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Authors: Lokman Yünlü

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Residual Stress Analysis in Machining of a Near Beta Ti Alloy, Ti-5553 Under High Pressure Cooling and Lubrication

Lokman Yünlü*

[1]Burdur Mehmet Akif Ersoy University, Engineering Faculty, Mechanical Engineering Department, Turkey.

*Corresponding Author: lokmanyunlu@yahoo.com
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ABSTRACT: Ti-5553 (Ti–5Al–5Mo–5V–3Cr) one of the titanium alloys, is a recently developed near beta Titanium alloy, which is frequently used in the aerospace industry such as landing gear. When machining these superalloys, surface integrity can be affected by cutting and cooling conditions. An experimental study was conducted on Ti-5553, also known as beta-like titanium alloy, to understand the role of High Pressure Cooling and Lubrication conditions on surface integrity. In this study, high pressure coolant levels and other machining parameters (cutting speed, feed rate) were chosen as variable factors. These various levels were selected in different values and used in the tests to emphasize the relations of the accepted shear conditions from the effective data in the formation of residual stresses, which is also a parameter of the surface integrity. The results demonstrate the need to prepare coolant pressure levels to improve work surface integrity in such a material. In order to reveal the consistency of the coolant pressure values with other determined cutting parameters and the accuracy of choice, a relationship optimization has been tried to be explained.

Keywords: Residual Stress, Ti-5553 Alloy, High Pressure Cooling, Surface integrity

1. INTRODUCTION

Titanium alloys generally have high ductility, strength and low fatigue properties. However, it is a heat treatable alpha-beta alloy produced to combine increased high temperature operating performance with high strength properties [1]. These alloys are known as two-phase titanium alloy with high corrosion resistance, good strength and ductility. Therefore, it is used in aerospace, automotive and other industries. Ti-5Al-5V-5Mo-3Cr (Ti-5553), also called beta-titanium alloy, has high strength, good temperature resistance and favorable ductility, depending on the heat treatment applied [2], [3]. This alloy has a higher tensile strength properties compared to other Ti alloys from the same family. Due to this superior ability, Ti-5553 is especially preferred in the aviation industry [4].

Titanium-based superalloys are widely used in many industries, including the aerospace, biomedical and automotive industries, due to their unique/superior properties. These alloys are frequently preferred especially in jet engines due to their good temperature resistance and higher corrosion resistance [5]. Titanium alloys are known as more expensive materials compared to other metals [2], [27]. The main reasons are due to the difficulties encountered in the extraction process, melting and workability. It makes these materials special is not only their place of use, but also that they are special in terms of manufacturing processes such as machining and cutting. Although the latest point in material technology has increased the use of these alloys, it is still considered an industrial problem in terms of machining and manufacturing [6], [7], [8]. These materials are known as hard-to-cut alloys. The main reasons for the hard machinability of titanium alloys are due to their high chemical reactivity, low thermal conductivity and modulus of elasticity. Recently, some cooling techniques have been developed to improve the cutting performance of low machinability alloys such as titanium [9]. These methods are; These are applications that provide better dimensional accuracy of the parts produced after machining, improve the increase the tool life and surface integrity of the material [10]. Research has focused on improving the machinability of titanium alloys, such as conventional cooling, dry cutting, minimal lubrication (MQL), high pressure cooling/lubrication (HPC) and cryogenic cooling. In this study, the focused cooling strategy is the HPC system [11].

In machining difficult-to-cut materials, the effect of high-pressure jet coolant on the cutting zone can increase machining efficiency and ensure sustainability through better chip breaking and removal [12]. Proper selection of cutting method and parameters can increase the efficiency of the process while minimizing production costs. HPC is one of the methods aimed at increasing the machinability of hard-to-machine alloys by using high-pressure coolling water or an emulsion injected between to chip tool interface [11]. Some studies have revealed that directing the HPC system to the cutting zone provides control of chip formation, lowers temperatures in the cutting surface and facilitates chip removal [13]. This has also shown that it plays an important role in increasing tool life. However, High pressure cooling assisted cutting method offers an advanced method for achieving the desired surface quality finish and surface integrity of hard-to cut alloys such as titanium [14]. With this method, it is aimed to reduce the negativities such as cutting tool cost by preventing the dangerous situations in terms of health and environment in the traditional machining method.

Surface roughness, hardness, wear, internal stresses are also known as surface integrity factors that determine machining quality and fatigue life [8]. These factors are one of the most vital aspects of the quality of the machined surface, especially after processing very sensitive materials [15]. Therefore, determining the relationship between machining conditions and residual stresses, then revealing the most optimal machining parameters is one of the primary goals of the researchers [9]. Residual stress is the most common properties used to determine the quality of the machined workpiece surface, especially when manufacturing critical special structural components [6]. This is a feature that is emphasized in precision machining made of titanium alloys used in large proportions in the aerospace and medical industries [16].

Machining also known as surface integrity is an effective process on microstructural and topographic conditions of the machined surface [25]. Surface integrity, which expresses the state at the end of the cutting process in machining, covers the resulting microhardness, surface roughness, crystal structure, and all possible surface defects (microchip debris, material picking, tearing, dragging and contamination) [11], [17]. Residual stresses are the result of heat generated in the surface and subsurface layer as a result of the mechanical interaction between tool and workpiece during machining [3] [18]. In short, it is an effect of friction and heat on the surface and substrates in the machining process. The distribution of residual stress on the machined zone and substrate at the end of the cutting process reveals the functional performance of these components, including fatigue life and corrosion resistance.

Experimental design (DoE) defines the input parameters and levels, the response variable, the choice of test parameters, and a set of operations used to analyze the experimental results [18], [24]. This experimental method developed to evaluate the performance and effects of factor variables [19]. It defines the input parameter levels for optimal response variables and requires determination of appropriate experiment design, careful planning, correct experiment placement, and analysis of results [11] [18]. During the experiment, as the number of processing variables increases, so will the number of experiments that need to be done [20]. In Taguchi experimental design, the selection of an optimal orthogonal sequence should be made to describe the input variables (factors) and their interactions [14], [21]. Using statistically derived orthogonal arrays to plan experiments greatly reduces the number of tests in determining the quality of the analysis [22].

The aim of the current research: to reveal the effect of cutting parameters (feedrate f, depth of cut DoC, cutting speed Vc, and Coolant pressure P) on residual stress. The depth of cut of 2 mm was used as a fixed input parameter in the experiments. However, using the shear parameters determined by the experimental design method of the Ti-5553 alloy, to determine the optimum shear parameters that minimize the residual stress formation in the surface and subsurface layer [23]. In this study, three input factors were selected and a full factorial DoE consisting of three levels for each factor was designed and used to analyze the amount of residual stress produced at the end of machining. Turning of Ti-5553 was performed using a (Ti, Al) N+TiN carbide coated cutting inset.

2. EXPERIMENTAL PROCEDURES

Due to the high hardness of the new generation Ti-5553 alloys during machining, a chemical reaction occurs between the cutting insert and the workpiece material. This causes rapid wear on tool and thermal stresses on workpiece surface [28]. A process diagram related to the experiment plan is given Figure 1. below in order to anticipate this whole process and not to overlook possible problems.

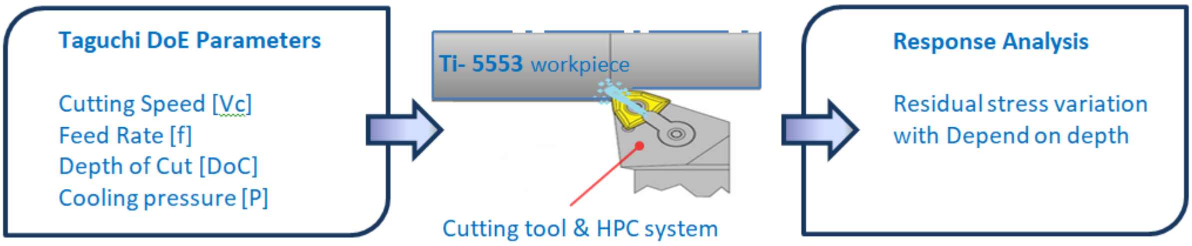


Figure 1. Schematic view of machining process.

2.1. Workpiece and Machine Tool

Ti-5Al-5V-5Mo-3Cr contains 20% of the α phase, this is known as a near β alloy. It has a Young's modulus similar to Ti64 in research. However, these two materials differ significantly in terms of mechanical property. Ti-5553 has 30% higher yield and tensile strength, but also lower ductility.

The workpiece used in the tests is a hot rolled cylindrical bar material made of Ti-5553 material, which is expressed as a titanium alloy close to β. The tests were carried out using Ti-5553 alloy with a diameter of 65 mm and a length of 200 mm. When this material is annealed, its tensile strength can reach up to 1080 MPa [26]. At the same time, when this material is heat treated, its tensile strength can exceed 1500 MPa. When Ti 5553 alloy is compared with other ti alloys; It stands out with its properties such as hardness, high strength and fracture toughness. The chemical composition and mechanical properties of this alloy are given in Tables 1 and 2, respectively.

Table 1. Chemical composition of Ti-5553 alloy.

Ti	Al	Mo	V	Cr	Fe	Si	O	C	Zr	H
Base.	4.4-5.7	4.0-5.5	4.4-5.5	2.5-3.5	0.3-0.5	≤0.15	≤0.18	≤0.1	≤0.30	≤0.015

Table 2. mechanical properties of Ti-5553 alloy.

Parameter	Value	Parameter	Value
Density (g/cm^3)	4.58	Specific heat capacity(J/(kg·k))	775
Melting point (K)	860	Young's modulus (GPa)	110
Poisson's ratio	0.31	Elongation (%)	11
Thermal conductivity (W·m^{-1} C^{-1})	8.3	Hardness (HV)	317 ± 5

Machining experiments were carried out on an ANL-75 CNC machinin center with a spindle speed ranging from 35 to 3500 rpm and a motor power of 15 kW, supported by a high-pressure submersible pump providing a maximum pressure of 35 MPa and a flow rate of 21 l/min.

2.2. Cutting Tool and Application of Cooling Method

For use in the experiments, (Ti,Al)N+TiN coated carbide cutting insert were preferred by using the literature. The tool has a corner radius rε = 0.8 mm. A SECO Jet stream tool holder, cutting rake angle, γa = -6°, back rake angle, γb = –6°, approach angle is Kr = 95° and nozzle diameter d = 1,5 mm It is shown in Figure 2.

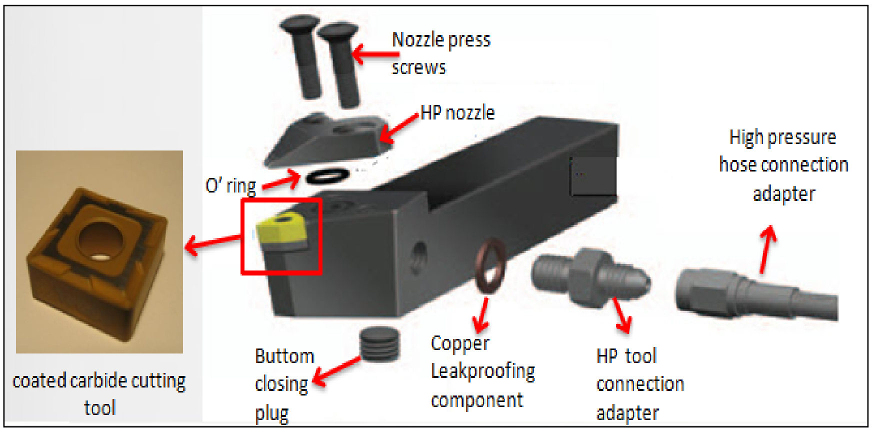


Figure 2. Cutting tool and HPC connection equipment

Before each cutting test, the worn tool was replaced with a new tool to maintain the surface integrity of the machined surface.Llubricating/Cooling fluid used in the experiments, 5% concentration, water-soluble oil chemical-based oil was used. Swisslube BCool 650 oil is injected at a low angle (tool rake angle of about 5 to 6°) to chip and tool interface.

2.3. Residual Stress Measurement Method and Application

Residual stress is elastic stress that remain in the part after various production/manufacturing stages. Plastic deformations or thermal changes that remain without homogeneous distribution in the material as a result of welded manufacturing, surface treatments, casting and heat treatments are the causes of residual stress. The residual stress subsurface can measured using the method of X-ray diffraction (XRD) [27]. Chemical etching is a common technique used in etching material to determine the amount of residual stress in the subsurface layers. In the study, residual stress was measured from the machined surfaces using the XRD method. The measured values in the σ_{xx} (axial) and σ_{yy} (radial) directions are calculated. In this process, residual stress values were calculated in ten reps from the surface of the material to a depth of 150 micrometers. Then, material was removed from the surface using the electropolishing process, measuring the residual stress value at every 10 micrometer depth. This method does not cause any damage to the internal structure of the material [29]. After the high pressure cooling assisted turning where the residual stress is measured and the schematic representation of the application of the HPC system are shown in the figure 3. The entire procedure regarding the experiment, material and method of the study is given below in table 3.

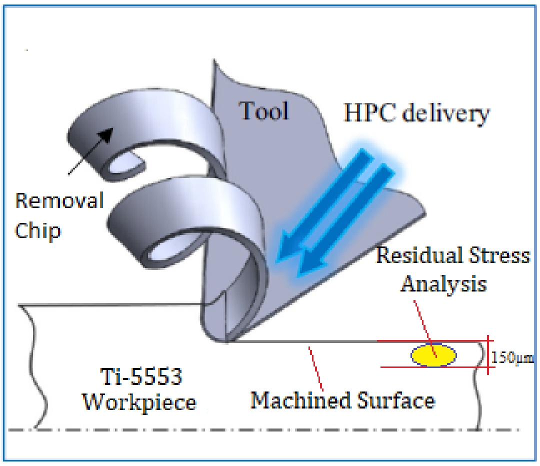


Figure 3. HPC processing and residual stress measured surface.

Table 3. Technical specifications of the machine tools, machining parameter factors, tool and cooling properties.

Category	Specifications
Machine tool	A general-purpose ALEX ANL-75 CNC lathe, (15 kW, speed range: 35 to 3500 rpm), Fanuc control system.
Work material	Ti-5Al-5V-5Mo-3Cr or known as near beta Ti alloy (Ti-5553)
Dimensions	Ø65 × 200 mm
Cutting Tool and Cutting Tool Holder	Rhombic shape CNMG 120408, (Ti,Al)N+TiN coated carbide SECO Jet stream PCLNR tool holder.
Cutting speed, Vc (m/min)	80, 100, 120
Feed, f (mm/rev)	0.1, 0.15, 0.2
Depth of cut, DoC (mm)	2 mm
Cooling environment	Conv (0.6), 15, 30 MPa The cooling/ lubrication fluid (CLF) chemical-based 5% concentration water soluble oil 5 to 6° with the cutting tool rake angle 21 l/min with 1,5 mm brass nozzle diameter.

2.4. Design of Experiment and Application of Machining Methods

A Taguchi orthogonal array, L_9 (3^4) is adopted in the turning process. Processing parameters selected in the application of the tests; Vc; 80-100-120 m/min, P; 0.6-15-30 MPa f; 0.1-0.15-0.2mm/rev, and a constant DoC; 2 mm. The response result parameter obtained of the tests is the average residual stress (axial and radial direction) values. Three levels were chosen for each input factor to increase the accuracy of the cutting parameters. The contents of the experimental design are given in Table 4.

Table 4. Cutting parameters and their levels

Symbol	Cutting parameters	Level 1	Level 2	Level 3
Vc (m/min)	Cutting speed	80	100	120
f (mm/rev)	Feed rate	0.1	0.15	0.2
P (MPa)	Cooling pressure	0.6	15	30

2.5. Empirical Model and Analysis of Residual Stress

The mean residual stress values measured at the end of each test were calculated according to Ri and Kij. Kij is calculated in Eq. (1) since the average residual stress is j at the selected level, of the machining parameter is i. At the end of these processes, Kij was calculated smaller is the best to obtain its desired effect compression stress [30].

The value calculated as the lowest level of Kij is the optimum level for each input factor. The calculated Ri value is Eq. (2) determines the order of importance of cutting parameters over residual stresses. As a result, by calculating the relationship between Kij and Ri, its effect on residual stress and its optimum levels can be determined [13] [30].

$$K_{ij} = \frac{\sum R_a(k)}{3} \tag{1}$$

$$R_i = max(K_{i1}, K_{i2}, K_{i3}) - min(K_{i1}, K_{i2}, K_{i3}) \tag{2}$$

in this equation; respectively; i = 1,2 and 3 (cutting speed, feed rate, and indicates cooling pressure), respectively; j = 1, 2, 3 shows level 1, 2 and 3, which are equal to the processing parameters, k = 1, 2, .. 9 is the test sequence number; Ra (k) represents the average stresses on the finished surface at the shear parameter;k.

Residual stresses at a distance of up to 150 micrometers in ten steps in total by descending 15 micrometers from the workpiece surface for each test; Ra was calculated and the average of these values was taken. These values are calculated in both axial and radial directionsis given in Table 5.

Table 5. Average residual stress results in axial and radial directions

Exp. No	Vc Cutting speed ($m.min^{-1}$)	f Feed rate ($mm.rev^{-1}$)	P Cooling pressure (MPa)	R_{AXIAL} Average axial residual stress (MPa)	R_{RADIAL} Average radial residual stress (MPa)
1	80	0.1	0.6	61	23
2	80	0.15	15	-94	-78
3	80	0.2	30	-170	-121
4	100	0.2	0.6	-172	-170
5	100	0.1	15	-134	-189
6	100	0.15	30	-259	-263
7	120	0.15	0.6	-229	-278
8	120	0.2	15	-345	-302
9	120	0.1	30	-294	-284

Exp.	Vc	f	P	Depth	R_{axial}	R_{radial}
1	80	0,1	0,6	0	65	12
				15	277	237
				30	241	181
				45	181	77
				60	-13	-13
				75	-127	-127
				90	-98	-78
				105	-61	-41
				120	-15	-15
				150	1,6	1,6
				Average	61	23

The experimental design and response results for these three levels of cutting parameters using the L_9 (3^4) orthogonal array are given in Table 4 [12]. The average residual stress values (in both directions respectively) found according to equations 1 and 2 and their relations calculated for each level are given in the table 6 and 7 below.

Table 6. Average residual stresses in Axial direction of Kij and Ri calculations

Symbol	Cutting parameters	Kij Level 1	Kij Level 2	Kij Level 3	Ri
Vc [m/min]	Cutting speed	-58.7	-207	-288	229.3
f [mm/rev]	Feed rate	-150	-206	-197.7	56
P [MPa]	Cooling pressure	-141.7	-189.7	-222.7	81

When the correlation between R values is calculated

$$Ri_{axial} = R1 > R3 > R2 \quad (3)$$

Table 7. Average residual stresses in Radial direction of Kij and Ri calculations

Symbol	Cutting parameters	Kij Level 1	Kij Level 2	Kij Level 3	Ri
Vc [m/min]	Cutting speed	-67.7	-188	-289	221.3
f [mm/rev]	Feed rate	-122.3	-194	-229	106.7
P [MPa]	Cooling pressure	-113.3	-191	-241	127.7

When the correlation between R values is calculated

$$Ri_{radial} = R1 > R3 > R2 \quad (4)$$

To calculate the average residual stresses in both directions; the Kij equation is used. These results are written at levels of input parameters in field in tables 6 and 7, respectively.

K11 = (61 – 94 – 170) / 3

K12 = (–172 –134 – 259) / 3

K13 = (– 229 –345 –294) / 3

… ..

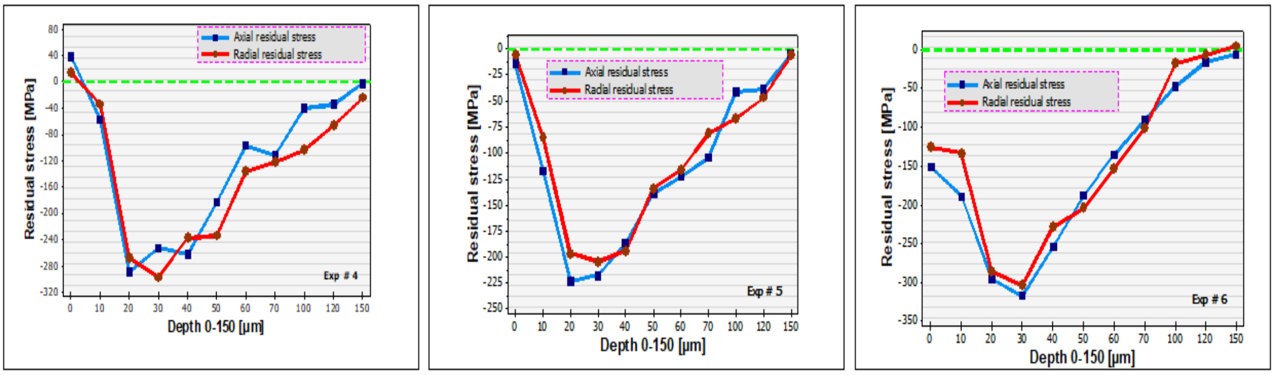
K33 = (–170 –259 –294) / 3 (5)

3. EXPERIMENT ANALYSIS and VALIDATION

There are many residual stress measurement methods in practice. The xrd method, which is the most preferred method in determining the residual stresses on the surface in metal cutting process, is a non-destructive measurement method. The surface and subsurface residual stress can be found using the Bragg law calculation used in the X-ray diffraction method. The chemical etching method is often preferred technique used in high pressure cooling-assisted metal cutting to remove layers from the surface to obtain residual stresses.

At the end of the cutting tests, the residual stress values in both directions (axial and radial) were calculated mathematically by using the $\sin^2\psi$ method [15]. In each test, two values were calculated for each layer of the workpiece, both in the axial and radial directions. In the electropolishing process, layers of 15 µm from the surface were etched each time using a solution of phosphoric and sulfuric acid. These processes were repeated in ten steps until a total of 150 µm was reached.

When the results are examined carefully; In general, tensile residual stresses reach near zero when the depth exceeds 150 µm. This situation; This leads to the conclusion that the mean residual stress can be characterized by the variation of residual stress with depth. In order to fully understand the HPC effect, instead of presenting all nine experiments graphically, three different cooling pressures at a constant shear rate were evaluated graphically and the residual stress profiles are shown in Figure 4.

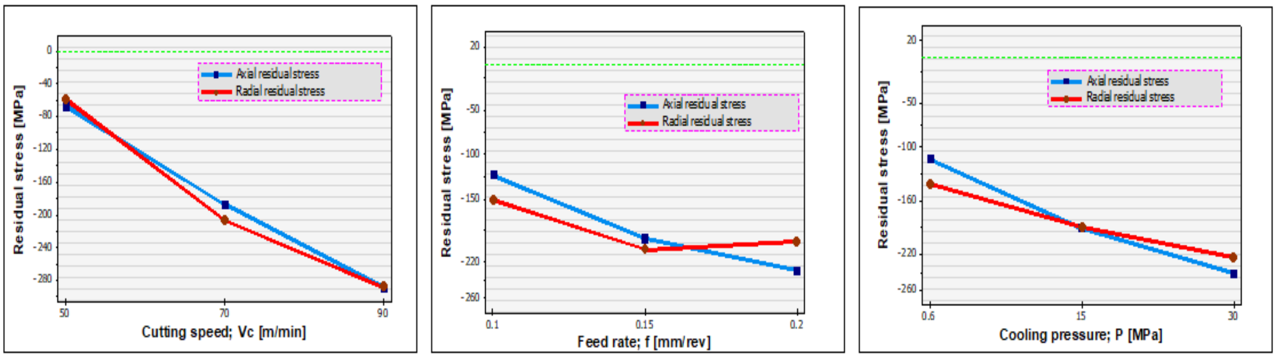


Figures 4. Residual stress variation in both directions of #4 #5 #6 tests

To better understand the residual stress change, one parameter at a time was assumed as a constant value. Thus, the effect of the other two parameters could be observed more easily. In these three graphs, the average residual stress changes at a constant shear, feed rate, and cooling pressure are presented graphically, respectively.

In the Taguchi experimental design method, optimal levels were determined for machining parameters (Vc;80- P;0.6- f;0.1) using the principle of smaller-better for Kij in the calculation of axial and radial residual stress values. The results indicates that the optimal Vc is common to the axial and radial compressive residual stress (see Figure 5). Ri value was calculated to determine the effect of shear parameters on residual stresses. Therefore, it has been observed that the feed rate has a decisive effect on the residual stress occurring in the axial direction.

When the Ri value given in Table 6 and Table 7 is examined, it is understood that the cutting speed has a greater effect on the residual stresses in both directions. However, cooling pressure and feed rate were found respectively to be the most effective factors on residual stress.



Figures 5. Kij value for each levels of cooling pressure, cutting speed and feed rate

4.CONCLUSION

According to these calculated results; we can reach the conclusion that machining parameters have different effects on residual stresses in both directions. The cooling pressure, which produces the lowest average residual stress value, appeared at level 3 of the cooling pressure for both the radial and axial directions. However, when the feed rate was selected at level 1, the minimum average residual stress value in both directions was obtained. Considering the effect of the feed rate on the average residual stress values formed in both directions; It was observed that the lowest stress occurred at the 3rd level and the highest average residual stress occurred at the 1st level. However, considering the effect of shear speed on the average residual stress, the maximum average stress value occurred at level 3 in the axial direction, while it occurred at level 2 in the radial direction.

The axial and radial determination of residual stresses in the turning process of Ti-5553 alloys, also known as difficult-to-machine materials, under high pressure cooling fluid support, was investigated experimentally.

Taguchi experimental design method was used in this process. Different levels of 3 input parameters were used in the experiments. Residual stress values in axial and radial directions were calculated from the results obtained and optimum machining parameters were proposed with a series of optimization processes.

If we evaluate the scientific results obtained from this study;

- When the effect of the feed rate parameter on the mean residual stress is examined, the level 1 value is slightly larger than the level 2. So we can select the feed rate as level 1 for the optimum machining level.
- When the average residual stress in the subsurface layer are examined, it is seen that the cutting speed; Vc is the most important parameter, respectively followed by the cooling pressure, and the feed rate in the radial direction,
- When the graphs are examined, the average residual stress when machining under the effect of cooling pressure is 0.6 MPa measured to be higher than the residual stress at 15 MPa cooling pressure.
- In the graphs showing the residual stress change depending on the depth, when the residual stresses in both directions are examined at 150µm from the surface, it is seen that the cooling pressure is more effective on the residual stress in the radial direction.

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