Journal of Stress Analysis
Vol. 4, No. 1, Spring − Summer 2019
Bu-Ali Sina University

Experimental Study of Residual Stresses Due to Inconel X-750 Creep-feed Grinding by the Electropolishing Layer Removal Technique

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Article info

Article history:
Received 21 July 2019
Received in revised form
11 September 2019
Accepted 18 September 2019

Keywords:
Residual stress
Measurement
Creep-feed grinding
Electro polishing
Layer removal

Abstract

Creep-feed grinding is an accurate and efficient machining method. In this study, the effects of the cooling condition on surface residual stresses distribution in the creep-feed grinding of Inconel X-750 superalloy have been experimentally investigated. Some test samples were prepared and subjected to creep-feed grinding with dry and flood grinding at different flow rates. The variation of residual stresses in depth was obtained by the electropolishing layer removal technique. Results were shown highest creep-feed grinding forces were developed in dry grinding condition and these forces were declined by increasing the coolant quantity. According to results, by increasing about 71% of fluid flow under flood cooling, the normal and tangential forces decreased by roughly 30%. The results also demonstrated that the measured residual stresses on creep-feed grinded specimens are in the tensile form and using the coolant led to an overwhelming decrease in magnitude and depth of penetration of these stresses.

1. Introduction

Inconel X-750 is a Ni-Cr-based precipitation-hardened superalloy including titanium, aluminum, and niobium. This alloy is extensively used in wheels of gas turbines, pressure vessels, tooling, thrust reversers, and hot-air ducting systems on account of its excellent properties such as high-temperature oxidation and corrosion resistance, good formability, high tensile strength up to 600°C, and high creep and rupture strength up to 820°C [1-2].

Grinding is an important machining process to produce components, requiring a high surface integrity and precise geometries. Creep-feed grinding as an abrasive or small-chip machining can replace the milling or broaching process in the machining of complex forms in difficult-to-machine materials, including hardened tool steels and advanced alloys. This process aims to reduce process time by minimizing the number of grinding passes. To this end, the depth of the cut should increase with several orders of magnitude over conventional grinding. Given that the process completes a part in a single fixturing and in one pass, the creep-feed grinding decreases the overall cycle time and cost and increases machining efficiency.

There is always a trade-off between efficiency and surface imperfection in grinding processes. Increasing the material removal rate causes an increase in heat generation and local temperature due to the wheel-workpiece friction and local plastic deformation in the contact zone. Part of the heat generated in the creep-feed grinding area is eliminated by the chips and other parts are removed by the coolant. Nevertheless, a workpiece subjected to grinding usually expe-

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http://dx.doi.org/10.22084/jrstan.2019.19668.1098
ISSN: 2588-2597

riences a rapid heating-cooling cycle. When heating leads to a very high temperature, significant surface alteration and subsurface damage may occur, such as micro-cracking, phase transformation, hardness variation, tears and laps, and harmful residual stress distributions. Grinding surface property is affected by material properties, grinding parameters such as wheel speed and feed rate, and the proper application of the coolant in creep-feed grinding and affects workpiece behavior such as fatigue strength as well as wear and corrosion resistance of the machined parts [3].

Depending on their nature, grinding residual stresses are either beneficial or harmful. Mechanical grinding forces, increased temperature in the grinding area, and phase transformation caused by grinding temperature history are the three main factors for producing residual stress in the grinding process. The first and third factors have a more compressive nature, while the second one has a tensile nature [4]. Similar to grinding parameters, cooling conditions also greatly affect the grinding forces and temperature and, accordingly, determine the compressive or tensile residual stress generated in grinding.

Because of the importance of this topic, it is necessary to study the effects of cooling conditions on thermo-mechanical loads in grinding and even the resultant residual stresses in the workpiece materials. Wenfeng et al. reported that, from among the three creep-feed grinding parameters, i.e. depth of the cut, workpiece speed, and wheel speed, the depth of the cut exerts the most important effect on the residual stresses during the process. In fact, upon increasing the cutting depth, the amount of the compressive residual stresses decrease. They measured the residual stresses in the workpiece with the X-ray diffraction technique [5]. Moreover, Gostimirović et al. examined the influence of cutting forces on the performance of the creep-feed grinding process. They concluded that there are higher cutting forces in creep-feed grinding in comparison with the traditional multi-pass grinding. Besides, the results showed that increasing the feed rate leads to a decrease in grinding forces by reducing the cross-section of the influenced layers of the material via grinding grains while increasing the cutting depth boosts grinding forces [6]. Gostimirović et al. investigated the temperature state of high-speed steel (DINS 2-10-1-8) for testing a range of cutting depths and workpiece feed rates in the creep-feed grinding process. They reported that, upon increasing the depth of the cut and decreasing the feed rate up to four times, the temperature of the grinding zone increases by about 2.5 times [7]. From among methods used for measuring residual stresses, the layer removal technique is suitable for measuring non-uniform residual stresses without much cost and difficulty in obtaining the stress at high thicknesses [8]. Kruszynski et al. analyzed the residual stresses generated in the flood grinding of SKS3 steel using the layer removal method. They reported that tensile residual stresses are dominant on the surface of the workpiece while they are turned into comprehensive stresses in the depth of the workpiece [9]. Quite a few researchers are interested in studying the residual stresses' distribution due to creep-feed grinding. They attempt to use advanced methods to measure residual stresses and consider cooling effects.

In this paper, an experimental study of creep-feed grinding residual stresses' distribution of the Inconel X-750 was conducted. As the residual stresses caused by phase transformations do not occur in this super alloy and with regard to high yield strength of that, it is expected that the thermal residual stresses will be dominant. Therefore, the reduction of these unwanted stresses is of particular importance. The purpose of this study is to investigate the effect of different flow rates of flood cooling condition on magnitude and penetration of residual stresses in Inconel X-750 superalloy. The electropolishing layer removal technique was employed for the evaluation of non-uniform residual stresses created by creep-feed grinding process.

2. Experimental Procedure

2.1. Material and Creep-feed Grinding Process

The material used in this experimental study was Inconel X-750 superalloy. Specimens were cut off from an Inconel plate with the length, width, and thickness of 95mm×18.4mm×1.7mm, respectively. Before grinding, the initial stresses of materials were relieved at the temperature of 1149°C for 2h, and then the specimens were subjected to aging heat treatment. The mechanical properties and chemical composition of the incorporated material after preparation are presented in Tables 1 and 2, respectively.

The creep-feed grinding process was performed using a grinding machine type MST300 with the spindle motor power of 87kW. Fig. 1 illustrates the moving system of the creep-feed grinding machine. The system includes an inverter model YD101, a DC motor with the rotational speed of max. 2860rpm, and a set of gearboxes with the ratio of 1:15 and 1:45, respectively.

Table 1
Mechanical properties of X-750 Inconel superalloy.

Density (g/cm^3)	Modulus of elasticity (GPa)	Thermal conductivity (W/m K)	Specific heat (kJ/kgK)	Yield strength (MPa)	Tensile strength (MPa)
8.276	213.7	12	0.43	979.1	1503.1

Table 2
Chemical composition (wt. %) of X-750 Inconel superalloy.

Ni	Cr	Fe	Ti	Co	Mn	Nb+Cb	Al	Cu	C
$\geq 70\%$	14-17%	$5.0-9.0\%$	$2.25-2.75\%$	$\leq 1.0\%$	$\leq 1.0\%$	$0.70-1.2\%$	$0.40-1.0\%$	$\leq 0.50\%$	$\leq 0.08\%$

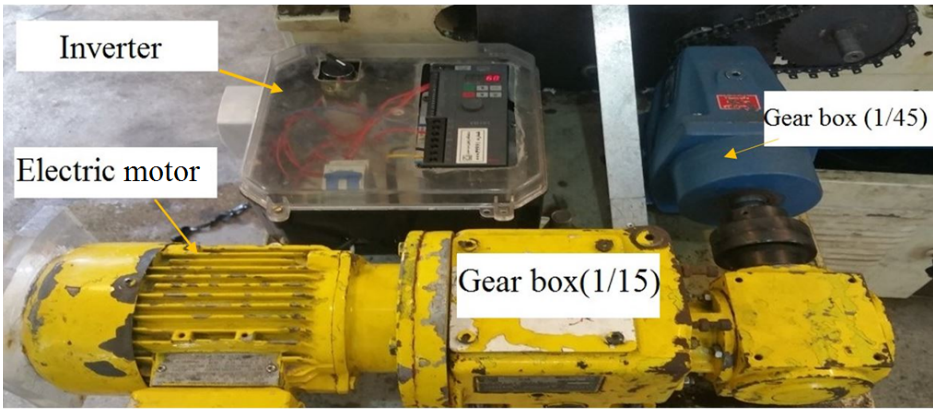

Fig. 1. Moving system of longitudinal feed for the grinding machine.

Table 3
Creep-feed grinding conditions.

Grinding machine model	MST300
Grinding mode	One pass surface grinding, down cut
Grinding wheel	Aluminum oxide (32A46-G12VBEP)
Grinding cooling liquid	Water-solute grinding liquid (5vol %)
Wheel speed Vs (m/s)	20.6
Magnetic table feed speed V_w (mm/s)	1.6
Cutting depth a (μm)	150
Grinding coolant flow rate (L/s)	0.036 (Flood 1) and 0.021 (Flood 2)
Cooling grinding environments	Dry, flood with different flow rates

An aluminum oxide grinding wheel with the dimensions of 250×32×76 (diameter, thickness, and hole size, respectively) and specifications 32A46-G12VBEP with the liner speed of 20.6m/s was employed. Each experiment was conducted three times to achieve reliability, and their average values were employed for the analysis. The grinding process was performed in one pass and in the direction of the grinding wheel. Grinding conditions are presented in Table 3. The creep-feed grinding set-up is depicted in Fig. 2. Coolant nozzle 4.5mm in diameter was placed in the angle of 15° relative to the horizon and at the distance of 15mm from the contact zone. In order to investigate the cooling effects on surface residual stresses magnitude and distribution, three cooling conditions were prepared by controlling the flow rates of the coolant.

In this study, the output flow rates of the coolant were fixed at two quantities, i.e. 0.036L/s and 0.021L/s at the constant pressure. Dry grinding, as the third condition, was performed in addition to the flood one to compare the effects of changing the flow rate on grinding forces and residual stresses. In each creep-feed grinding condition, two specimens were prepared and the normal and tangential creep-feed grinding forces were measured by a two-axial dynamometer mounted on a magnetic table during grinding.

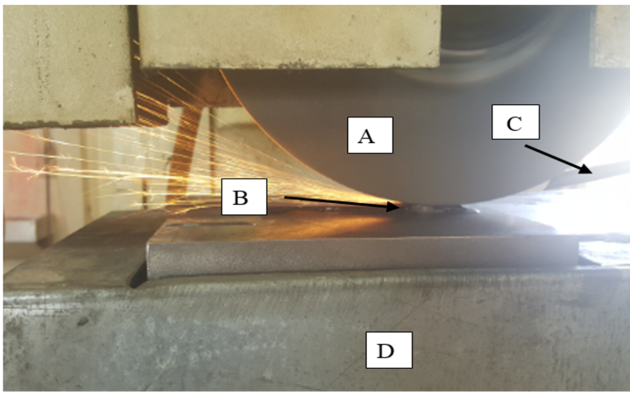

Fig. 2. Creep-feed grinding set-up, a) Grinding wheel, b) Specimen, c) Coolant nozzle, d) Dynamometer.

2.2. *Measurement of Surface Residual Stresses*

Residual stresses were obtained by the electropolishing layer removal technique. In this method, uniform thin layers are chemically removed from the surface of the specimen. Residual stresses can be estimated by obtaining the curvature of the specimen with the thickness of the removed layer. By performing multiple experiments, the appropriate electropolishing condition and the layer removal rate of the Inconel X-750 in the electropolishing method were obtained. By controlling the chemical conditions, in addition to creating flat and smooth surfaces, it is possible to estimate the thickness of the removed layer at any moment. The possibility of accurately estimating the thickness of the removed layer using the results of this section was checked and verified several times.

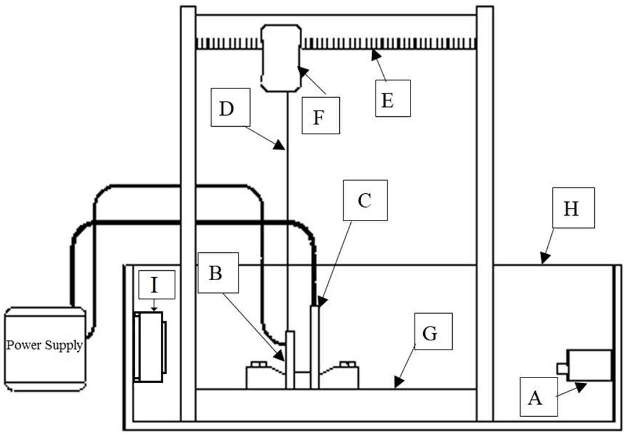

Fig. 3. The scheme of the electropolishing layer removal measurement system; a) Pump, b) Specimen (anode), c) Cathode, d) pointer, e) Scale, f) Camera (in front of the pointer), g) Holder, h) Tank, and i) Cooling system.

To measure residual stresses in the ground sample, an electropolishing layer removal system was designed and developed. Based on Fig. 3, the electropolishing layer removal system included a tank, small electric pump, cathode and anode, power supply, certain electrolyte, holder, cooling system, pointer, scale, and camera in front of the pointer. The camera measurement precision was $\pm 10\mu$m and was used to continuously record the deflection amounts of the specimen during the process. In this set-up, a stainless steel plate was employed as the cathode and the distance between the cathode and the anode surface was about 20mm. The area of the cathode surface was greater than that of the anode with a 4 to 1 ratio. Previous experiments showed that, for appropriate machining conditions, the quality of the cathode surface should be much better than the level of the anode, and these two are exactly parallel. Also, the electrolyte used in this study contained 10mL of HCL, 5mL of HNO_3 and 85mL of ethanol (95%) and, with a small electric pump, the uniform temperature of 25°C was applied over the test time. A major issue in this process is the current density; in this study, the current of 652 (A/m^2) was applied to the workpiece. This value of current density was obtained after some attempts for the uniform removal of the specimen's surface for several workpiece materials. All the considered process control parameters and their values are given in Table 4.

All specimens were subjected to electropolishing layer removing operations separately, and the thickness changes were continuously recorded against the curvature of the sample. In this study, the third-order polynomial curve fit was obtained from the graph. Eventually, a stress calculation program was developed to calculate the grinding residual stresses in each removed layer.

3. Result and Discussion

3.1. Creep-feed Grinding Force

Fig. 4 illustrates the average values of tangential forces F_t and normal forces F_n under different cooling conditions in the creep-feed grinding process. It is evident from Fig. 4 that dry grinding without any coolant generates the highest magnitude of normal and tangential forces during the process, although this undesirable condition and its being detrimental to the health of the workpiece can be curbed with flood cooling. In fact, these forces decrease by increasing the coolant quantity. Thus, fewer thermal damages occur on the ground surface due to the reduction of the amount of heat flux input to the specimen. Flood (1) and flood (2) are indicative of creep-feed grinding with 0.021 and 0.036L/s flow rates, respectively.

3.2. Creep-feed Grinding Residual Stresses

The analysis of the results indicated significant changes in the residual stress distribution in the depth beneath the surface of the specimen, depending on the coolant quantity. The results of residual stresses measured in dry creep-feed grinding are shown in Fig. 5. The stresses were calculated at some random points where deflection changes were considerable.

Table 4
Information on the electropolishing process.

Electrolyte	10ml HCL+5ml HNO_3+ 85ml ethanol (95%)
Cathode material	316 Stainless steel
Anode material	X-750 Inconel super alloy
The ratio of area of the cathode to the anode	4 to 1
Electrolyte temperature (°C)	25
Current density (A/m^2)	652
Distance between the cathode and anode(mm)	20

Fig. 4. Measured average tangential and normal creep-feed grinding forces at different cooling conditions.

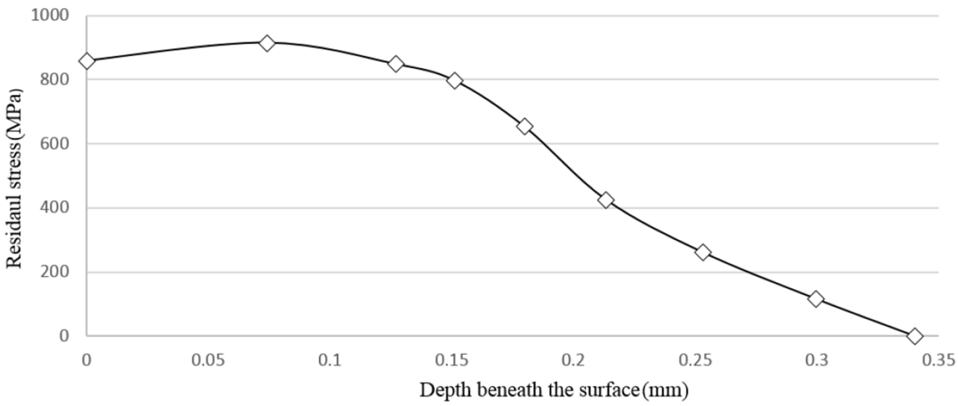

Fig. 5. The values of residual stresses along the depth of the specimen during creep-feed grinding for the dry condition.

As expected, the residual stresses near the surface are tensile while reaching the highest value at the distance of 70μm from the surface. With an increase in the depth beneath the surface, tensile residual stresses approach zero. It is obvious that tensile stresses in dry grinding have penetrated more in the depth, and there are considerable values (250MPa) in the depth of 260μm. However, the residual stresses are significantly lower in flood grinding than the dry one (Figs. 6 and 7). In the state where the flow rate of the coolant is 0.021L/s, the tensile stresses are dominant on the surface while precipitously approaching the low-quantity residual stresses until finally becoming close to zero. For the 0.036L/s flow rate, the residual stress near the surface is 151MPa and, with moving toward the depth, stresses tend to zero. It should be noted that the amount of the layers removed depends on the magnitude of stresses and their penetration into the workpiece. In this study, the amount of the material removed varied from 130μm to 340μm, depending on cooling conditions.

With regard to the X-750 Inconel superalloy, phase transformation does not occur during temperature changes and, therefore, only thermal and mechanical effects cause residual stresses in the specimen and stresses since phase transformation is not considered. Regarding the measured grinding forces during the empirical tests, it can be observed that these forces divided by the area of grinding contact are very small in comparison to the yield stress of the material. Thus, it is expected that the measured residual stresses in this study are often due to thermal loadings. On account of the constant cutting speed, feed rate, and contact length across the three tests, it is clear that reducing tangential forces has a paramount impact on the measured residual stresses due to increasing the coolant quantity. In fact, using the coolant, the amount of tensile residual stresses significantly decreased on the surface of the specimen. For example, the highest tensile stresses in the dry creep-feed grinding mode were 914Mpa, while stresses equaled 708MPa and 151MPa, respectively, for the flood creep-feed grinding mode with the flow rates of 0.021 and 0.036L/s.

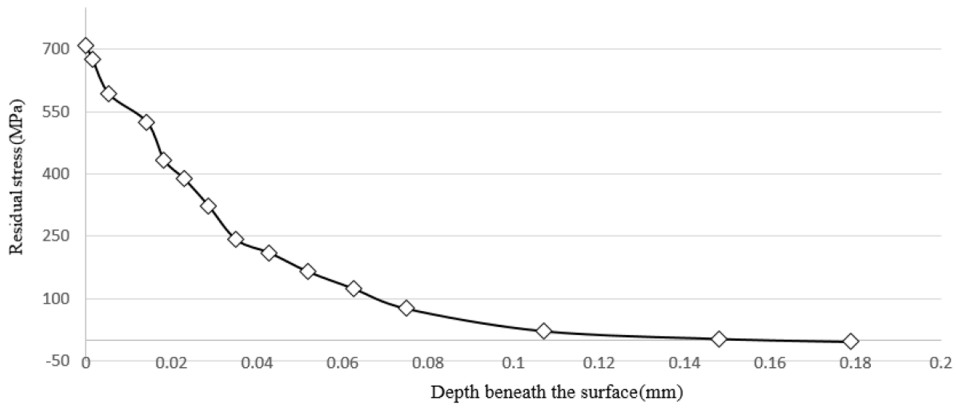

Fig. 6. The values of residual stresses along the depth of the specimen during creep-feed grinding for the flood 1 condition.

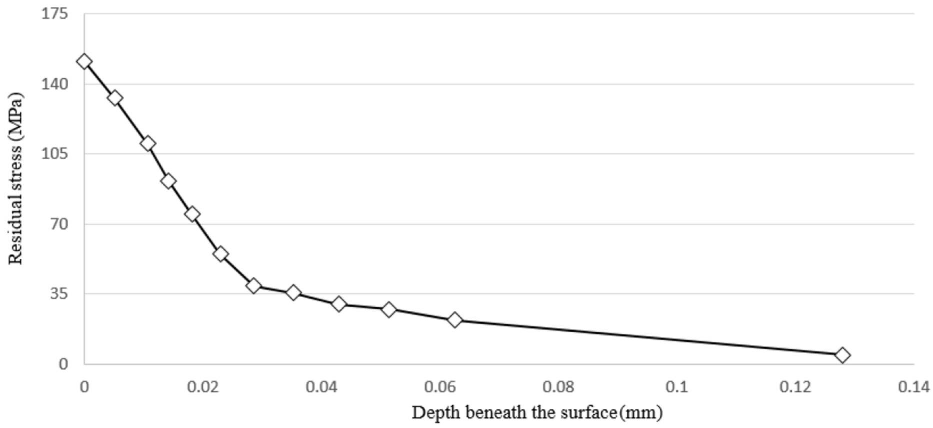

Fig. 7. The values of residual stresses along the depth of the specimen during creep-feed grinding for the flood 2 condition.

It should be noted that decreasing the heat flux applied to the specimen reduces the heat penetration into the specimen. For instance, the residual stress of 260MPa for dry grinding is in the depth beneath the surface about 0.25mm, whereas this amount is about 0.032mm for flood grinding with the flow rate of 0.021L/s. On the other hand, it was observed that by decreasing about 71.42% of flow rate under flood cooling, the penetration of tensile stresses substantially reduced so that the residual stress of 22MPa was obtained in depth of 0.170mm for flood (1) cooling condition while this amount was observed in depth of 0.0626mm for flood (2).

4. Conclusions

In the present study, the analysis process revolved around the study of the nature of residual stresses in Inconel X-750 superalloy creep-feed grinded plates. The effects of coolant quantity on the magnitude and penetration of residual stresses were also investigated. Based on the results of this study, the following conclusions can be drawn:

- The highest creep-feed grinding forces were observed in dry grinding, while by increasing the coolant quantity, these forces were reduced. The results also demonstrated that by increasing about 71% of fluid flow under flood cooling, the normal and tangential forces decreased roughly 30%.

- Due to negligibility of pressure stresses and the absence of phase transformation factor, the nature of residual stresses created by creep-feed grinding process was observed in the form of tensile stresses.

- Increasing the flow rate of the coolant resulted in the less penetration of tensile stress into the specimen and lower magnitude of them

- The highest and lowest residual stresses on the surface of the specimen were observed in dry and flood grindings (with a 0.036L/s flow rate).

The electropolishing layer removal technique can be used as a destructive method to accurately measure grinding non-uniform residual stresses along thickness.

5. Acknowledgement

The authors wish to thank the staff of the Analysis, Measurement, and Engineering of Residual Stress (AMERS) Research Lab for their consultation and technical support in this research.

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