DE GRUYTER OPEN

Management Systems in Production Engineering

2017, Volume 25, Issue 3, pp 158-162

Date of submission of the article to the Editor: 10/2016
Date of acceptance of the article by the Editor: 04/2017

DOI 10.1515/mspe-2017-0023

STABILITY ANALYSIS OF RADIAL TURNING PROCESS FOR SUPERALLOYS

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Abstract:
Stability detection in machining processes is an essential component for the design of efficient machining processes. Automatic methods are able to determine when instability is happening and prevent possible machine failures. In this work a variety of methods are proposed for detecting stability anomalies based on the measured forces in the radial turning process of superalloys. Two different methods are proposed to determine instabilities. Each one is tested on real data obtained in the machining of Waspalloy, Haynes 282 and Inconel 718. Experimental data, in both Conventional and High Pressure Coolant (HPC) environments, are set in four different states depending on materials grain size and Hardness (LGA, LGS, SGA and SGS). Results reveal that PCA method is useful for visualization of the process and detection of anomalies in online processes.

Key words: *stability detection, radial turning, PCA*

INTRODUCTION

The common use of planes engines, are growing the demand of materials with high mechanical resistance at high temperatures, what has incremented the development of superalloys. These materials are lighter and smaller than usually used alloys, what enable to reduce the fuel consume.

Superalloys are also able to support high temperatures and they have a high mechanical resistance, what fit them perfectly in the aerospace sector.

These materials usually need to be machined and due to their strength, they are considered as hard turning materials. In this case, a radial turning process is applied to three of the wide variety of superalloys that can be founded.

Radial turning is a machining process that removes material from the outer diameter of a rotating cylindrical alloy. The tool is moved linearly parallel to the rotation axis. Turning is a complex process which involves various physical phenomes such as plastic deformation, contact friction, etc. Hard turning refers to a material with high hardness, such as superalloys, which usually are heat treated before they are performed. These materials produced bigger wear and forces during the process due to their hardness.

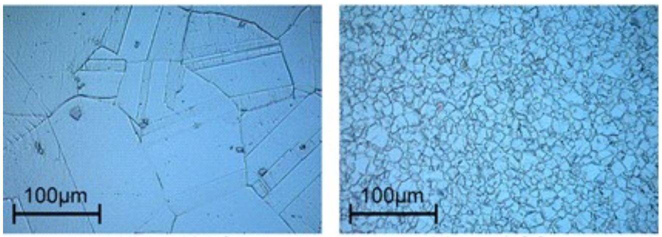
Industries which work with radial turning processes have always been looking forward to production optimization. Improving the tool life is one of the usual topics in this area, what is obtained by reducing tool wear. Choudhury and Srinivas [7] and M. Murua [1] predicted tool wear using some regression models, while Tugrul and Yigit [8] used also neural networks for tool wear and surface roughness, which is another prediction topic in machining processes. Tool wear also depends on the alloy hardness, cutting parameters as Sardinas [6], Sahu [3] and Bonilla exposed on their articles, the cooling conditions [4], where A.Suarez concludes that HPC produces less wear than conventional lubrication, grain size [2, 5] where Olovsjo demonstrate notch wear predominance for materials with large grains (LG) against materials with small grain (SG). Kumar [13] optimize a multi-objective process for laser cutting process of superalloys using PCA method. Parameters exposed, also affect to the cutting forces and the final quality. According to the forces, R.S. Pawade [16] demonstrates that larger cutting forces generated poor surface finish and extensive surface damage and Cedergren [17] deduce the importance of considering work material microstructure when studying cutting forces. In this paper, stability is used as a basic parameter to improve radial turning processes with experimental data.

EXPERIMENTAL ANALYSIS

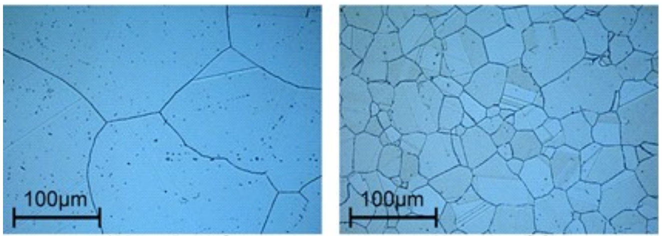
In this paper a study of the stability of a radial turning process for superalloys is done. This process is based on the forces that the ceramic tool supports during the turning against three different superalloys. All of them are Nickel-based superalloys, which differ from the others in the rest of the chemical components. These superalloys are Inconel 718, Waspalloy and Haynes.

Mentioned materials can be found in wide variety states, which are set by thermal heating and cooling processes such as annealing, which is used in this study. Annealing is a process that induces microstructural changes such as recrystallization and grain growth [11]. An alloy treated at high temperature and for big annealing periods, modifies the structure causing a recrystallization. Grain growth can also be obtained by heat treatment. This is achieved by controlling the times of heating and cooling.

Depending on the grain size, two states have been obtained for this study, which are called Large Grain (LG) and Small Grain (SG). In Fig.1 it can be shown the difference between these two states. In terms of strength, Aged (A) and Solutioned (S) are differentiated, where Aged is called to the stronger one.



Alloy 718 LG Alloy 718 SG



Waspaloy LG Waspaloy SG

Fig. 1 Difference between LG and SG

Superalloys are also lubricated to reduce the high temperature and forces generated during the machining process. In this case, conventional lubrication of 6 bar and High Pressure Coolant (HPC) of 80 bar are chosen to achieve that temperature reduction. In radial turning processes, test is called to a determined number of passes through the workpiece. A transition of the tool from the surface of the superalloy until the centre of it is considered as a pass.

A test is made by an accumulation of passes and on each material the number of passes is not the same. In the case of Inconel 718 and Waspalloy, 6 passes are done to complete a test, while 4 passes are needed for Haynes. In the Table 1, is shown the number of test measured for each superalloy.

Table 1
Number of tests

		SGS	SGA	LGS	LGA
Inconel	Conventional	2	2	2	2
	HPC	X	3	X	2
Haynes	Conventional	X	X	2	2
	HPC	X	X	1	1
Waspalloy	Conventional	2	2	1	1
	HPC	1	1	1	1

Other parameters are also set on this study. These parameters are the same for every material during the experiments: entering angle (91°), rake angle (0°), inclination angle (0°), nose radius (0.4 mm), cutting speed (30 m/min), feed rate (0.1 mm/rev) and cutting depth (2 mm).

While one of the passes is running, the force between the tool and the superalloy is measured, (F). Resulting cutting force breaks down into 3 components called Fx, Fy, Fz (see Figure 3) and this forces are measured using sensors, which are perpendicular each other. Fy force, has the direction of the cutting speed, Fx is in the radial direction and Fz is the orthogonal direction. When a pass is finished, 2 different tool wear are also measured, Flank wear and Notch wear. The Notch wear consist on the wear that appears where the tool and the superalloy are in contact. However, Flank wear is measured in 9 different points into the tool just after the Notch one. In Fig. 2 is shown how the tool seems when a pass is made.

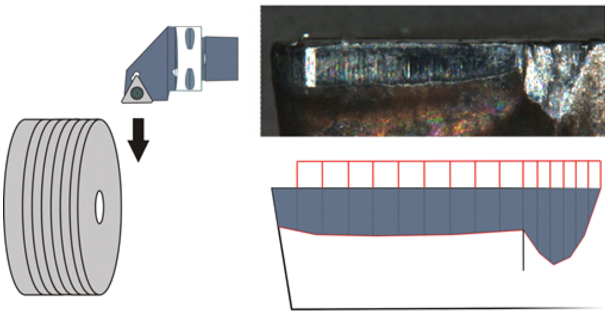


Fig. 2 Wear measurementeen

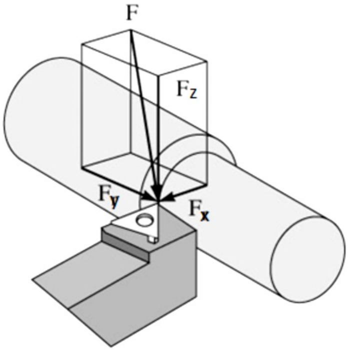


Fig. 3 Force components

In Fig. 4, forces from the 3 components are represented. These signals are a particular example taken from one pass, but in general, the signals obtained due to any of the passes has the same appearance. In this paper, force signals where analyzed to obtain the stability for each superalloy on each state and lubrication.

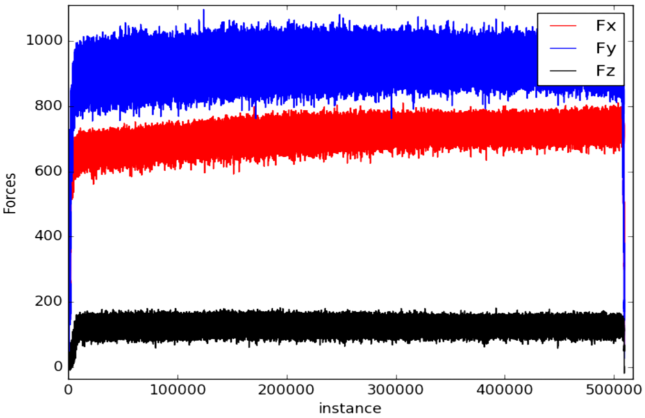


Fig. 4 Measured forces for a pass in the 3 components

EXPERIMENTATION

In this section the experimentation done is exposed, which is based on the forces and achieves to classify instability for every state. A filter to the force signal is done, where the initial and the final part of the signal are deleted. This filter is made to remove the warm-up and the stop of the process, which are not going to appear in the real machining processes. Let us call $x_i = (x1,\ldots,xt)$, $y_i = (y1,\ldots,yt)$, $z_i = (z1,\ldots,zt)$ the three components of the filtered signal in the i^{th} pass, where $i = (1,\ldots,6)$. In Figure 5, the filtered signal is shown.

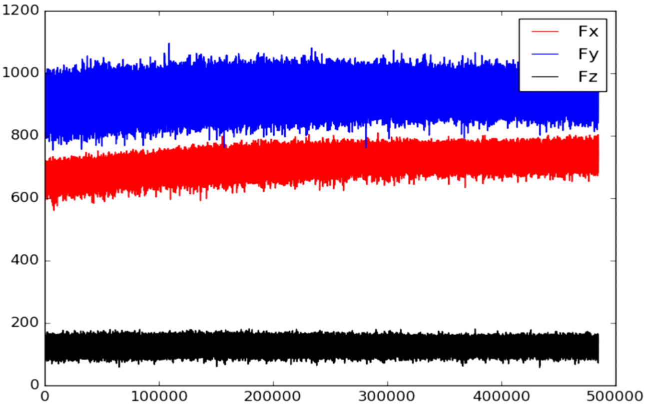


Fig. 5 Filtered forces for a pass in the 3 components

Two different methods are exposed. On one side, the first pass of every test stability is studied. Each force component is studied independently and then mixed. A robust three-sigma edit rule is used, which was proposed by Maronna [9]. This test is applicate following the next steps. Firstly median of each force is calculated, which is the center value of the sorted data Mex; Mey; Mez. Next step is to calculate a vector of the standard deviation from the median.

$$F_{xi}-M_{ex} = V_x \quad (1)$$

$$F_{yi}-M_{ey} = V_y \quad (2)$$

$$F_{zi}-M_{ez} = V_z \quad (3)$$

Where Fzi is the i^{th} value of the force in component z. Median is extracted from those vectors and divided by 0.6745.

$$MADNx = Median(|F_{xi}-M_{ex}|)/0.6745 \quad (4)$$

$$MADNy = Median(|F_{yi}-M_{ey}|)/0.6745 \quad (5)$$

$$MADNz = Median(|F_{zi}-M_{ez}|)/0.6745 \quad (6)$$

Finally, a quantitative value is obtained to classify the stability, which is the value of dividing the maximum of (1) with (2).

$$P_x = Max(|F_{xi}-M_{ex}|)/MADNx \quad (7)$$

$$P_y = Max(|F_{yi}-M_{ey}|)/MADNy \quad (8)$$

$$P_z = Max(|F_{zi}-M_{ez}|)/MADNz \quad (9)$$

P_x, P_y, P_z are then limited by an expert to expose when is considerable stable and when is unstable.

On the other side, the stability of the first pass is analyzed while the machining process is running. This achieve is obtained in three steps. Firstly, a statistic technique (PCA) is used to reduce the dimension from the 3 force component to only two of them, so that it can be seen easily. PCA is based on combining input components to obtain new ones (C1; C2) that are linearly independent between them and maintain as much original information as possible. This technique is used many times in the literature due to its easy way of programming. Some of the applications of this technique are to achieve objectives such as surface roughness [14], structural damage diagnosis [15], multi-objective optimization [13].

In this case PCA is applied to the first pass of the test to obtain a dimensional reduce which enable to represent the variables into a graphic, from 3 components (Fx, Fy, Fz) to 2 new axis (C1; C2). After representing data into the new axis the centroid of the pass is calculated.

$$O_1 = \Sigma C_{1i}/N \quad (10)$$

$$O_2 = \Sigma C_{2i}/N \quad (11)$$

Where O_1 and O_2 are the values of each axis of the centroid. After that, other passes are represented on the same principal components, so the progress of the test can be seen graphically. Instead of classifying graphically, a quantitative measure is calculated, which is the maximum distance from any of that pass point to the centroid of the first pass.

$$D = Max(\sqrt{(C_{1i}-O_1)^2+(C_{2i}-O_2)^2}) \quad (12)$$

These distances are represented for each test, what would provide the progression of this value during the machining process. A test is considered unstable if the distance for any of the passes is 200% times the value obtained for the first pass

RESULTS

As it was mentioned in section III, the first step is to filter the signal. Initial and final parts are removed. Figure 6 shows how the signal remains after removing those parts. This filter had gone through the signals of the study, which had been used after the filtering process for the rest of the methods.

Results are exposed for tests classified as stable and unstable. These tests are presented on Table 1. In Figure 7, first pass of a test is shown.

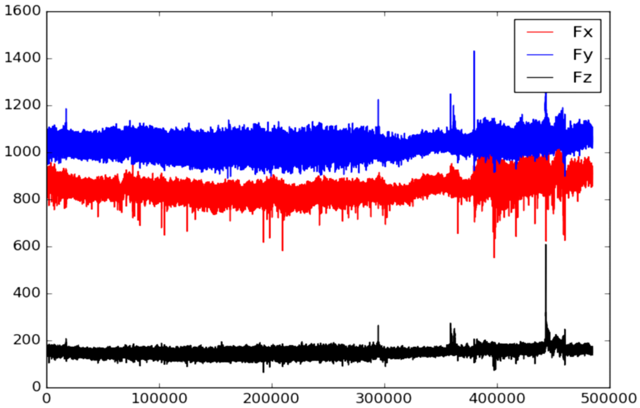


Fig. 6 First pass of Waspalloy SGS Conventional

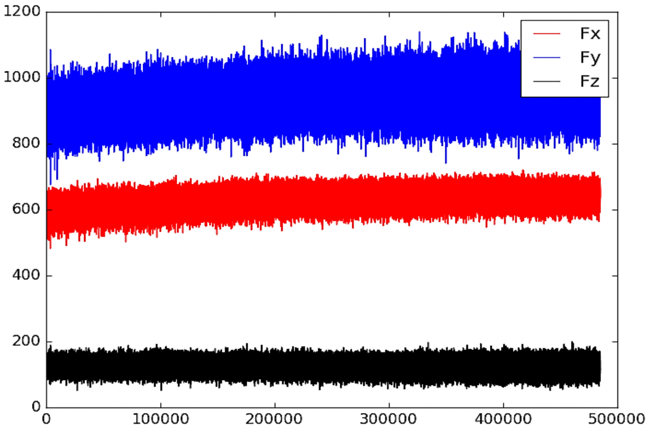


Fig. 7 First pass of Haynes LGA HPC

Stability by the force

In this section, classification for the first pass of the test is obtained. To achieve it, some quantitative values have been taken from each of the force component (F_x, F_y, F_z). Chosen variables are the median of the filtered force, maximum distance between mentioned median and measured forces and the median value of all the distance measured. 3 values are calculated for each force component. From all the values obtained for each pass, a combination of them is made for getting a quantitative value, which classifies the tests.

The measure chosen is the mean value of the 3 components called force proportion, which is referred to the maximum distance value divided by the median distance value. This quantitative measure classifies between stable and unstable tests, where stable will be when a low value appeared an unstable when a great value is obtained. In this case, 7.33 is obtained for Haynes LGA HPC and 26.52 for Waspalloy SGS Conventional.

This results obtained confirms the hypothesis of detecting instability with the force. Validation of this method should be obtained by testing with more data. This process can also be used into the rest of the passes of each test, what could provide a good reference to determine when to stop the machining process. The main problem of this method is that this method is not able to be used into online processes. This objective is solved by using the method exposed in IV-B.

Stability in function of the first pass

In this section the stability of the test is studied based on its first pass. Principal Component Analysis (PCA) is applied to the first test and the centroid of the result is obtained before overleaping the rest of the passes PCA. PCA analysis has been realized to reduce the number of variables to 2 dimension, so that the result can be graphically exposed.

Figure 8 and Figure 9 shows the PCA for both cases of Waspalloy and Haynes respectively. In both graphics, the full test in shown, where each of the passes has a different colour to be appreciated. Fixing on Figure 8 and Figure 9 it will be possible to classify each test easily.

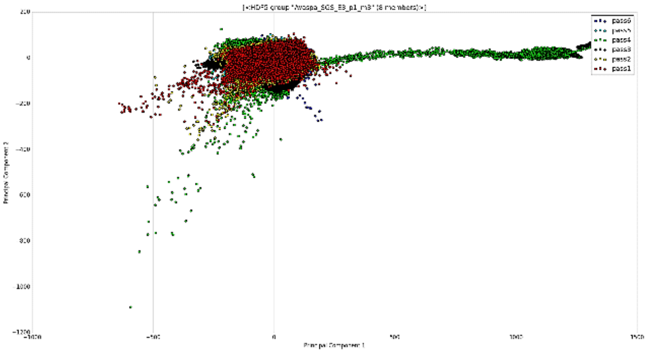


Fig. 8 Waspalloy SGS Conventional 6 passes

Note that 4th pass of Waspalloy is gone far through the first principal component, while Haynes remains in the same space every pass. Instead of doing it graphically, a quantitative measure is calculated. Measured value consists in the maximum distance measured for each pass to the centroid of the first pass. This measure can also be obtained online when the centroid is calculated.

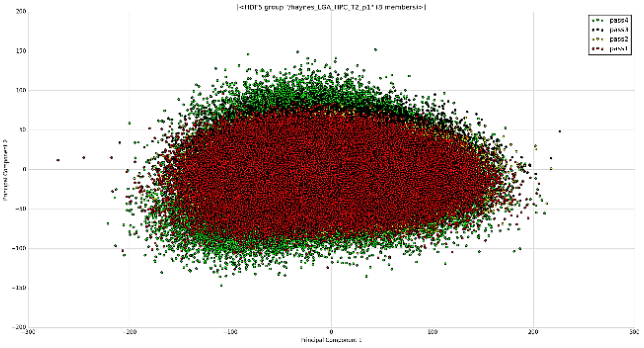


Fig. 9 Haynes LGA HPC 4 passes

A very useful system can be obtained with this method to detect anomalies while the process is running. When a test distance increase heavily, it will be considered that this test is instable. In Figure 10 and Figure 11, the maximum distance for each pass is represented.

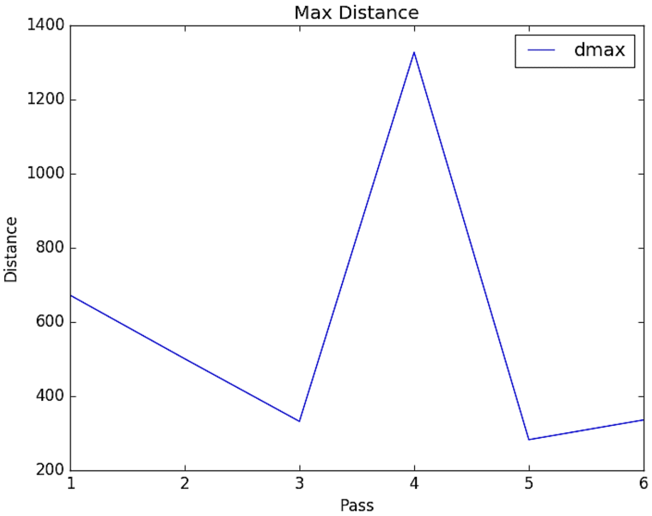


Fig. 10 Maximum distance to the centroid of the first pass for each pass in Waspalloy SGS Conventional

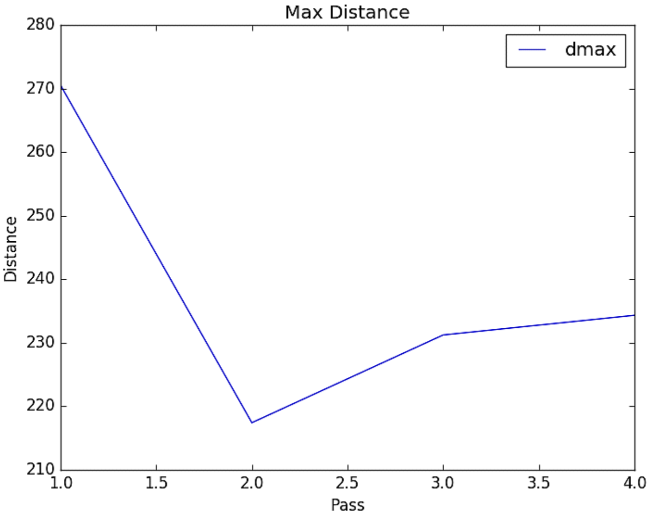


Fig. 11 Maximum distance to the centroid of the first pass for each pass in Haynes LGA HPC

It can be seen that in this case, Waspalloy has distances between 600 and 800 while Haynes has no measure bigger than 300. This result confirms the theory of the stability for

Haynes LGA HPC test and instability for Waspalloy SGS Conventional.

CONCLUSIONS AND FUTURE WORKS

Development of stability detection models for machining processes using forces is a difficult task due to all the factors that have impact on the force measured. In this paper, two different models have been exposed:

On the first method, the median values are calculated, what means that a range of data is needed to do it, what makes it an offline method. This method can be used not only for the first pass but also for all the passes of each test, providing a stability test when a pass is finished.

On the other method, an intuitive 2 dimension representation of forces is done, what makes easier to understand the relationship between forces in different components. The main problem of this method is that it is supposed that the first pass of each test is stable, what means that if the first pass is instable, this test could bring a stability result that will not be according to the reality.

That reason makes the development of a new method necessary, which could be a combination between both explained methods in terms of detecting stability. This will consist in the use of the first method to detect the stability of the first pass and when this stability is confirmed, apply the second method online in order to find any instability that would activate an alarm to stop the machining process. This machining process can not be stopped in any point, it is necessary to maintain machining until a specific point where stopping the process do not mean breaking the material.

In this study, two methods had been applied to two different tests that where classified previously. In order to validate these algorithms, more tests should be used, what would be done in future work when the rest of the tests are classified as stable or instable.

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