value. After reaching this value, the residual stress value would decrease close to zero with increasing depth.

Sadat[4] also experimented with the orthogonal cutting of Inconel-718 nickel base super alloy. The surface integrity at the work piece at various cutting speeds, depths of cut and chip-tool contact lengths was investigated. The experimental work involved the determination of residual stress, plastic strain and micro-hardness distributions in the surface region. Both residual stresses and plastic strains decreased and the quality of the machined surface improved with an increase in cutting speed, a decrease in depth of cut and with tools having controlled chip-tool contact lengths.

Schlauer[5] examined the near-surface residual stress distributions that originate during turning in the nickel-based super-alloy Inconel 718. The effects of the cutting speed and feed on the residual stress distribution measured using an optical, and a transmission electron microscopes, were investigated. The work showed that tensile surface residual stresses were due to nano sized grains while shear bands in the subsurface corresponded to compressive stresses.

Celalettin KARAAGAC [6] presented, the failure (fracture) of an agitator shaft with a circumferential notch was selected as investigation topic. However, this study is intended for introducing fracture mechanics from an application viewpoint.

Manouchehr Vosough [7] used Titanium alloys for finding the effect of high pressure cooling on residual stress. Manouchehr Vosough investigated the properties of the machined surface with regards to measurement of residual stresses. The results achieved by X-ray diffractometry were compared with the results using a simulating method with the same cutting data for checking the accuracy of these two methods. The same procedure was checked using Finite Element simulations. The results obtained from the investigation clarified that, 1. The residual stress measurement by X-rays was quite accurate in comparison with finite element simulation on the surface generated by turning on titanium alloy. 2. There were compressive residual stresses in the cutting and feed directions of the cut. Residual stress is beneficial for delay of crack propagation. 3. High-pressure cooling produced and increased compression residual stresses.

D. Ulutan, B. ErdemAlaca, I. Lazoglu [8] developed analytical model for prediction of residual stresses in machining. In this model the thermal model of workpiece and mechanical forces are coupled. Stresses resulting from thermal and mechanical loading are computed using an analytical elasto-plastic model and a relaxation procedure. The model was verified with experimental measurements of residual stresses on bearing steel 100Cr. By using analytical model substantial reduction in computational time is achieved in the prediction of residual stresses.

A.W. Warren, Y.B. Guo[9] presented true residual stress profiles by hard turning and grinding AISI 52100 steel. This study aims to clarify the pressing issues for five surface types: hard turned fresh, hard turned with a white layer, ground fresh, ground with a white layer, and as-heat-treated. The key findings are: (i) hard turned fresh surfaces produce surface compressive residual stress and subsurface maximum compressive residual stress, while ground fresh surfaces only generate surface maximum compressive residual stress; (ii) hard turned white layer surfaces generate a high tensile stress in the white layer, but has highly compressive residual stress in the deeper subsurface than the hard turned fresh surfaces; (iii) hard turned white layer surfaces change the basic shape of residual stress profiles, while ground white layer surfaces do not; (iv) Tensile residual stress in hard turned white layer surfaces is higher than that the ground white layer surfaces. However, the residual stress for the ground white layer does not become compressive in the subsurface; and (v) Machining is the deterministic factor for the resulting residual stress compared with heat treatment.

TadeuszLeppert • Ru Lin Peng[10] presented residual stresses in surface layer after dry and MQL turning of AISI 316L steel. In this paper the effects of dry, MQL cutting and cutting with emulsion conditions together with cutting parameters on residual stresses after turning AISI 316L steel were investigated.

T. Ozel& D. Ulutan[11], presented the prediction of machining induced residual stresses in turning of titanium and nickel based alloys with experiments and finite element simulations. Residual stresses were measured in radial and circumferential directions using X-Ray diffraction technique. 3-D finite element (FE) modeling is utilized to predict forces and machining induced stress fields. The feasibility and limitations of predicting machining induced residual stresses by using visco-plastic finite element simulations and temperature dependent flow softening constitutive material modeling are investigated. A friction determination method is utilized to identify friction coefficients in presence of tool edge radius.

A.K. Mishra, P. Shandilya[12], presented FEM Analysis on Residual Stresses induced in Ti–6Al–4V titanium under dry turning. In this paper many aspects of surface integrity are discussed with more focus on residual stress. In case study residual stresses are calculated experimentally by X-ray diffraction technique as well as predicted by finite element method for Ti–6Al–4V titanium alloy.

Walid Jomaa, Victor Songmene and Philippe Bocher[13], presented Surface Finish and Residual Stresses Induced by Orthogonal Dry Machining of AA7075-T65. The surface finish was extensively studied in usual machining processes (turning, milling, and drilling). For these processes, the surface finish is strongly influenced by the cutting feed and the tool nose radius.

III. Experimental Method and Materials

The reason for this study is to find the residual stresses have reached a level where they could be performed on a daily basis or not. Experimental analysis was done by using CNC lathe machine and residual stresses were found by X-ray diffraction method. The result of X-ray diffract meter is the graph of intensity v/s 2 Theta. Based on these values we have calculated residual stresses. The validation of these results we will use ABAQUS, a commercial and state of the art software package.It will be used to provide 2D as well as full three-dimensional (3D) FE simulations of the turning operation. Every engineering based process has certain limitations and obstacles that add to its level of complexity. Understanding these limitations could provide a wide range of solutions and possibly save time and money.

A. Workpiece Material

In the turning trials a bearing steel material, AISI 304 steel, is used. After purchasing AISI304 steel from market, it is necessary to examine it's chemical composition.Chemical composition- C<0.08%, Cr=18-20%, Fe=66.345-74%, Mn<2%, Ni=8-10.5%, P<0.045%, S<0.03%, Si<1%. The properties of material are shown in Table 1. The workpiece dimension is170mm (length) × 45mm (dia.). Two no of work piece are taken for conducting experiment under dry & coolant environment.

TABLE I
MATERIAL PROPERTIES

Material Properties	
Density	8 gm/cc
Poisson's Ratio	0.29
Young's Modulus	210 GPA
Thermal Conductivity	16.2 W/moC
Brinell Hardness	123
Modulus of elasticity	200 GPA

B. CNC Lathe Machine:

A CNC machine make Takamatsu Machinery Co., Ltd, Japan was used to performed the experimentation. The specification of this machine is mentioned in Table 2.

TABLE II
SPECIFICATION OF CNC LATHE MACHINE

Technical Data	
Make & Model	TAKAMATSU Machinery, Japan. XL-150
Chuck Size	8 Inch
Spindle Bearing ID	Dia. 100 mm
Spindle Speed	Mx. 3500 rpm
Type	X=190, Z=400 mm
Rapid Traverse Rate	X=18, Z=24 m/min
Spindle Motor	AC 11/ 7.5 KW
Dimension (LxWxH)	1,690 x 1,600 x 1,535 mm

C. X-Ray diffractometer:

The X-Ray diffractometer used is D8 Advance and its specification and photograph is shown in Table 3 and Fig. 2 respectively.

TABLE III
SPECIFICATION OF X-RAY DIFFRACTOMETER

Technical Data	
Configurations	Vertical Goniometer, Theta/2 Theta or Theta/Theta Geometry
Measuring circle diameter	Predefined at 500 mm & 600 mm or any intermediate setting.
Angular Range (Without accessories)	360 deg.
Max. Usable angular range	-110o < 2Theta < = 168o (20o to 80o)
Angle positioning	Stepper motors with optical encoders
Maximum angular speed	20o/s
Exterior dimension (h x w x d)	1,868 x 1,300 x 1,135 mm 73.7 x 51.2 x 44.7 inch
Weight	770 kg
Maximum power consumption	6.5 kVA

D. Experimentation:

Raw material AISI304 (2 nos. Dimension- 170 × 45mm) was purchased from the market. On that work piece material 4 steps of 25mm thickness can be prepared by CNC lathe machine under dry & coolant condition. To determine the residual stress profiles it is important to consider a tool suitable for AISI 304. Machining was done on work piece with varying feed rate, depth of cut and varying cutting speed as shown in Table 4.

TABLE IV
CUTTING CONDITIONS

Cutting Speed (m/min)	**Feed (mm/rev.)**	**Depth of cut (mm)**
100	**0.08**	**0.5**
100	0.08	0.4
100	0.10	0.5
100	**0.10**	**0.4**
150	**0.08**	**0.5**
150	0.10	0.5
150	0.08	0.4
150	**0.10**	**0.4**

We have selected a KORLEY PC9030 HA insert for turning on CNC lathe.

The Taguchi method involves reducing the variation in a process through robust design of experiments. The Taguchi method was developed by Genichi Taguchi. He developed a method for designing experiments to investigate how different parameters affect the mean and variance of a process performance characteristic that defines how well the process is functioning. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varied. Instead of having to test all possible combinations like the factorial design, the Taguchi method tests pairs of combinations. This allows for the collection of the necessary data to determine which factors most affect the product quality with minimum amount of experimentation, thus saving time and resources. In this case we have 3 parameters and two levels. We have selected L4 orthogonal array from array selector.

After application of cutting conditions on workpiece 8 small pieces are to be cut from main workpiece of 18x13x1.5 mm by wire cut method. These small pieces are now X rayed on X-Ray diffract meter. X-Ray diffract meter used is D8 Advance.

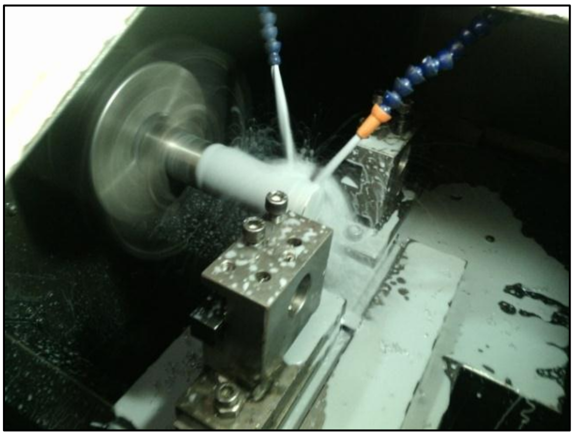

Fig.1 Turning of AISI304 work piece material on CNC lathe under coolant.

The X-ray method is non-destructive technique for the measurement of residual stresses on the surface of materials. When metal is under stress, applied or residual stress, the resulting elastic strains cause the atomic planes in the metallic crystal structure to change their spacing. X-ray diffraction can directly measure this inter-planar atomic spacing, from this quantity the total stress on the metal can then obtained. Output of X-Ray diffractomer is related with the strain developed in the material. The measurement of residual stress by X-ray diffraction relies on the fundamental interactions between the wave front of the X-ray beam and the crystal lattice.

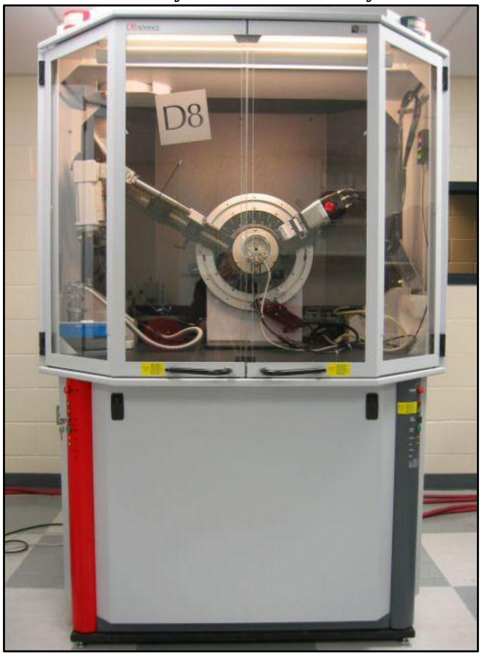

Fig.2 D-8 Advance BrukerX-Ray diffractomer

Residual stresses can be calculated on the principle of Bragg's Law. Crystalline material made up of many crystals, where a crystal can be defined as a solid composed of atoms arranged is a pattern periodic in three dimensions. These periodic planes of atoms can cause constructive and / or destructive interference patterns by diffraction. The nature of the interference depends on the inter-planer spacing d and the wavelength of the incident radiation λ[15]. Bragg deduced an expression for the conditions necessary for diffraction to occur in such a constructive manner.

$$n\lambda = 2d \sin \theta$$

This is commonly known as Bragg's law and it forms the fundamental basis of X-ray diffraction theory and particle size determination by Hall-Williamson (H.W.) Plot.

$$\beta \cos \theta = k\lambda / D + \eta \sin \theta$$

Where,

λ= X-ray Wavelength

θ = The Bragg angle

β = Full width of the diffraction line at half of the maximum intensity.

η = Strains in the crystallites

D = Size of the crystallites

k = Constant close to unity & ranges from 0.8-1.39

After plotting the graph of $\beta \cos \theta$ vs. $\sin \theta$, straight line has been observed with slope η and intercept $k\lambda/D$.

Slope of this line η is nothing but the strain generated in the workpiece due to machining conditions. Therefore residual stress is given as,

$$\sigma = E\,\varepsilon$$

Where,

σ = Residual stress.

E = Modulus of elasticity

ε = Strain measured by X-ray diffraction.

IV. NUMERICAL ANALYSIS

Numerical model is developed to predict residual stresses induced in the machining using numerical model to metal machining in software ABAQUS 6.14. In this software first we have generate 2D model for machining. In this modelling both tool geometry (Fig-3) and work piece geometry (Fig-4) is created. After modelling it is necessary to assign sections. In this section AISI 304 steel material model is assigned to work piece material and tool geometry considered as rigid body.

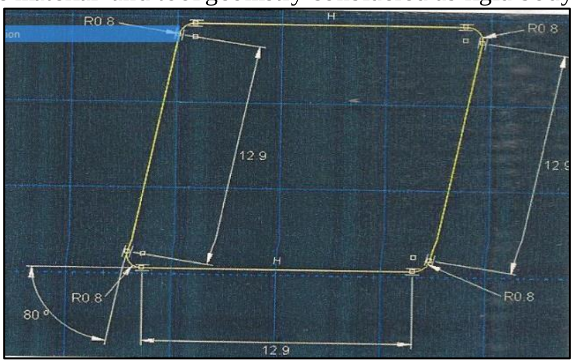

Fig.3 Tool Geometry

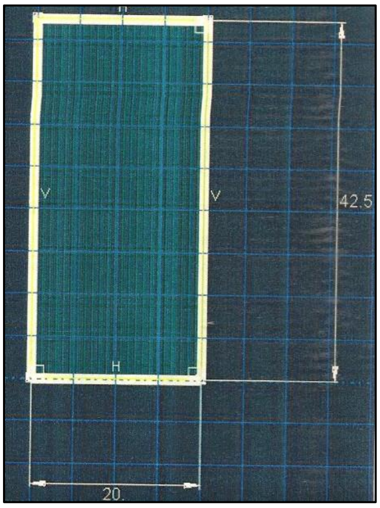

Fig.4 Tool Geometry

Boundary Conditions:

Fig. shows 2D model for finite element simulation. Length in the x-direction is 20mm and y-direction is 42.5mm. The nose radius of tool is 0.8mm. Motion of the work piece is restricted in the x and y direction.

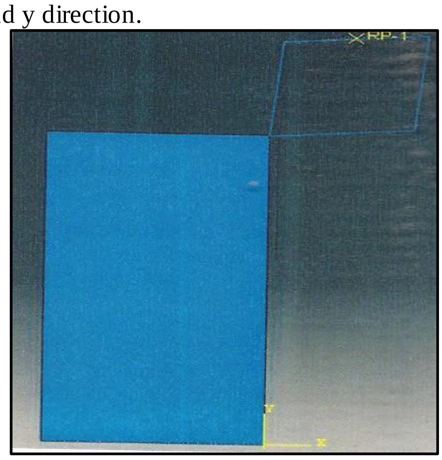

Fig.5 Assembly of Tool & Work piece geometry

Meshing:

Structured mesh technique generates structured meshes using simple predefined mesh topology. ABAQUS/CAE transforms the mesh geometry in a square or cube shape. For tool meshing element size considered 0.2 and for work piece material 0.05.

Processing:

After execution of modelling last step is job execution and results obtained for the measurement of residual stresses.

V. RESULT & DISCUSSION

There are 4 conditions from above table for wet and dry cutting condition and for each condition residual stress has been calculated. Following graphs shows exact overview of residual stresses. For experimental analysis we have used Hall-Williamson method. Fig. 3 to Fig. 10 shows result obtained by x-ray diffraction method for various cutting speed, feed rate and depth of cut.

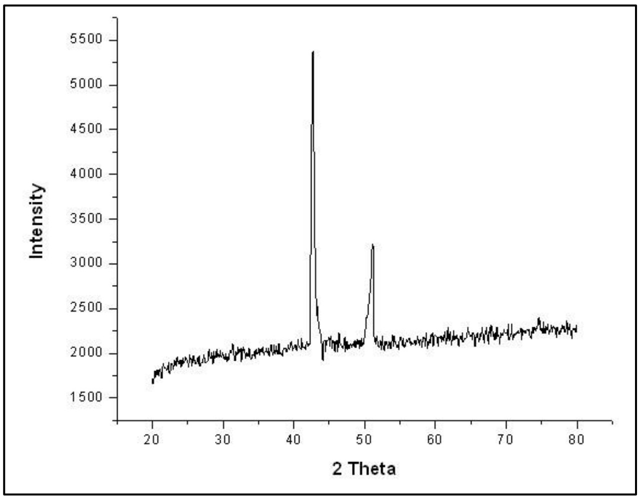

Fig.6 X-ray diffraction result for *Vc*= 100m/min and *f*=0.08mm/rev under coolant condition.

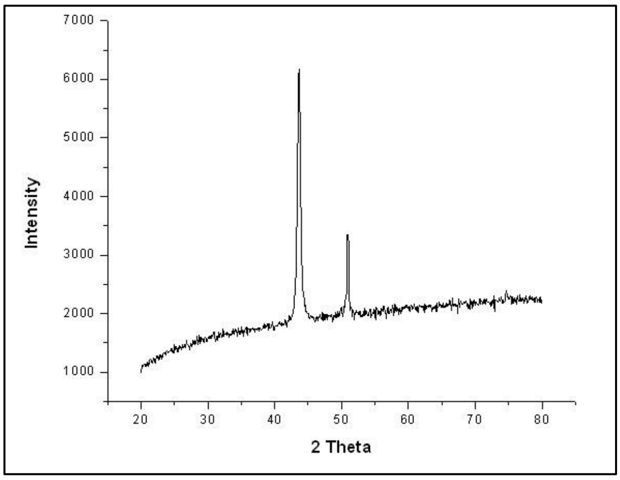

Fig.7 X-ray diffraction result for *Vc*= 100m/min and *f*=1mm/rev under coolant condition.

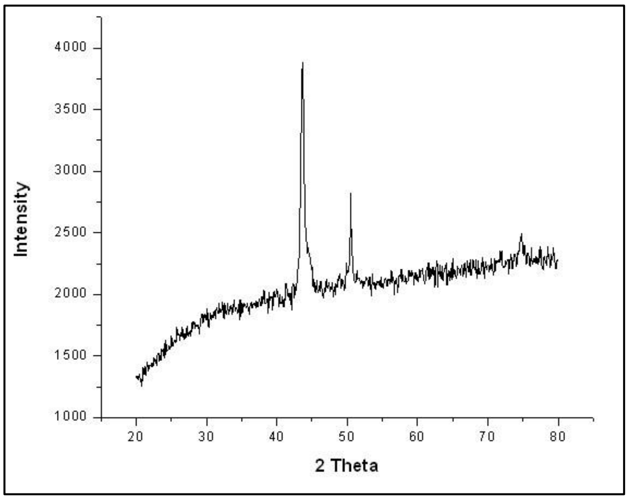

Fig.8 X-ray diffraction result for *Vc*= 150m/min and *f*=0.08mm/rev under coolant condition.

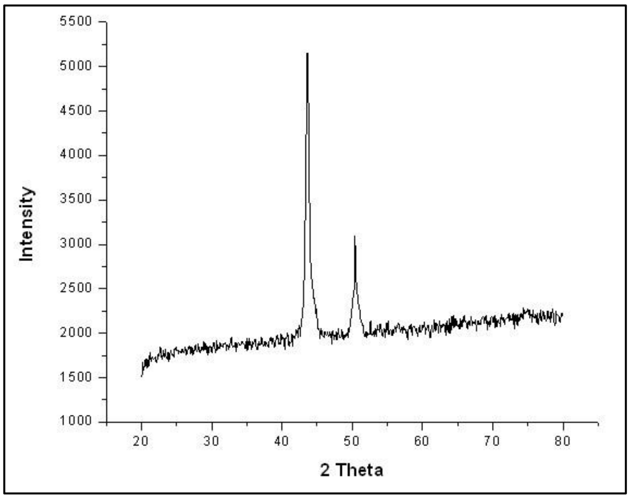

Fig.9 X-ray diffraction result for *Vc*= 150m/min and *f*=1mm/rev under coolant condition.

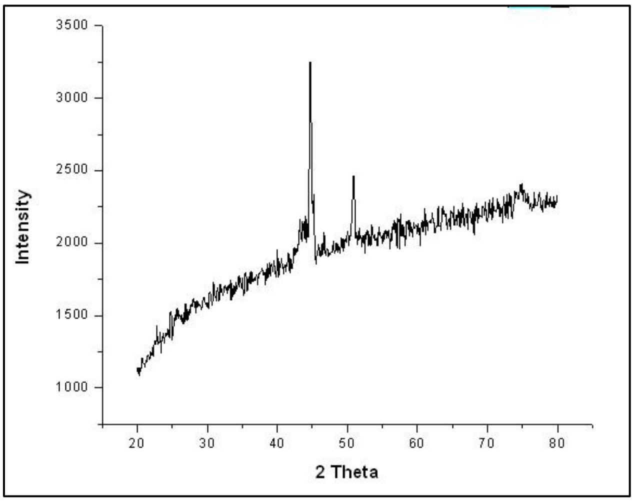

Fig.10 X-ray diffraction result for *Vc*= 100m/min and *f*=0.08mm/rev under dry condition.

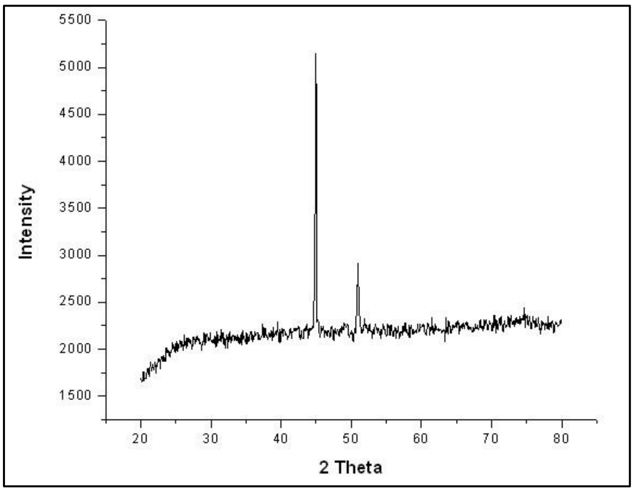

Fig.11 X-ray diffraction result for *Vc*= 100m/min and *f*=1mm/rev under dry condition.

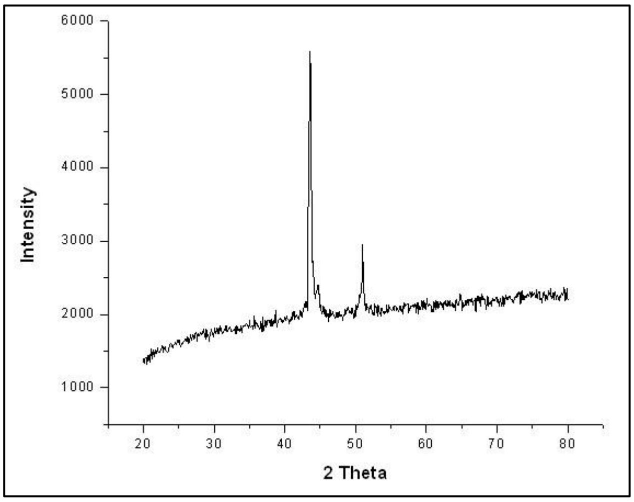

Fig.12 X-ray diffraction result for *Vc*= 150m/min and *f*=0.08mm/rev under dry condition.

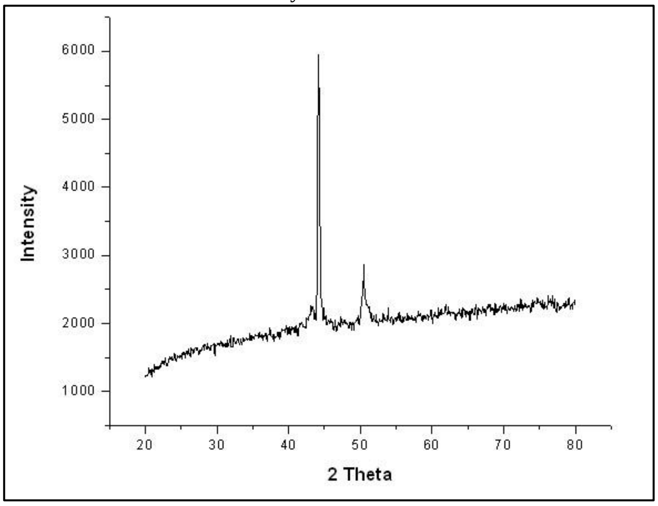

Fig.13 X-ray diffraction result for *Vc*= 150m/min and *f*=1mm/rev under dry condition.

Residual Stress Calculation:

Calculation for first peak-

Range of 1^{st} Peak= Intensity1- Intensity2

Half of Max. Intensity= Intensity1 + (Intensity2-Intensity1)/2

$\beta 1$ = the full width of diffraction line at half of the max. intensity.

$= (2theta_{max}-2theta_{min})/2 \times \pi/180.$

$\theta 1$ = the Bragg angle

= 2θ value at highest peak/2

Repeat the same procedure for second peak to find $\beta 2$ & $\theta 2$.

$$\text{Strain } (\eta) = \frac{(\beta 1 \cos \theta 1 - \beta 2 \cos \theta 2)}{(\sin\theta 1 - \sin\theta 2)}$$

Residual Stress= η X E

TABLE V

RESIDUAL STRESS

Cutting Speed (m/min)	**Feed (mm/rev.)**	**Depth of cut (mm)**	**Residual stress (Coolant)**	**Residual stress (Dry)**
100	0.08	0.5	436.11	111.64
100	1.00	0.4	462.28	300.04
150	0.08	0.5	348.89	401.22
150	1.00	0.4	409.34	565.20

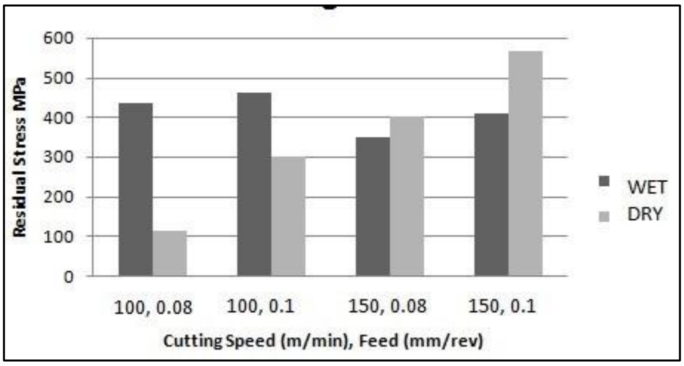

Fig.14. Residual stress v/s cutting speed and feed rate for dry & wet environment.

TABLE VI
RESIDUAL STRESS BY EXPERIMENTAL & NUMERICAL METHOD

Cutting Speed (m/min)	**Feed (mm/rev.)**	**Experimental values of Residual stress N/mm2**	**Numerical values of Residual stress N/mm2**
100	0.08	111.64	123.61
100	0.10	300.04	304.34
150	0.08	401.22	404.36
150	0.10	565.20	336.53

Fig. 6 to Fig. 13 shows the x-ray diffraction result for determination of surface residual stress in the cutting direction. The graph pattern of intensity v/s 2 theta does not give exact relationship between feed rate and cutting speed. Experimental results are validated by numerical methods by using ABAQUS/CAE. It has been observed that experimental results are validate by numerical model for all conditions except Vc=150m/min and f= 0.10 mm/rev machining conditions. In this numerical value deflected from experimental value

VI. CONCLUSION

The conclusions for residual stress are as follows:
1) The residual stresses increases with feed rate.
2) Under coolant machining condition residual stress increases with cutting speed.
3) At minimum speed residual stresses are very less under dry cutting condition.
4) Residual stress increases as cutting speed increases.
5) Residual stress is more in wet condition than dry condition.
Therefore from all above conclusions we only conclude that as feed rate, depth of cut or cutting speed increases compressive residual stress increases.
It has been observed that experimental results are validate by ABAQUS/CAE software for all conditions except Vc=150m/min and f= 0.10 mm/rev machining conditions. In this numerical value deflected from experimental value

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