Stiffness analysis of clamping the workpiece in the turning process

SUMMARY

The achievement of the highest accuracy is an important factor in machining. The dynamics and statics of the system, ultimately, is affecting the process precision\(^1\). The stiffness of MGFT system (machine tool – grip – fixture – tool) is significant in process of machining. Dynamics of the machining system is related to its some parts like machine dynamics, tool dynamics or clamping workpiece\(^2\). The rigidity of workpiece – toolholder subsystem has an enormous influence of machining\(^3\). The paper provides stiffness analysis of workpiece made of Waspaloy, nickel-base superalloy material. The workpiece was clamped into hydraulic three-jaw chuck. The workpiece – turning turret subsystem was strained in the radial direction of the shaft. These measurements were repeated on various phases of turbine shaft turning. This component was burdened and disburdened in terms of 0–2000 N. Based on this research the deflection characteristics in relation to load \(y_x = f(F)\) were determined. The purpose of the study was to identify at what stage of the turning process subsystem stiffness will be forfeited. Additionally, impact of number of machined passes on loss of stiffness was determined.

Key words: turning, static stiffness, three-jaw chuck clamping.


\(^2\) Ibidem.

Introduction

The development of new machining technologies like High Speed Cutting (HSC), dry machining (without use of cutting fluid) or hard machining is related to the application of more powerful and cutting speed\(^4\). It is important to selected optimal machining conditions in order to minimal surface roughness\(^5\). These requirements shall apply to turning difficult-to-cut materials like Waspaloy. Nowadays, the nickel-base superalloy such Waspaloy is very often used in machining. Turning of this material is difficult, so there are some new techniques for example Laser Assisted Machining (LAM)\(^6\). This type of hybrid method allowed increasing the machinability of material. The cutting forces or centrifugal force arises during machining. As a result, the high radial and axial forces or bending moments are created\(^7\). This forces and moments are carried form workpiece on the spindle. This is done by clamping device along with the suitable gripping force. Definition of the required gripping force is necessary. It ensures safety clamping of the workpiece, especially during High Speed Machining. In turning process, the three jaw-chuck clamping is the preferred option, because of its centering capabilities\(^8\). During the last years, papers about dynamic stability of workpiece – tool subsystem have been developed. For example, various studies show analysis of deformable workpieces like thin-walled components\(^9\). Most research builds on defining acceleration, velocity or vibration amplitude for various parts of system. There are some monitoring systems built on analysis of vibration signals capable the deflection of workpiece\(^10\). The determination of natural frequency for different elements of machining system may be relevant. This will allow to avoid the instability caused by resonance. It is important to determine which component has the biggest influence on the stability of MGFT system\(^11\). During the machining, the dimensional and geometric inaccuracies are created. This means a different stiffness along the entire length of workpiece. The cutting forces have an impact on these variations. Additionally, these forces have influence on the elastic forces.


deflection of workpiece. In this regard, the main purpose is to obtain the dimensional tolerance, which is required.

During the machining, workpiece is burdened by cutting force $F$. In turning, the main cutting force $F$ has three components: cutting force $F_c$, feed force $F_f$ and radial force $F_p$. Radial force $F_p$ has the most significant impact on the deflection of workpiece. Furthermore, this constituent of force affects the machine and tool stiffness. To know about value of radial force $F_p$ provides opportunity of estimate amount of stiffness.

Based on investigations, the clamping device stiffness is higher than the tailstock stiffness. However, it is not a rule, it depends on chuck type. For example, in studies, the circularity of workpiece clamped in three jaw-chuck was measured. The measurements were carried out applying minimal gripping force $F_{u, min}$. Additionally, the offset of the axle shaft was determined. Figure 1 depicts the profile of deformed shaft. The triangular shape seen at the picture, can be correlated with places, where the jaws were closed.

Fig. 1. Profile of deformed shaft fixed into three-jaw chuck (own elaboration based on: Z. Murčíková, K. Vasilko, *The real shape of the workpiece after turning and milling*, „Journal of Production Engineering“ 2013, vol. 16, p. 33–36.)

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13 Z. Murčíková, K. Vasilko, op. cit.
14 Ibidem.
16 Z. Murčíková, K. Vasilko, op. cit.
In paper\textsuperscript{17} the dynamics of the system while turning of long and susceptible workpiece, was presented. In this study, the natural frequency of component was determined. The investigation states that with the increase of workpiece diameter, increased the natural frequency and stiffness of component. Then, the high precision of machining can be obtained. The axial force was applied along the tailstock, the increase of force resulted in decrease of natural frequency, due to excessive burden of shaft.

The problem occurring mainly during High Speed Cutting, when workpiece is clamped into three-jaw chuck. In turning, the great axial force that has an impact on the fixture appears\textsuperscript{18}. Influence of axial force might lead to issues in HSC. Insufficient gripping force could result in to eject a workpiece from fixture. It may lead to very serious injuries or damages. In order to decrease a gripping time, the automatic clamping is often used\textsuperscript{19}. There are a lot of types of grippers in CNC (Computer Numerical Control) machines like hydraulic, pneumatic or electromagnetic clamping. Nowadays, three-jaw chucks are upgraded for example: light jaws made of aluminium or materials with glass fiber. The main purpose of these changes is reduction of dynamics clamping force losses. This allows for maximum spindle speed\textsuperscript{20}. Testing of the three-jaw chuck stiffness and its influence on dynamics clamping forces can provide safety HSC process during turning. In paper\textsuperscript{21} the relations between centrifugal force and clamp stiffness are presented. The lower the workpiece stiffness and higher three-jaw chuck rigidity, then the losses of dynamics clamping force is much lower. This leads to efficient HSC process during turning.

**Experimental details**

The objective of research involved the measurement of static stiffness of workpiece made of Waspaloy. The workpiece – turning turret subsystem was strained in the radial direction of the shaft. These measurements of static stiffness were repeated on various phases of turbine shaft turning. This component was burdened and disburdened in terms of 0-2000 N. Figure 2 depicts the scheme of measurement of subsystem static stiffness. Three measurement points were selected, which was shown on figure. Extreme points were chosen in order to stiffness changing along the entire length of shaft. The A position is the most integral point, which is the nearest to tailstock. This is why, the following section of paper increasingly is based on loss of subsystem stiffness in A position. The displacement of shaft was

\textsuperscript{17} N. Seghedin, M. Horodincă, D. Chitariu, R. Drosescu, op. cit.


\textsuperscript{21} P.F. Feng, D.W. Yu, Z. J. Wu, E. Uhlmann, Jaw-chuck stiffness and its influence...
monitored by Heidenhain incremental length gauge MT 12B. The dimensions of clamped shaft: diameter $D = 82.5$ mm, length $L = 317.5$ mm. Semi-finished product was made from nickel-base superalloy material Waspaloy. Density of material $\rho = 8138$ kg·m$^{-3}$.

![Figure 2](image1.png)

Fig. 2. Scheme of measurement of the workpiece – turning turret subsystem static stiffness (own elaboration)

Workpiece was clamped into hydraulic three-jaw chuck in CNC machine CTX 310 ECO-LINE. Figure 3 shows the set-up of experimental apparatus: force sensor K1505-5 kN connected with indicator for measuring strain gauge force sensors and incremental length gauge MT 12B connected with digital display Heidenhain D-83301.

![Figure 3](image2.png)

Fig. 3. The scheme of experimental apparatus (own elaboration)
The measurements based on the following procedure:
- for force $F = 0$ N, the displacement $y_{x0} = 0$ mm was assumed,
- next, the system was strained by force $F = 100$ N and a displacement $y_{x1}$ was saved,
- then, the force $F$ was increased every 100 N as far as the value of maximum force $F = 2000$ N and displacement $y_{x}$ was written at a time,
- this procedure has been repeated during relieve of workpiece from 2000 N to 0 N,
- all measurements of displacement $y_{x}$ were saved.

Based on investigations, the deflection characteristics in relation to load $y_{x} = f(F)$ were determined.

**Results and discussion**

Research results show the measured displacement $y_{x}$ during burdening of workpiece. On the basis of investigations, the linear function $y = ax+b$ in the form of $y_{x} = aF+b$ was determined. In this equation the coefficient $a$ is a value of static susceptibility. If friction forces would not exist in system, then a coefficient $b = 0$. The static rigidity is a characteristic of element, moreover this is a ratio of relief gain to the displacement gain (which is measured in certain direction). Based on coefficient $a$ (from linear function), the static stiffness $j$ was indicated. Because the static rigidity is a opposite of susceptibility. Figure 4 depicts change of workpiece movement $y_{x}$ in function of load $F$ (during burdening and disburdening in terms of 0 – 2000 N) in the three position (A,B,C).
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Fig. 4. Change of workpiece movement $y_x$ in function of load $F$: a) in A position, b) in B position, c) in C position (own elaboration)

The value of rigidity $j$ in every place of shaft is indicated by diagrams (fig. 4). Nevertheless in this work the position with the lowest stiffness of workpiece was inspected. The primary objective of turning large-size shafts is to determine the changes in stiffness. Figure 5 shows the comparative analysis of rigidity in every extreme point. Every measurement position was placed in different distance $l_x$ from three-jaw chuck.

Fig. 5. Comparative analysis of rigidity in every measurement point (own elaboration)

Research results show the highest static stiffness in C position. This point is measured in the nearest position of three-jaw chuck. It has been linked to relevant gripping force. However, shaft loses its stiffness near the tailstock (in A position). This is a drop of 48% in comparison with C position. This affect in particular on machining thoroughness. Along the whole shaft length, the surface roughness is also changing (with constants turning parameters).
In this conjunction it is good to remember when low surface roughness is required. Most experiments have been found that the larger the stiffness, the lower roughness of workpiece. This result from the fact that apart from spindle, the rigidity is higher than beside tailstock.

After the conducted tests, the stiffness of subsystem after turning was determined. The displacement was measured in the same positions A, B, C as before. After ten machined cuts, measurement procedure of deflection was repeated. Figure 6 depicts change of workpiece deflection under the action of load F in A and B position.

On the basis of the presented results, one can observe that these relations are similar to analysis in Figure 3. It can be noted that the bigger the distance of spindle, the loss of stiffness is lower. The measurement procedure was repeated again, after fifteen machined cuts. The comparison of rigidity in A position (on the next point of tailstock) was the last step of researchers.

The stiffness of workpiece – turning turret subsystem in point as far away from spindle changed only slightly. The next machined cuts is not influenced by system rigidity in A position. Figure 7 depicts change of shaft displacement after fifteen machined passes.
Additionally, during turning the radial deflection of workpiece was measured using photoelectric length sensor optoNCDT ILD1700-10 LL Micro-Epsilon. The measurement range of sensor – 10 mm, having a measurement accuracy of 0.5 μm. Type of ILD sensor has numerous value of sampling. Therefore, it is perfect for displacement evaluation in dynamics processes. Measurement range must be adapted accordingly before experiments.

At this stage, the displacement was obtained in different rotational speed $n$: 450, 600, 800, 1000 and 1200 rpm. Figure 8 depicts influence of rotational speed $n$ on radial displacement $y_x$.

On the basis of the presented graph, one can observe that displacement increases with an increasing of rotational speed. Therefore, the doubling rotational speed $n$ (from 600 to 1200 rpm) leads to more than 50% of radial displacement growth. This leads to reduction of static stiffness in High Speed Cutting.
Finally, the stiffness of semi-finished shaft and workpiece after turning was compared. Figure 9 show rigidity of system in A position in different turning phases.

![Graph showing rigidity comparison](image)

**Fig. 9. Comparison of system rigidity for different turning phases [own elaboration]**

The difference between various system rigidity is not numerous. The preliminary machining has not influence of subsystem stiffness on the point of the most workpiece deflection, value of rigidity changes only slightly. This is due to the ratio of static stiffness to workpiece diameter. Change of diameter in short range of values affects the change of stiffness is unnoticeable.

**Conclusions and summary**

Based on this research, the following conclusions were drawn:

- The subsystem has the minimum stiffness in the nearest position of tailstock. Despite the workpiece was supported by tailstock, in this point the subsystem lost its rigidity mainly. If we compare a result of shaft rigidity in C position (near the spindle) with stiffness in A position (near the tailstock), one can observe losses of A point rigidity by almost 48%. On the basis of the provide example it can be seen that the longer workpiece is, the place near tailstock support is more burden. It is important in turning of large-size shafts of high density like Waspaloy \( (\rho = 8138 \text{ kg} \cdot \text{m}^{-3}) \).
- Research shows that the preliminary machining has not influence of subsystem stiffness on the next point of tailstock. Value of rigidity in the most burdened part of shaft changes only slightly. Rigidity of system in A position in different turning phases oscillates around 20 N·μm⁻¹.
- On the basis of the presented investigation, one can observe that displacement increases with an increasing of rotational speed \( n \). This is lead to reduction of static stiffness in High Speed Cutting.
- Finish machining of long shafts is highly problematic. When the workpiece stiffness is changing along the whole length, the surface roughness is also changing. In this conjunction it is good to remember when low surface roughness is required.
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STRESZCZENIE

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Analiza sztywności zamocowania półfabrykatu na różnych etapach procesu toczenia


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