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Experimental setup for long term high-precision static friction tests for clamping systems of rotary tables in cutting machine tools

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Abstract
The objective of the scientific investigation is the determination of the coefficient of static friction for clamping systems of rotary tables in cutting machine tools. New developments in this field of research are able to lead to an enhancement in tolerable cutting forces and machine accuracy or to the minimization of the required clamping forces and the constructed space too.
In this context the requirement profile of the investigated clamping systems is more than complex. Since they have an immediate influence on the machine accuracy only smallest movements between the friction partners in the range of a few micrometres are tolerable. Furthermore a clamping system needs to withstand more than 100,000 clamping cycles and also braking applications in case of emergency. Against this background an experimental setup consisting of two testing benches was developed. The first testing bench offers the possibility of quick measurements of the coefficient of static friction by a linear movement to investigate a high number of different samples for a selection process. The second test bench in addition offers the possibility of testing the relevant samples by a torsional load for more than 100,000 clamping cycles and in braking applications. In a study the two test benches are validated and compared against each other based on a state of the art clamping system of a tempered steel on the basis of the determined coefficients of static friction. In addition the results of the long term friction experiments and the observed wear are discussed.

friction enhancement, machine tools, wear, clamping systems, rotary axis, coefficient of static friction, friction test bench

1. Introduction

This article presents the results of investigations into clamping systems used to fix the position of rotary tables in cutting machine tools. An essential requirement is that even under the influence of the highest machining forces only smallest movements of the rotation axis take place.In addition they perform as an emergency brake in case of an accident. An increase in the tolerable frictional torques of the clamping system enables the realisation of higher machining forces, a reduction in constructed space or the use of alternative systems for normal force transmission with significantly reduced forces. This presents a complex tribological and design requirement profile:

- The permissible relative movement of the friction partners is limited to a minimum due to the direct influence on the machining accuracy. A limit of 5 µm was set for the investigations.
- Due to the largely static loading in normal cases, thermally induced tribochemical effects cannot be used to increase friction.
- The clamping system must still be fully operational after several braking operations (emergency stop).
- Contamination of the friction surfaces by cooling lubricants or hydraulic oil is possible and must be included in the considerations.

Due to this requirement profile, there are currently great uncertainties in the design of clamping systems with regard to the static friction values to be used. Against this background, a test methodology is presented in this article on the basis of an exemplary sample pair, which enables the determination of the coefficient of static friction for clamping systems in machine tools close to the application.

In the past, investigations have already been carried out to determine and increase the coefficient of static friction. According to Leidich [1], friction partners can already perform a relative movement in the order of magnitude of a few up to several hundred micrometres before the maximum frictional force is reached. Consequently, the relative movement of the friction partners must be taken into account when determining the coefficient of static friction. In [1], ground friction partners made of the material 42CrMo4 were examined. Here, at surface pressures of for example 30 N/mm², a coefficient of static friction of 0.2 could be determined in the initial test with a micro-slide distance of 10 µm.

Köhler [2] also carried out static friction tests with up to 250 cycles. Using the example of a pair of samples made of the material X5CrNi18-10, he was able to determine that the coefficient of static friction was subject to a periodic fluctuation between 0.1 - 0.4. Thus, coefficient of static friction is by no means constant and can change with the number of loads.

The test scenarios presented in the article represent an extension of the state of the art in science and technology. The test samples are loaded for more than 100,000 static clamping cycles while maintaining an accuracy limit (max. permissible relative movement) of 5 µm. Subsequently, five emergency stops are realised with the same test samples using an emergency stop scenario developed for this purpose. The following chapters present the developed static friction test benches and the exemplary results of a test procedure on a friction pairing made of the material 42CrMo4.

2. Sample setup

Two different test benches were developed to determine the coefficient of static friction: on the one hand, a linear static friction test bench which, due to the simplicity of the test samples and the short time required for the test procedures, allows a preselection from a large number of different friction pairs, and on the other hand, a rotational static friction test rig on which only the most promising friction pairs are to be tested in endurance tests with more than 100,000 clamping cycles and emergency stops.

The properties of the friction pairings examined in this article are summarised in Table 1.

Table 1. Experimental setup of the friction pairings

Property	Friction partner I	Friction partner II
Material	42CrMo4	42CrMo4
Hardness /HRC	45	30
Roughness R_z/µm	6.3	6.3
Final machining	grinding	grinding

The geometry of the test samples was adapted to the respective test benches. The alignment of the grinding grooves was done as shown in Fig. 1.

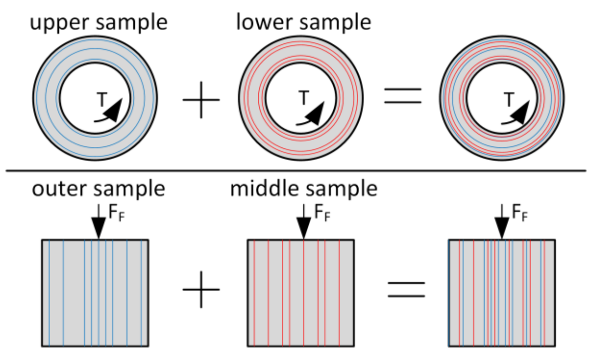

Figure 1. Orientation of the grinded surface structure (colored) for the samples at the rotatoric (top) and linear (bottom) friction test bench

All experimental investigations were carried out at a surface pressure of 20 N/mm².

3. Linear friction test bench

3.1 Setup of the linear friction test bench

On the linear static friction test bench, after applying a defined normal force F_N, a centre sample is moved relative to two floating outer samples under the action of the shearing force F_s (Fig. 2).

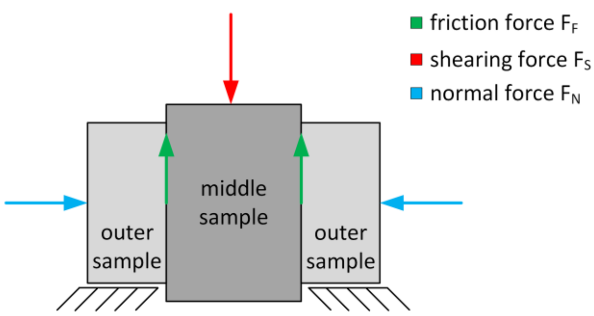

Figure 2. Arrangement of the samples at the linear friction test bench

During an experiment, the shearing and normal forces are continuously recorded. By means of an indirect displacement measurement system, the displacement of the centre sample to the outer sample is determined. Subsequently, based on the evaluation routine according to [1], the coefficient of static friction is determined at a micro-sliding distance of 5 µm. In the case of the applied surface pressure of 20 N/mm², a maximum static friction value of 1.2 can be measured. For the pre-selection between different test samples, test scenarios were developed which should simulate the relevant loads of clamping systems as best as possible within the possibilities of the test bench. Their procedure and results are presented in the following chapter.

3.2 Results of the linear friction test bench

To determine the coefficient of static friction in the initial test, the centre sample is loaded with such a high frictional force after the application of the surface pressure of 20 N/mm² that macroscopic sliding (>> 5 µm micro-sliding distance) begins. Subsequently, the coefficient of static friction at a micro-slide distance of 5 µm is determined on the basis of the recorded force-distance curve. The results of the coefficient of static friction in the initial test are shown for three different, new friction pairings in Fig. 3.

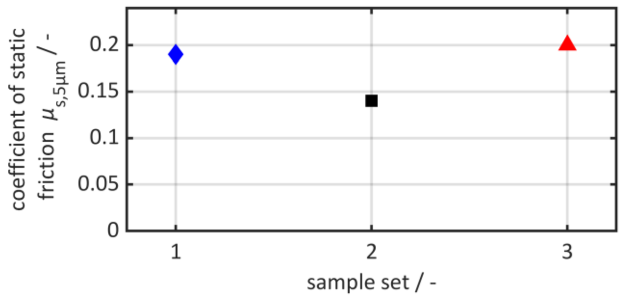

Figure 3. Coefficients of static friction of 3 different sample pairings at the linear friction test bench

The determined coefficients of static friction $\mu_{s,5\mu m}$ fluctuate in a range from 0.14 to 0.20. The cause for the low value in the first test of sample set 2 is assumed to be particularly protruding roughness peaks, which disturb the micro-contact of the friction partners and fail plastically at an early stage.

Subsequently, friction pairing 2 with a coefficient of static friction of $\mu_{s,5\mu m}$ = 0.14 was used for further experiments. The test procedure for determining the coefficient of static friction was carried out a total of 25 times. This corresponds to a repeated massive overload of the clamping system. Between the experiments, the normal force was reduced and increased again, which corresponds to an opening and closing of the clamping system. This resulted in the course of the coefficient of static friction $\mu_{s,5\mu m}$ shown in Fig. 4.

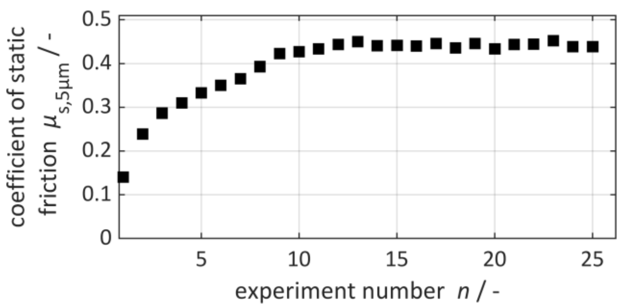

Figure 4. Coefficient of static friction $\mu_{s,5\mu m}$ of sample pairing 2 in 25 experiments at the linear friction test bench

The sample pairing shows an increase in the coefficient of static friction $\mu_{s,5\mu m}$ from 0.14 to a maximum value of 0.45 with increasing number of experiments, which is reached almost constantly from the 12th experiment onwards.

Friction pairing 2 was then used to simulate ten regular clamping processes. During the regular clamping process, the friction pairing was loaded with 80 % of the maximum static friction value determined in the course of the 25 experiments. This corresponds to a load limit of the coefficient of static friction of $\mu_S = 0.36$. During the ten regular clamping processes, the friction pairing remained below the permissible micro sliding distance of 5 µm.

Finally, friction pairing 2 was tested under contamination by hydraulic oil. The basic test procedure corresponded to the triple execution of a static friction experiment until the onset of macroscopic sliding (>> 5 µm). The results are shown in Fig. 5.

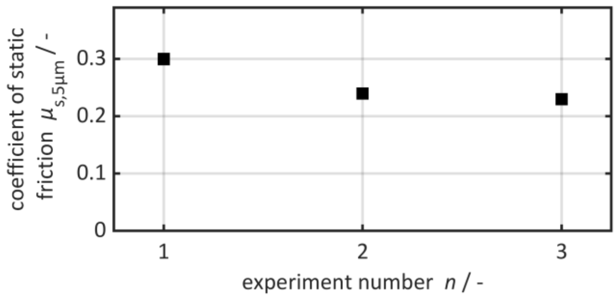

Figure 5. coefficient of static friction of a 42CrMo4 sample pairing in 3 experiments with lubrication by hydraulic oil at the linear friction test bench

Within the three experiments conducted, a reduction in the coefficient of static friction $\mu_{S,5\mu m}$ from an initial value of 0.30 to a value of 0.23 could be determined. This is due to the reduction of the adhesive interactions of the friction partners by the hydraulic oil. The friction surfaces were completely wetted with an oil film after the three static friction experiments. At the same time, the results show that a determination of the coefficient of static friction under the influence of lubricants should be based on at least three follow-up experiments.

4. Rotatoric friction test bench

4.1 Setup of the rotatoric friction test bench

On the rotational static friction test bench, two rotationally symmetrical test samples are rotated in relation to each other after applying the normal force F_N under the influence of a torque T (Fig. 6).

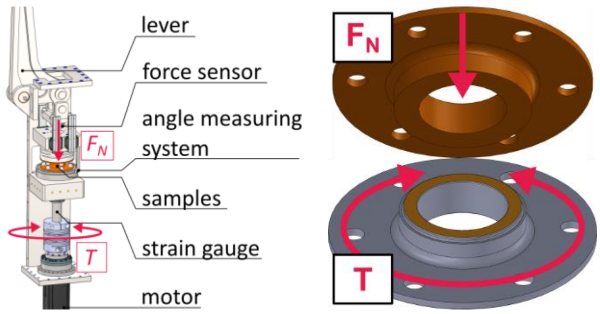

Figure 6. Rotatoric friction test bench and upper (friction partner I) and lower sample (friction partner II)

A force sensor, which is located directly in the normal force flow, is used to measure and control the normal force. A strain gauge full bridge is applied to the sample shaft to measure and control the torque. The relative rotation of the samples to each other is recorded by an optical angle measuring system. With this measuring system, smallest relative rotations of up to 1 µm in relation to the average diameter of the test samples of 62.5 mm can be measured. The design of the test bench was based on a surface pressure of 20 N/mm². The test bench is capable of applying torques of up to 780 Nm. In conjunction with the specified sample geometry, a coefficient of static friction of up to 0.8 can be reproduced.

A regular clamping process starts when the contact is opened. The rotation axis positions to a stochastic position with friction partner II. The clamping system is then closed and the surface pressure of 20 N/mm² is built up. Then the continuous torque is applied while measuring the sample rotation and held for 5 seconds. Finally, the torque is reduced again and the clamping system is opened, followed by the next clamping cycle at a new clamping position.

4.2 Results of the rotatoric friction test bench

At the beginning of the investigations on the rotational static friction test bench, a coefficient of static friction $\mu_{S,5\mu m} = 0.19$ was determined in the initial test for a new set of samples (Table 1). This corresponds to a torque $T_{max} = 245$ Nm. With 80 % of this torque, i.e. a value of 196 Nm or $\mu_S = 0.15$, the first endurance experiments were started. At the beginning of the endurance tests, a micro slideway of approx. 3 µm was found. But already after the 42nd experiment, the sample pairing exceeded the specified accuracy requirement of 5 µm (Fig.7).

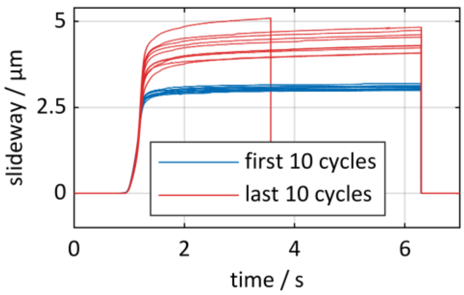

Figure 7. Microsliding of the 42CrMo4 friction partners depending on the applied friction tourque compared for the first ten and last ten loading cycles

This meant that it had to be determined that the sample pairing could not be used in the long term under the continuous torque used.

Against this background, the micro slideways of the first ten cycles (n = 1...10) and the last ten cycles (n = 33...42) were compared. It was found that the torque-displacement curves separate at a friction torque of around 105 Nm, which corresponds to a coefficient of static friction μ_S of 0.08. From this torque onwards, a reduction in the stiffness of the frictional connection can be assumed with repeated loading, which indicates plastic damage to the surfaces of the friction partners. Against this background, a further series of endurance tests was carried out with a new set of samples at the newly determined endurance torque of 105 Nm. The friction pairing showed an almost constant micro sliding distance of about 1.3 µm over 106.363 load cycles and can therefore be described as fatigue resistant. With reference to [2], it can thus be stated that a periodic fluctuation of the coefficient of static friction does not occur with a predominantly elastic deformation of the roughness structure of the friction partners.

Based on the knowledge gained, a final test plan summarised in Table 2 was defined for the third sample pairing. In addition the average diameter of the samples was slightly reduced from 65 mm to 62.5 mm, whilst the surface pressure remains constant, to have more backup for torque load during the emergency stops. Hence the torques to follow also are slightly reduced.

Table 2. Final testing procedure at the rotatoric friction test bench

step	procedure
1	100,000 clamping cycles at a longterm torque of 105 Nm every 10,000 clamping cylces determination of the torque at a micro sliding path of 5 µm
2	5,000 clamping at 80% of the new maximum torque
3	1st emergency stop
4	2,000 clamping cycles
…	…
11	5th emergency stop
12	2,000 clamping cycles

Accordingly, the third pair of samples was also loaded with a continuous torque of 105 Nm over the 100,000 clamping cycles. In addition, the coefficient of static friction $\mu_{s,5\mu m}$ (Fig. 8) was determined every 10,000 clamping cycles by increasing the torque until a micro slide distance of 5 µm was achieved. The endurance torque was not changed.

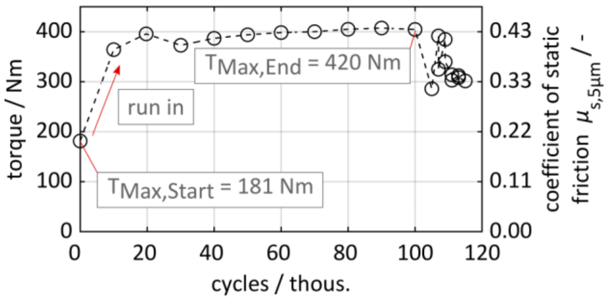

Figure 8. Coefficient of static friction $\mu_{s,5\mu m}$ of the third 42CrMo4 sample in 100,000 loadcycles and after the emergency stops

Analogous to the linear static friction test bench, a significant increase in the coefficient of static friction $\mu_{s,5\mu m}$ could be demonstrated. The sample pairing reached a coefficient of static friction $\mu_{s,5\mu m}$ = 0.43 from the 20,000th clamping cycle. At the end of the endurance tests, the fatigue strength was successfully confirmed in 5,000 further clamping cycles at 80 % of this maximum coefficient of static friction, i.e. at a coefficient of static friction μ_S = 0.34. Furthermore, the surfaces of the friction partners did not show any significant, visually recognisable change. It was not possible to measure the surfaces at this stage, as removal and installation of the samples from the test rig was to be avoided. The cause for the running-in behaviour and the associated increase in the coefficient of static friction is assumed to be primarily a mutual adaptation of the surface fineness of the friction partners and is to be investigated in more detail in further work.

Following the endurance tests, the same pair of samples was used to perform the five emergency holds, each with 2,000 intervening regular loads at a torque of 105 Nm. During the emergency stops, the samples were twisted against each other under a surface pressure of 20 N/mm² until a friction work of ~70 J was performed. Sliding paths in the range of 2.9 to 3.4 mm were observed. The measured coefficient of static friction before and after the emergency stops are also shown in Fig. 8. In general the coefficient of static friction drops with the emergency stops. However, it could be determined that after the first two emergency stops, the sample pair reaches a coefficient of static friction almost at the initial level at the end of the endurance tests within the 2,000 regular clamping cycles. From the third emergency stop, the coefficient of static friction $\mu_{s,5\mu m}$ drops to a value of around 0.33, as massive damage to the friction surfaces has obviously taken place. For this reason, the surfaces of the friction partners were measured after the 5th emergency stop (see Fig. 9).

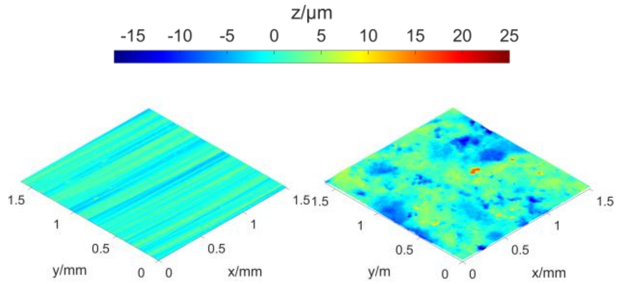

Figure 9. Surface of the 30 HRC sample in new condition (left) and after testing at the rotatoric friction test bench (right)

The surfaces show considerable adhesive wear after use, which was to be expected for a dry metal-on-metal friction pairing [3]. The original shape of the ground surface can no longer be found. Material has been torn from the surfaces of the friction partners, which can be found in the form of individual particles on the friction partners. These particles presumably contribute to a further disturbance of the contact between the two friction partners.

5. Summary

In this article, a test methodology was presented for the determination of durable coefficients of static friction for clamping systems in machine tools. Using an accuracy limit of 5 µm, a friction pairing made of the material 42CrMo4 was examined on a linear static friction test bench and on a rotary static friction test bench. The results of the two test benches show a high degree of agreement. It was determined during the experiments that a permanent coefficient of static friction of $\mu_{s,5\mu m}$ = 0.08 can initially be assumed. However, through a running-in process in a defined load regime, the coefficient of static friction can be increased to a permanently fixed value of $\mu_{s,5\mu m}$ = 0.34. Within the scope of the emergency stops, a critical wear behaviour of the friction pairing was shown in the form of strong adhesive wear, combined with a drop in the coefficient of static friction. Against this background, based on the test methodology developed, further experimental investigations are to be carried out on new types of friction pairings with the aim of achieving high coefficient of static friction from the first clamping process onwards as well as insensitivity to emergency stops in order to enable the design of clamping systems with significantly higher clamping torques. Results will be published accordingly in a timely manner.

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