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STABILITY MEASUREMENT – COMPARISON OF MEASURED VALUES WITH THE REGENERATIVE THEORY OF SELF-EXCITATION OSCILLATIONS

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Abstract

This paper deals with self-excited oscillations arising during the turning process. Several theories are known which attempt to explain the cause of self-excited oscillations. One of the most advanced theories is the reproduction of previous surface waviness. A simplified mathematical description of the stability diagram is created from this theory. In the experimental part, the mathematical theory is compared with the actual results of the value from the stability diagram. The stability diagram is created by TXF Metalmax. This article is focused on finding the optimal setting of the measuring set of the TXF Metalmax software which follows up on the article: "Measuring Stability of the Cutting Process when Turning Using TXF Metalmax Software".

Keywords: self-excited vibration; regenerative effect; measuring; TXF Metalmax

1. Introduction

By the end of the 20th century, production had been refined, which meant products were being machined with narrower tolerances and better surface quality, as well as with reduced production costs. From a comprehensive point of view of the production process, attention was increased on the area of stability of the cutting process. Today, the trend is to make machines and tools light and strong. This increases the natural frequency and makes it more difficult to achieve resonance. However, with today's diversity of complexity and high production, there are situations where tools must be machined as productively as possible, even with a large tool offset. However, the stability of the cutting process is affected by many factors such as cutting conditions, tool design, tool clamping, imbalance of machine parts, etc. The machining process is a dynamic phenomenon in which oscillations occur in most cases. These vibrations cause a deterioration in the quality of the machined surface, a reduction in tool life, an increase in machining time, and an increase in machine wear. That is why research into the dynamics of machine tools is in great demand today.[1][2][3]

This article is focused on finding the optimal setting of the measuring set of the TXF Metalmax software on the turning centre EMCO Maxxturn 25, which follows up on the article: "Measuring Stability of the Cutting Process when Turning Using TXF Metalmax Software", where it was found that the evaluated stability diagram does not correspond to the predicted results.[4]

TXF Metalmax is software developed by an American company based on research by Tlusty [5], which examined the stability of the turning process. This software has been primarily developed for measuring the stability of the milling process, but it is also possible to select a turning process. For the turning process, no comprehensive measurement manual has been created by Metalmax and the setting environment is not user friendly. This work is focused on the comparison of the measured values with the regenerative theory of self-excitation oscillations which creates a relationship between the spindle speed and the chip width limit.

1.1. Self-excited oscillations

Self-excited oscillations occur between the workpiece and the tool without a periodic external excitation effect and are manifested by noise and traces of vibration on the machined surface. (Fig. 1) To create it, it needs an initial impulse, which causes deflection of the tool or workpiece from the equilibrium position and the further course is maintained by the internal energy of the cutting process. [5]

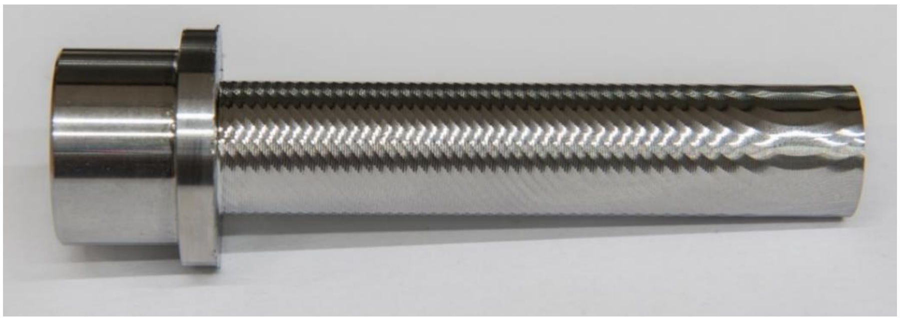

Fig. 1. Wavy surface of workpiece

The frequency of the generated oscillation is close to the frequency of one of the types of natural oscillations of the machine. The frequency changes to a lesser extent as the cutting conditions change. By changing the cutting conditions, the connection between the tool and the workpiece also changes, and thus also the frequency of the machine's own oscillations. The connection between the tool and the workpiece has the character of a spring, because as their relative distance changes, the magnitude of the cutting force acting on them changes too. There are several theories which explain the causes of self-excited oscillations. The most important are the two most theoretically and experimentally advanced theories.

- Variability of tool clamping stiffness in different directions
- Reproduction of previous surface waviness, the regenerative effect

The regenerative effect is important in this article.[5][6]

<u>Reproduction of previous surface waviness, the regenerative effect</u>

According to the regenerative principle, self-excited oscillations are generated in such a way that the oscillating tool edge Y (t) machines the vibrating surface Yo (t), which was created during the previous cut. (Fig. 2) The corrugated surface of the workpiece regularly changes the depth of cut and modulates the cutting force that excites the entire system. In this way, the waves are regenerated with each cut (at each spindle revolution). There is a certain phase shift between the undulation of the machined surface and the oscillations of the tool, which according to the regenerative effect is decisive for the occurrence of self-excited oscillations. If, for example, this phase shift is zero, the chip cross section will be constant so that the cutting force will not be modulated and the self-excited oscillation will not occur.[7]

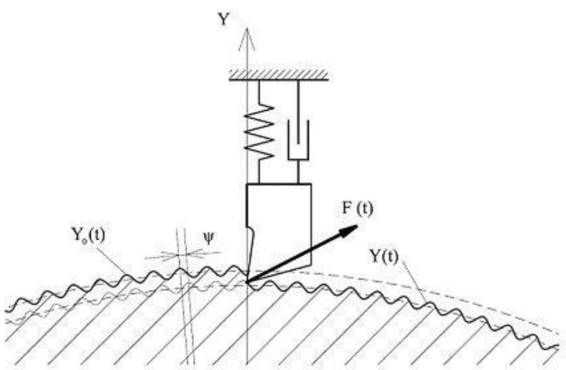

Fig. 2. Regenerative effect

1.2. Simplified mathematical description of the stability diagram

The regenerative effect creates a relationship between the spindle speed and the limiting chip width b_{mez}. The theory creates a stability diagram and allows the user to achieve the highest material removal in the machining process. To calculate the limit chip width b_{mez}, it is necessary to create a simplified machining scheme.

The simplification is as follows:

- The vibration system of the machine is linear.
- The direction of the variable cutting force is constant.
- The variable component of the cutting force depends only on the vibrations in the direction normal to the surface.

During the cutting process, the machine has two main shapes of oscillations. The deviations of these oscillations are projected into the x1 and x2 axes, which are rotated by angles α1 and α2 to the normal of the machined surface. The components of the cutting force in the axes cause oscillations, which are normally reflected as a wavy surface Y0 (t). In the following section, the system oscillates in the course of Y (t). Y0 and Y are the amplitudes of the tool oscillations and the corrugations of the machined surface and there is a phase shift ψ between them. (Fig.3)[8]

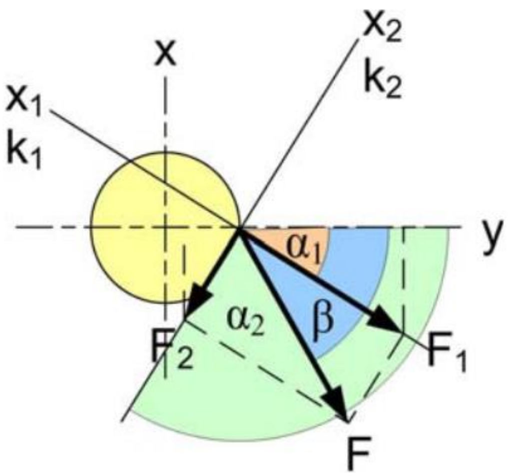

Fig. 3. Oscillation directions and angles

The variable cutting force is expressed by the relation:

$$F = R \cdot b_D \cdot (Y_0 - Y) \quad (1)$$

Where $(Y_0 - Y)$ is the chip width h_D which is a variable. The specific cutting force k_c is replaced by the coefficient R.

$$R = k_c \quad (2)$$

The oscillation deviation of the tool is given by the relation:

$$Y = \phi(f) \cdot F \quad (3)$$

Where $\phi(f)$ is a complex transfer function that is expressed as the ratio of the deflection and the excitation force.

$$\phi = \frac{Y}{F} \quad (4)$$

By expressing the deviation from equation (4) and substituting the force from equation (1), we obtain the equation:

$$Y = \phi \cdot R b_D (Y_0 - Y) \quad (5)$$

In addition, the condition of stability of the cutting process must be taken into account:

$$\frac{|Y_0|}{|Y|} = 1 \quad (6)$$

This equation expresses the requirement that the amplitude of the oscillations in successive sections not change. By combining equation (5) and the stability conditions of the cutting process, we get the following equation.

$$\frac{Y_0}{Y} = \frac{1+\phi R b_D}{\phi R b_D} \tag{7}$$

By modifying equation (7) we get:

$$\left|\frac{1}{R b_D} + \phi\right| = |\phi| \tag{8}$$

Because a complex transfer function consists of imaginary and real parts where the imaginary parts are equal, the equality of the real parts results in:

$$\frac{1}{R b_D} + Re(\phi) = \pm Re(\phi) \tag{9}$$

$$\frac{1}{R b_D} = -2Re(\phi) \tag{10}$$

From this equation, the limit chip width can be expressed:

$$b_{mez} = \frac{-1}{2R \cdot Re(\phi_{neg})} \tag{11}$$

This equation applies only to negative values of the real part of the transfer function. The negative minimum of this function indicates the minimum value of the chip width limit.[8] The following chapter is focused on the comparison of the chip width limit calculated according to equation (11) from the real measured data with the chip limit width from the stability diagram.

2. Part one of the experiment

This experiment is based on my master's thesis, where I created instructions for TXF Metalmax software. During the experiments it was found that the stability diagram did not correspond to the predicted results. Several experiments were performed as part of the investigation.

- The influence of measured axes on the resulting stability diagram (SD)
- The influence of entered parameters on the resulting SD
- The influence of selected impact hammers on the frequency response function
- The verification of the correctness of the conversion of a continuous signal to a discrete one
- The verification of the correct evaluation of the tuning fork's own frequency
- The evaluation of software TXF frequency excited by frequency generator [4]

After the analysis of the experiments, no error was found and therefore I followed up on this research with the following experiment.

Description of the experiment

The experiment was performed on an EMCO Maxxturn 25 turning centre. The semi-finished products have dimensions of Ø30 x 55 mm. Three materials were selected for the experiment.

- C45
- S235 JR
- 42CrMO4

Fig. 4. The semi-finished product

The measured semi-finished products were clamped in a collet chuck and were measured in the X direction and at a distance of 55 mm.

The material C45:
First, the coherence of the transmitted data was checked where the dependence of the excited signals reached high percentages in the range of 100 to 2700 Hz.

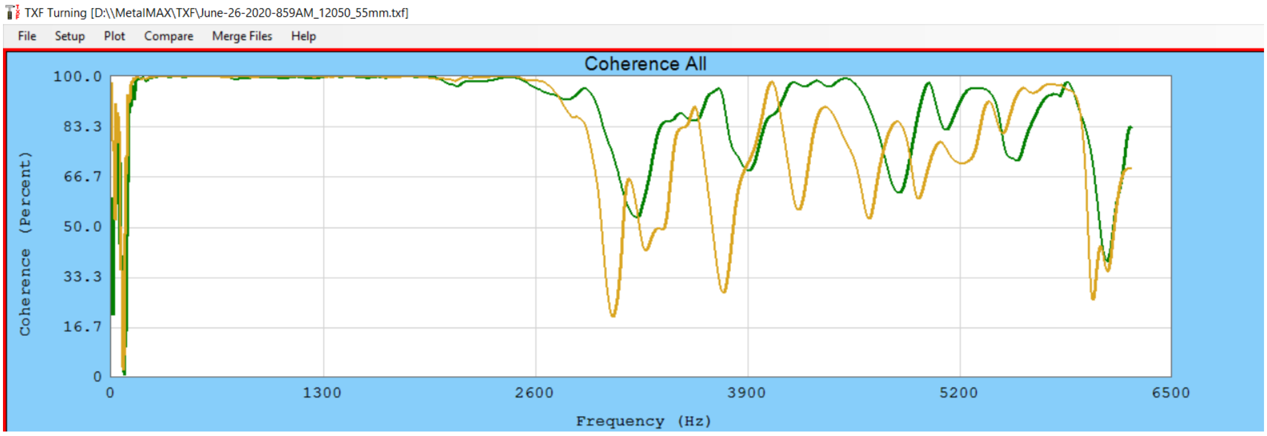

Fig. 5. Coherence of semi-finished product C45

The figure below shows the real part of the frequency response function (FRF) where the minimum value of the negative part of the FRF was found. In this case, the value is $-5.938 \cdot 10^{-8}[m/N]$=$-5.938 \cdot 10^{-5}[mm/N]$.

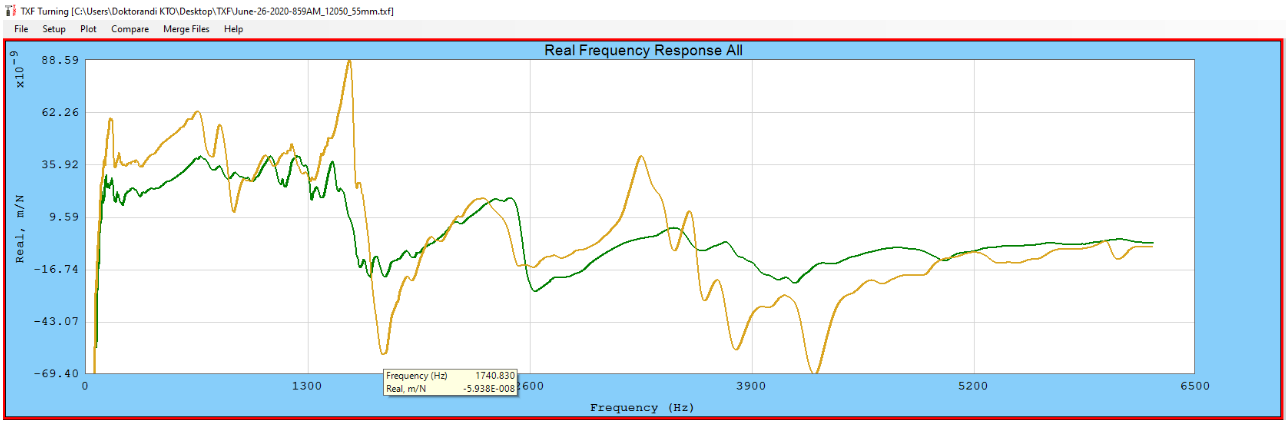

Fig. 6. Real part FRF semi-finished product C45

Subsequently, this value and the value of the specific cutting force were fitted to the equation. (11).

$$b_{mez} = \frac{-1}{2R \cdot Re(\phi_{neg})} \tag{12}$$

$$b_{mez} = 4.78[mm] \tag{13}$$

The calculated chip limit value was compared to the chip limit value from the stability diagram.

Where the resulting value was almost identical to the measured value, and therefore these values are marked as identical.

4.78≅4.72

The whole procedure described above was applied to the following two selected materials. For this reason, the whole process will no longer be described, but only the resulting graphs and values.

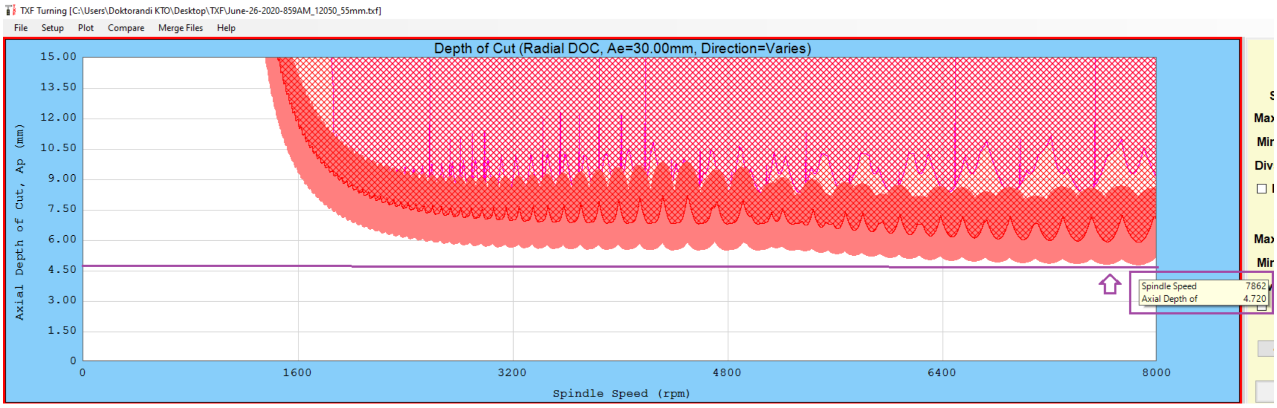

Fig. 7. SD of semi-finished product C45

<u>The material S235 JR</u>

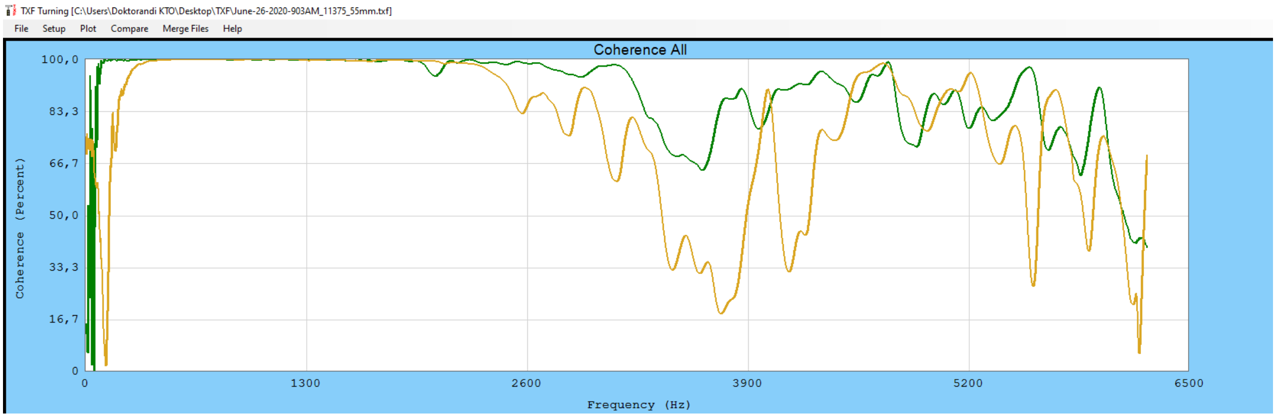

Fig. 8. Coherence of semi-finished product S235 JR

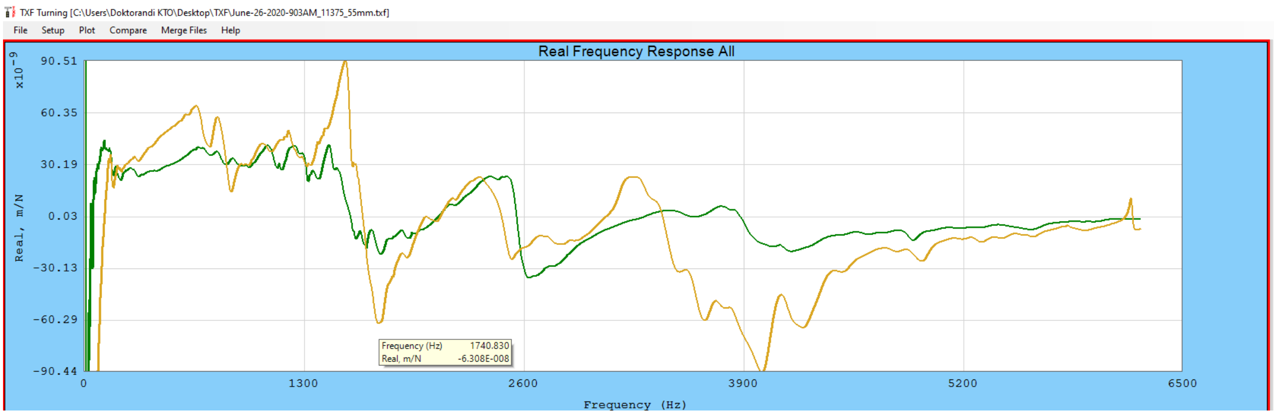

Fig. 9. Real part FRF semi-finished product S235 JR

The minimum value of the real part of the FOF is $-6.308 \cdot 10^{-8}[m/N]$=$-6.308 \cdot 10^{-5}[mm/N]$

$$b_{mez} = \frac{-1}{2R \cdot Re(\phi_{neg})} \tag{14}$$

$$b_{mez} = 4.8[mm] \tag{15}$$

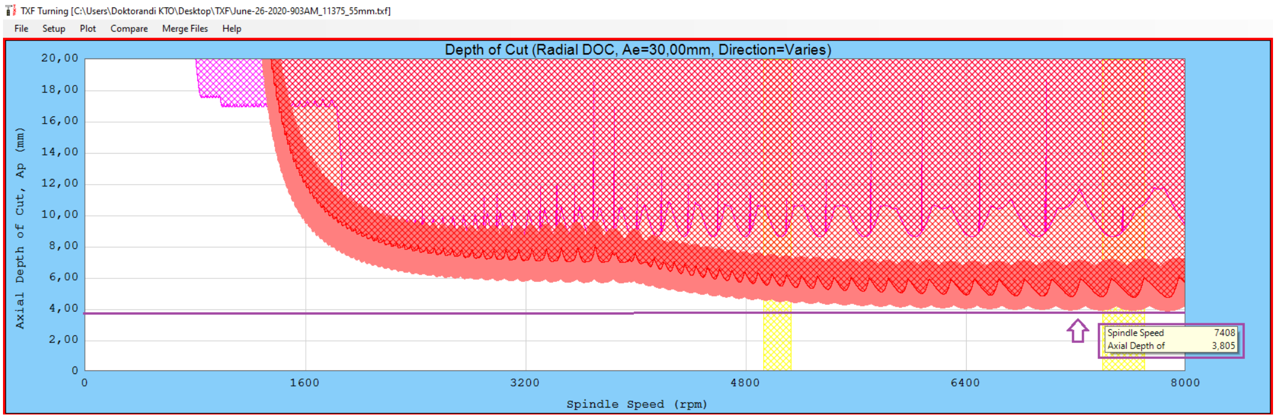

Fig. 10. SD of semi-finished product S235JR

Where the resulting value differs from the measured value by 1 [mm]. This value is still acceptable due to the measurement uncertainty recommended by the manufacturer and is 20%.

<u>Material 42CrMO4</u>

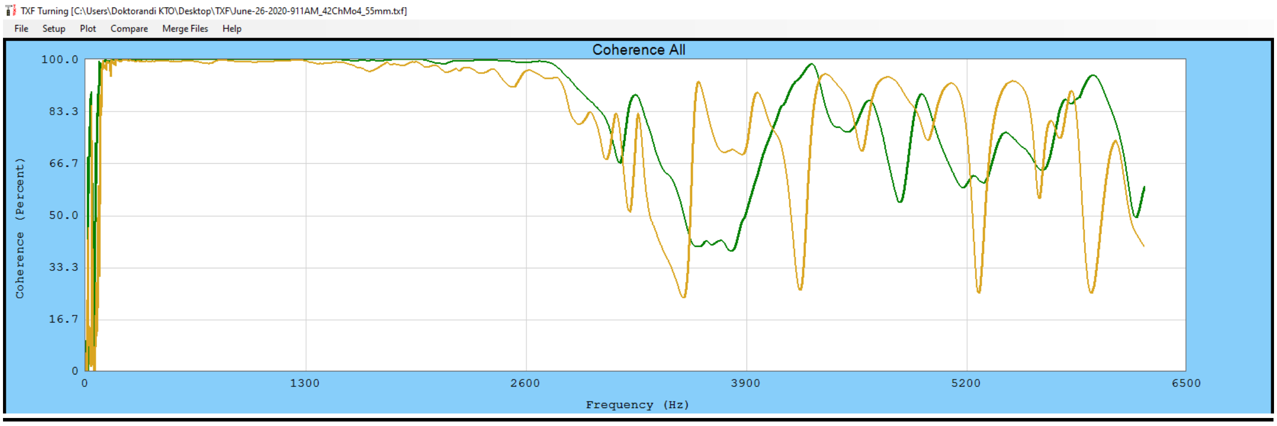

Fig. 11. Coherence of semi-finished product 42CrMO4

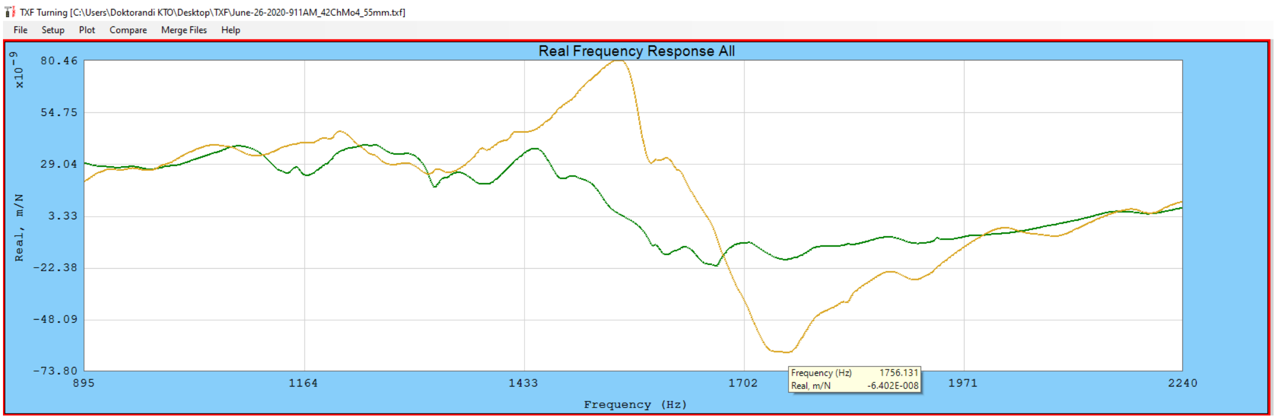

Fig. 12. Real part FRF semi-finished product 42CrMo4

The minimum value of the real part of the FOF is$-6.402 \cdot 10^{-8}[m/N]$=$-6.402 \cdot 10^{-5}[mm/N]$

$$b_{mez} = \frac{-1}{2R \cdot Re(\phi_{neg})} \tag{16}$$

$$b_{mez} = 3.8[mm] \tag{17}$$

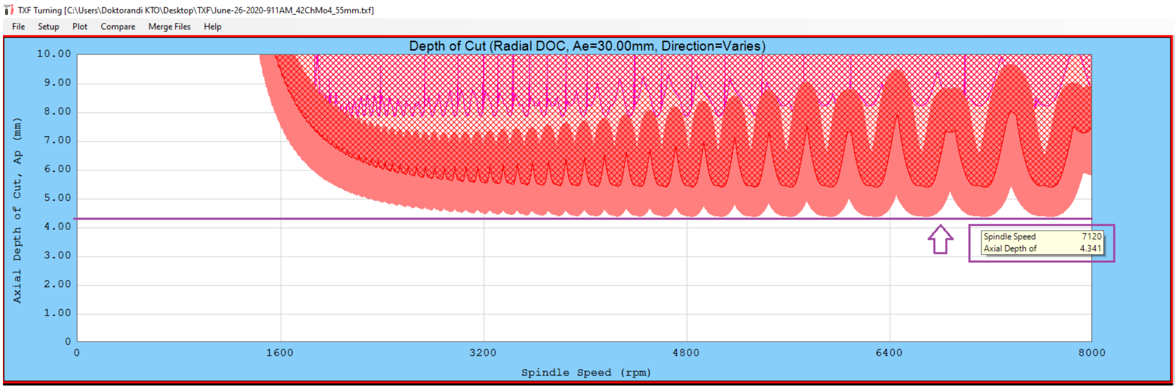

Fig. 13. SD of semi-finished product 42CrMo4

Where the resulting value is 0.5 mm, but it may not be possible to take these values as correct, because the measured value is below the limit of the range of values determined by the measurement uncertainty. For this reason, it was decided to perform another series of measurements on the 42CrMo4 blank.

3. Part two of the experiment

A semi-finished product with a diameter of 30 mm and a length of 55 mm was clamped in a chuck where the tool touched the semi-finished product. This setting simulates the cutting process and thus creates a closed circuit.

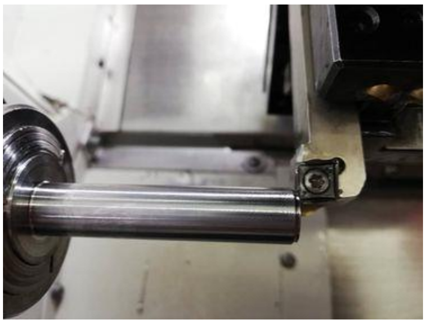

Fig. 14. Setting up the 42CrMo4 semi-finished product and tools

The measurements were performed on a semi-finished product with a length of 55 mm and in the direction of measurement X. As in the previous measurements, the coherence of the signals was checked. The resulting stability diagram and comparison of values is described below.

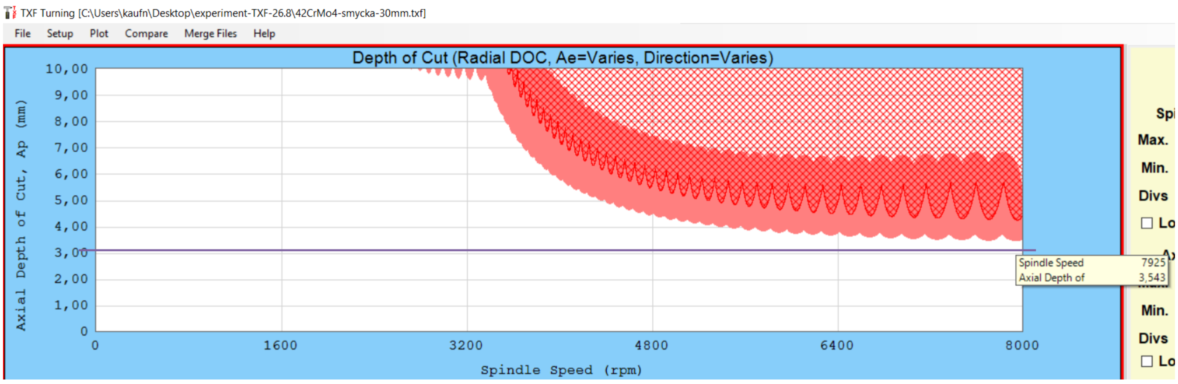

Fig. 15. Setting up the 42CrMo4 semi-finished product and tools

Subsequently, the b_{mez} between the measurement with a closed setting and with an open setting on a semi-finished product 42CrMo4 with a diameter of 30 mm was compared.

$$b_{mez\_clos} = 3.54\ [mm]$$
$$b_{mez\_open} = 4.34\ [mm]$$

The difference between the above values of the chip width limit is 1.2 mm. Furthermore, the resulting value of the chip width limit of the closed arrangement falls within the range given by the uncertainty of the chip limit width measurement calculated in the previous experiment.

$$\leq 3.04; 3.8 \geq$$

The semi-finished product made of 42CrMo4 material was further machined with cutting conditions, ap 0.5 [mm], vc 200 [mm / min], f 0.2 [mm / rev]. The measurement of the frequency response function was performed between each section with the measurement system closed. The semi-finished product was machined to a diameter of 11 mm where there was already an unpredictable self-excited oscillation.

4. Conclusion

The aim of this article is to find the optimal setting of the measuring set and measurement so that the resulting values of the stability diagram can be trusted. TXF Metalmax is software developed by an American company based on research by Tlusty [5], which examined the stability of the turning process. This software has been primarily developed for measuring the stability of the milling process, but it is also possible to select a turning process. For the turning process, no comprehensive measurement manual has been created by Metalmax and the setting environment is not user friendly. Therefore, this research deals with finding the optimal settings for this software and measuring set which builds on the previous article “Measuring Stability of the Cutting Process when Turning Using TXF Metalmax Software”.

This work is focused on the comparison of the measured values with the regenerative theory of self-excitation oscillations which creates a relationship between the spindle speed and the chip width limit. The experiments were performed on three semi-finished products. Each semi-finished product was made of a different material, namely C45, S235, 42CrMo4. The measurements were performed on an EMCO Maxxturn 25 turning centre. The semi-finished products were clamped in a chuck. The Kistler accelerometer was clamped at the free end of the semi-finished product and in the X direction. The input force was supplied by an impact hammer from Kistler. The measured values were processed using TXF Metalmax software. The first experiment shows that the chip limit value calculated with TXF Metalmax does not correspond to the calculated chip width limit using the mathematical formula derived from the cutting process.

The conclusion of the second part of the experiment is that the resulting value of the limit width for a closed setting is in the range ≤3.04, 3.8≥ and it follows that this setting is suitable for measurement. The 42CrMo4 semi-finished product was then machined with the selected cutting conditions. The FRF measurement was performed between each section with the measurement system closed. The semi-finished product was machined to a diameter of 11 mm where there was already an unpredictable self-excited oscillation. I explain this fact by inserting a unit specific cutting force (k_{c1}) into the software. But the specific cutting force changes with a change in the chip cross-section and, with a change in the rake angle, shifts the chip width limit, which the software does not allow. The output of this research is the TXF Metalmax software manual for the turning process.

5. Acknowledgments

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