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Safety of machinery - Proposals for an improved workpiece clamping in machine tools and its implementation in product safety standards

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The precise alignment of the clamped tool and workpiece is crucial to ensure precision and reproducibility in production. Modern CNC (Computerised Numerical Control) technologies enable automated control of these machines, allowing complex parts to be manufactured with high precision and efficiency. This process is critical in various industries, including automotive, aerospace, medical and many others, where high-precision metal parts are required. In doing so, the safety of workpiece clamping is of crucial importance in metalworking and other manufacturing processes. Improper workpiece clamping can lead to dangerous situations that can cause both personal injury and property damage. Various safety precautions are taken to ensure the safety of workpiece clamping, including the use of safe clamping devices, regular maintenance and inspection, operator training and adherence to safety guidelines. CNC machines may also be equipped with sensors and safety devices to detect unusual vibrations or movements and automatically shut down the machine in the event of a problem. The reliability of workpiece clamping when turning without support elements is particularly dependent on the clamping force applied and the process loads on the lathe chuck. It is therefore essential to correctly determine the process-dependent minimum clamping force required and to ensure that it is maintained during the process. The latter is addressed by innovative sensory jaws, which make it possible to record and control the clamping force in the clamping and turning process. As a guideline, instructive regulations exist for determining the clamping force of jaw chucks. In the Research Institute of the German Machine Tool Builders' Association (VDW), the interactions between the process, workpiece and clamping system were analysed in detail with the help of innovative measurement concepts using sensory jaws, and improved instructional specifications were derived.

Keywords: Safety, reliability, machine tools, workpiece clamping, sensory jaws, product standards

1. Workpiece clamping in machine tools

The technology of machine tools for metalworking, such as lathes or milling machines, is based on the precise alignment of a clamped tool and a clamped workpiece so that the target contour of the workpiece is produced by machining. The principle of machining removes excess material from the workpiece to achieve the desired shape. On lathes, the workpiece is clamped in a rotating position while the tool moves linearly. This enables the production of cylindrical parts, cones, threads and other rotationally symmetrical shapes. The tool cuts the material and the rotation of the workpiece creates the desired contour. In milling machines, the tool is set in rotation while the workpiece is moved linearly. The tool cuts off material and shapes the workpiece according to the desired contour, again. Milling machines are used to create flat surfaces and complex 3D shapes. The precise merging of the clamped tool and workpiece is crucial to ensure precision and reproducibility in production. Modern CNC (Computerized Numerical Control) technologies enable automated control of these machines. This technology is critical in various industries, including automotive, aerospace, medical and many others, where high-precision metal parts are required. The safety of workpiece clamping is of great importance, some reasons for this are:

1.1. ***Avoiding accidents***: Insufficient or unsafe clamping of the workpiece can cause it to come loose or be ejected during processing. This can result in serious injury to the operator or other persons present.

1.2.***Precision and quality***: proper workpiece clamping not only ensures safety, but also precision in production. If the workpiece is not securely clamped, this can lead to inaccurate machining results, which affects the quality of the parts.

1.3.***Avoiding machine damage***: improper clamping can also lead to damage to the machine tools. Loose or faulty clamping devices can cause vibrations and uneven loads, which in turn can damage the machine.

1.4.*Compliance with regulations*: In many countries and industries, there are strict regulations and standards for the safety of machine tools. Compliance with these regulations is not only required by law but is also crucial to ensure that the working environment is safe.

Fig. 1. Chuck and quill with 600 kg workpiece, source: A.Monforts, Mönchengladbach

2. Protection against released parts

Various safety precautions are taken to ensure the safety of workpiece clamping, including the use of safe clamping devices, regular maintenance and inspection, operator training and adherence to safety guidelines. CNC machines may also be equipped with sensors and safety devices to detect unusual vibrations or movements and automatically shut down the machine in the event of a problem. The final contribution of the 3-step method of risk reduction according to the ISO 12100 (2010) risk guidance standard are (separating) guards: To reduce the risks from released workpieces, this paper discusses some aspects of safe workpiece clamping. This includes probability values that can be tolerated as a maximum for a failure of the relevant control chains. Conversely, this leaves certain expected frequencies of released workpieces in the operational environment. These frequencies can be estimated using the individual failure probabilities multiplied by their numerical presence in a basic population to be considered. For example, all lathes that were operated in the Federal Republic of Germany in a period under consideration, last record of DGUV (2022).

Fortunately, however, the number of accidents caused by released workpieces on machine tools is very low, far lower than the relative frequencies estimated above. This is shown by the decreasing number of accidents over the last 30 years in Figure 2. However, if the workpiece clamping fails, the consequences are serious, see section 2.1.

The reason for the lower frequency of accidents is that there is a typical frequency distribution in the accident pyramid, as shown in Figure 3. The number of so-called “near-accidents” (e.g. with only property damage) is orders of magnitude higher than accidents (with personal injury). In the pyramid, there are around 13 near misses for every personal injury, which form a kind of intuitive “warning mechanism”. There are various reasons for this ratio, such as the fact that there are no machine operators in the vicinity of highly automated machines most of the time. Another reason is the complex motion sequence of a possibly released workpiece, in which dangerous directions of movement towards the operator's position do not always occur, see Bold (2004). For metalworking machine tools, it is a proven effective principle to protect the operator completely from released fragments by means of a properly dimensioned full enclosure (according to a certain failure hypothesis with corresponding masses, energies). And this design convention protects the operator at least at least partially from entire released workpieces, but certainly not all.

2.1 *Need for action as indicated by accidents*

The evaluation of accident figures for production machines shows that after years of declining accident figures, stagnation is occurring (Mödden 2018). The accident statistics of the BGHM (German Occupational Safety Organisation for metalworking machines) also show that the cause of fatal or serious accidents is very often the loss of workpieces. In most cases, an inadequate clamping situation was the cause (Kesselkaul, Meyer 2016). The accident figures mentioned above are proof that the real situation is not satisfactory.

2.2 *Research on separating guards*

When it comes to reducing the risk of hazards from the work area, safety doors and vision panels are of considerable importance; the generic term for this is “guards”. Since the 1980s, design and dimensioning recommendations for guards on machine tools have been continuously investigated at TU Berlin in a particularly well-equipped ballistic test laboratory (Bold 2004).

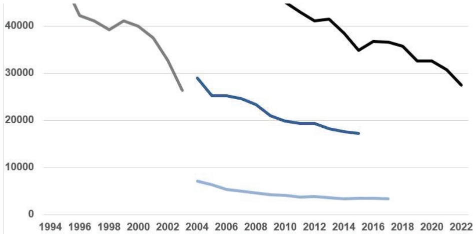

Figure 2: Reportable accidents involving machine tools from 1993 to 2022 (Sources: HVBG and DGUV)

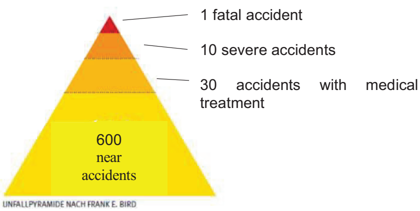

Figure 3: Accident pyramid (source: Arbeit und Gesundheit magazine 4/2023, aug.dguv.de)

Two research projects are currently being carried out there. The DGUV's testing institute, the IFA in St. Augustin, has a similarly long history and continues to carry out impact tests to determine the withstand capability of safety doors, vision panels and elements of a full enclosure. Both competence centers have contributed valuable results to the safety standards for machine tools. The focus here is on so-called failure hypotheses.

2.3 *Failure hypotheses for machine tools*

Since the introduction of the Machinery Directive in 1995 (update in 2006), it has been a declared aim of safety standardization to provide designers with uniform dimensioning recommendations. So-called "failure hypotheses" have proven their worth for the following key standards:

a) ISO 16090-1 for milling machines: Milling cassette in the cutter head is released.
b) ISO 23125 for lathes: Top jaw of the three-jaw chuck on a lathe is released.
c) ISO 16089 for grinding machines: A ceramic grinding tool disintegrates, releasing a worst-case "third-part fragment".

On the last point, there is a fruitful collaboration with a Japanese ballistic testing laboratory in Tokyo, see Figure 4 and Yui (2016).

These failure hypotheses are based on empirical values from the operational environment. The focus is on the question: What maximum loads are likely to be expected in the event of an impact event from the working area.

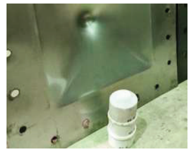

Figure 4: Example of a passed impact test, material sample and projectile, source: JMTBA, Japan

Dimensioning recommendations are derived from this. These also cover a certain proportion of released workpieces, although such an dramatic event can only be technically controlled to a limited extent. It is therefore always better to prevent the release of workpieces with all available technical (e. g. "iJaws") and instructional safety measures.

2.4 *VDW supports new standards projects*

2.4.1 *Design conventions for guards*

A new standardization committee (NA 122-10-10 AA, 2024) was founded at the beginning of this year in the DIN standards committee for machine tools in the "Safety" department. The aim of the committee is to draw up or further develop standards and/or specifications that deal with the design and dimensioning of guards on machine tools. Extensive new findings are available on the performance of tests and the statistical interpretation of the results, which are primarily of importance for the test laboratories where impact tests are carried out. However, designers have also gained new insights into the application of the standard specifications, for example with regard to the combination of different technologies in one machining center. This requires minor adjustments in the standards to the design conventions that have been in place for more than 20 years. Backwards compatibility is particularly important in order to maintain a successful design practice overall. However, dealing with the operational ageing problem of polycarbonate protective screens is a common issue for all types of machinery. In 2023, a compilation startet on the state of the art for design conventions, it ought to become a technical specification by ISO entitled "Design conventions for guards on machine tools". Its focus is on a revision of the test specifications for impact tests. This research area has developed significantly, for example in terms of the statistical evaluation of a overwhelmingly complex test technique.

2.4.2 *Standardization for workpiece clamping*

The German mirror committee NA 122-08-01 AA "Workpiece spindles and lathe chucks" is currently revising ISO 16156 (2004). The safety measures have the purpose to eliminate or at least reduce risks when clamping workpieces by means of technical safety requirements and protective measures. Extract from ISO 16156:
"*This document was developed to ensure the general safety of machine tools, such as lathes, milling machines, machining centers and others. It can be used as a reference to describe specific health and safety requirements for machine tools. … This document deals with the significant hazards, hazardous situations or hazardous events that apply to clamping devices when used as intended…*"
In addition, the type C product standards for machine tools contain detailed specifications for the functional safety and operational safety of workpiece clamping, e. g. ISO23125 (2015). It is important to precisely define the respective safety functions (i.e. triggering event, signal processing, safety-related reaction); and to select requirements for component quality etc. based on industry-specific operational experience that are actually available on the market. This always results in very complex considerations ranging from a overall risk assessment to the tolerable residual risk (with transfer to user responsibility) of a specific technical solution for the specific aspects of machine tools.

3. Research activities of the VDW on safety

3.1 *Functional safety in machine tools project with the IFA (St. Augustin)*

With the introduction of ISO 13849-1 (2023), the "category" as the previously relevant parameter for risk reduction has been replaced by the more complex "Performance Level" (PL). The now required quantitative determination of the PL represents an additional effort during development on the one hand, but on the other hand can also open up new design possibilities.
How the new requirements for common machine tool components can be technically implemented was presented in a VDW working group for the safety function "Workpiece clamping on lathes". The particular difficulty identified was the modelling of a safety-related block diagram and the calculation of the probability of a dangerous failure. For the necessary abstraction of a real system into a safety-related block diagram, designers need practical suggestions, for example universally agreed examplary solutions, which enable the designer to use analogy conclusions and simple parameter adaptations to evaluate the safety of the many different safety-relevant functions in machine tools probabilistically and in a reasonable amount of time. In the VDW research report "FWF Project 3501 Functional Safety in Machine Tools" (2011), numerous sample solutions for typical safety functions in machine tools are compiled, for example for the safe clamping of workpieces, an excerpt of which is shown in the electronic control of the hydraulics in Figure 5:

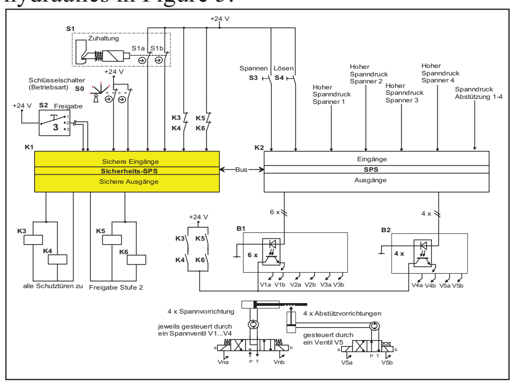

Figure 5: Circuit diagram for safe workpiece clamping on the machining center

3.2 *Exemplary calculation with the BGHM*

In 2014, VDW also developed an exemplary calculation for safe workpiece clamping for lathes and agreed it with the German Employers' Liability Insurance Association (BGHM, Mainz). The starting point was the lathe shown in Figure 1 from DGUV-BGHM (2022). Figure 6 shows some safety functions, the reliability of which was assessed according to the state of the art using the methods of ISO 13849-1. This includes design documents, see principle circuit for a hydraulic chuck in Fig. 7.

3.3 *Work with the University of Wuppertal*

In 2013 and 2014, project work was carried out for the VDW, whereby a manufacturer of lathes provided access to its machine data over a long period of time, see Guennel (2014). The aim was to quantify the reliability and safety of clamping

	Spindle n [rpm]	Reaction in case of failure
SF1	n>0	Spindle stop
SF2	n=0	Prevention of spindle start
SF3a	n>0	Spindle stop when electrical failure occurs.
SF3b	n=0	If failure of power supply occurs, a spindle stop follows as soon as possible

Figure 6: How the safety functions work (example)

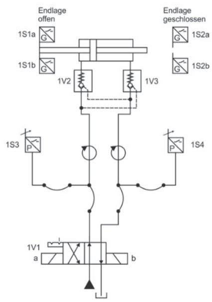

Figure 7: Schematic diagram of hydraulic chuck

functions in an operational environment. If possible, a "proof of operational reliability" was to be developed in order to fulfill the requirements of ISO 13849-1/2. Figure 8 shows the evaluation of the failure behaviour of a clamping function (i.e. relevant machine data records were evaluated, on the basis of so-called fault codes.) and compares it with model hypotheses (e. g. Weibull distribution).

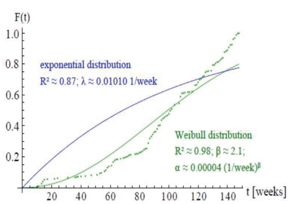

Figure 8: Clamping failure probability

3.4 *Cooperation with the TU Chemnitz*

Since 2016, there has been a partnership between the VDW and the Technical University of Chemitz on safe workpiece clamping.

3.4.1 *User study on human reliability*

In order to better assess human reliability as the greatest weak point of the MMI "workpiece clamping for vertical turning", investigations of human (erroneous) actions were necessary. The operator working errors were therefore practically quantified during the clamping process, which can lead to incorrect assembly states and ultimately to accidents.

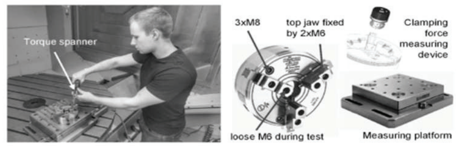

Figure 9: Testing of chuck and measurement rig

3.4.2 *Research project „MTZ-Dreh"*

Subject of "MTZ-Dreh" was "Recording and comparability of human and technical reliability for improved workpiece clamping during vertical turning". The aim of the research project was to develop a new assessment method of the cause-effect relationship in the event of possible workpiece clamping failures using the example of vertical turning in order to significantly increase machine safety by means of improved operator instructions. In the project, the clamping device behavior was investigated experimentally, taking into account technical safety-relevant parameters and human reliability. The aim is to understand why instructions are often not effective enough and why accidents still occur. The solution approach therefore focuses not only on technical reliability, but above all on human reliability. The essential new approach is the use of real statistical data, which was determined in empirical user studies on the clamping process of workpieces.

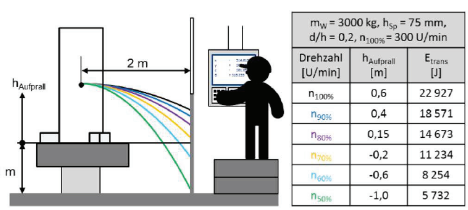

Figure 10: Characteristic map for speed reduction to reduce the impact height

3.4.3 *Qualified measurement concept for in-process analysis of workpiece clamping*

As part of the VDW study "SensoSpann", the Technical University of Chemnitz investigated the properties of sensory clamping jaws and the speed-dependent change in the clamping state of a three-jaw chuck using an in-process measurement concept. One aim is to avoid an inadequate clamping effect through sensor monitoring. Until now, one of the main obstacles to electrical monitoring of the workpiece clamping system has been the rotation of the rotary table, which makes it difficult to transmit electrical signals. The sensor-integrated clamping jaws “iJaws” presented by Röhm at the EMO Milan 2021 trade fair address this problem. They can be used to continuously measure the clamping force 1. before (stationary state) and 2. during turning (dynamic state). Checking the actual clamping force before machining offers the possibility of upgrading the current state of the art. Up to now, pressure and travel of the usual clamping jaws have been monitored for this purpose, as shown in Fig. 7. This is associated with an annoying recurring experience, namely that a lack of maintenance of the chuck (such as cleaning and lubrication) results in an increasing loss of clamping force with the time of use, which can eventually lead to a loss of the workpiece. For this reason, end customers of machine tools repeatedly complain to manufacturers when workpieces are released (luckily very rare, usually with only material damage). The manufacturer's on-site inspection of the user then usually leads to the cause of insufficient lubrication of the chuck, which is responsible for the loss of clamping force, i.e. an operational problem and not a design defect. On this background, an important aspect of the new diagnostic options of the “iJaws” in a stationary state is therefore to measure the actual clamping force before the workpiece spindle starts to rotate. This is because a loss of clamping force due to insufficient lubrication of the chuck (or due to contamination or wear) would then be detected in good time before the workpiece is released (due to insufficient clamping force). This is hardly ever used at present. Real-time monitoring during machining (dynamic state) can also detect deviations from set values and initiate measures (e.g. stopping the rotary movement) to prevent workpiece release or crushing of the workpiece due to insufficient or excessive clamping forces, at least in part.

A central objective of the study was therefore to analyze and test the “iJaws” with regard to their suitability as a measuring device and the comparability of the clamping-relevant properties with conventional standard clamping jaws. It was shown that the clamping forces can be measured with a high degree of accuracy using the “iJaws” (see Figure 11 with the test setups).

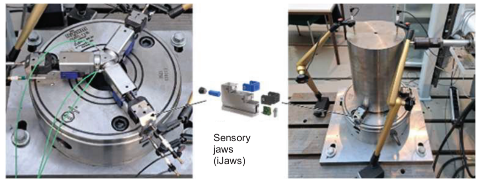

Figure 11: Test setup for clamping force adjustment and deformation analysis (left) and determination of the limit tilting moments (right), TU Chemitz laboratory.

The periodic clamping force fluctuations, which are caused by the cutting force and the workpiece rotation, were successfully measured for each clamping jaw (see Figure 12, bottom right). In order to examine the influence of the rotational speed on the clamping effect, the clamping force amplitudes at the beginning and end of the turning operation were compared at different rotational speeds and with the same cutting forces (Figure 12). In Figure 13, a diagnosis option for non-round workpieces is illustrated.

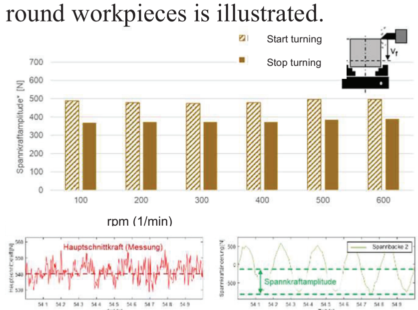

Figure 12: Average values of the clamping force amplitudes related to the cutting force

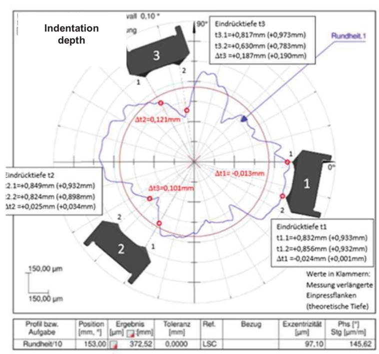

Figure 13: Test setup with non-round blank and measurement protocol

3.4.4 *Reliability requirements for diagnostics during workpiece clamping*

For more than twenty years, monitoring the clamping pressure and the clamping stroke before starting the rotation of the workpiece spindle has proven to be a reliable way of clamping rotating workpieces on lathes. The spindle can only be started if both parameters are within the tolerance window. There are detailed considerations on the functional safety of the relevant control chains (see IFA 2011). These have also been incorporated into the product safety standards. It has recently been considered to bring these complex interrelationships into the wood working machines using “artificial intelligence” (AI) see Schroeder (2022). If the functional safety of the “iJaws” is high enough, then it would be possible to replace the conventional path query for workpiece clamping via the “iJaws”. This raises the question of how reliable autonomous “AI functions” must be as a minimum, see Figure 13. The VDW's “Safety Technology” working group is currently investigating how a performance level of PL=b can be achieved for the “iJaws”; this would correspond to the reliability of the chuck pressure and stroke monitoring currently used.

	A	$\overline{A}$
B	$P(A \cap B)$	$P(\overline{A} \cap B)$
$\overline{B}$	$P(A \cap \overline{B})$	$P(\overline{A} \cap \overline{B})$

Figure 13: Probabilities of a hypothesis test

As shown in Figure 13, when monitoring the workpiece clamping, a state $\boldsymbol{A}$ (clamping state is safe) can be correctly detected, i.e. the diagnosis $\boldsymbol{B}$ (safely clamped) with a probability of $\boldsymbol{P(A \cap B)}$; this so-called “specificity” should be as high as possible. However, a supposed diagnosis $\boldsymbol{B}$ can always be displayed incorrectly if the complementary condition $\overline{\boldsymbol{A}}$ (clamping condition is not safe) is actually present; this requires a probability of $\boldsymbol{P(\overline{A} \cap B)}$; this should be as low as possible. In the same way, it is always possible that a state $\overline{\boldsymbol{A}}$ (clamping status is not safe) can be displayed correctly; this is the diagnosis $\overline{\boldsymbol{B}}$ (failure of clamping) with a probability of $\boldsymbol{P(\overline{A} \cap \overline{B})}$; this so-called “sensitivity” should also be as high as possible. However, a supposed condition $\overline{\boldsymbol{A}}$ with the diagnosis $\overline{\boldsymbol{B}}$ can always be displayed incorrectly if the complementary condition $\boldsymbol{A}$ is actually present; this requires a probability of von $\boldsymbol{P(A \cap \overline{B})}$; this should be as low as possible.

3.5 *Cooperation with the TU Stuttgart*

3.5.1 *Proof of operational reliability for safe workpiece clamping*

A full enclosure dimensioned in accordance with the standard offers a high level of protection against most malfunctions in the work area. Figure 14 shows a typical full enclosure of a lathe that has been designed in accordance with the aforementioned dimensioning recommendations. In addition, there is an operational reliability study by the Technical University (TU) of Stuttgart, which uses field data to prove the safety of the operator from released workpieces or other parts from the work area over a very long period of time (Nowizki, 2016). The results from the field data were compared with ISO 13849-1. This standard assumes a service life of 20 years; this means a maximum machine service life of 175,200 hours. For this period, an exponential distribution for the failure behaviour can be assumed as a simplification. A Weibull distribution was also considered in the study. In the relevant guiding standards for proof of operational reliability, a confidence level of at least 70% is specified; this was adopted here as a one-sided upper confidence level.

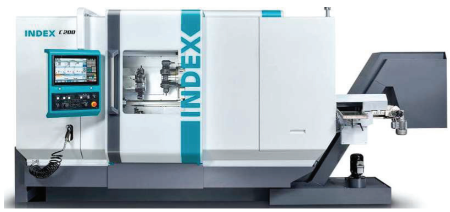

Figure 14: Automatic lathe with closed safety door and viewing window into the work area, source: INDEX

An event density function was determined that matches the field data. From this, it was possible to estimate a reliability of the clamping function of approx. 99.3% over the intended period.

3.5.2 *Force prediction for the design of workpiece clamping*

The basis for the collaboration was a project at the TU Stuttgart entitled: “Force prediction for the design of workpiece clamping (ProSpann)”. This project was completed in Gutsche (2023). The aim of the project was to provide prediction methods for the design of safe workpiece clamping when using innovative turning processes. These novel turning processes are characterized by force vectors that deviate from standard processes in terms of both magnitude and direction. Machining tests were carried out to determine the acting force collectives. The series of tests to determine the influence of clamping parameters (clamping force, tailstock force) on the dynamic component behaviour under cyclic loading were successfully completed, and calculation methods for the 3-jaw chuck are known from the literature and standardized in the form of VDI 3106.

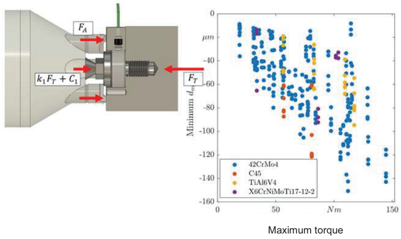

Figure 15: Force and Torque measurements (Gutsche)

4. Summary and outlook

With the newly developed measuring concept for in-process analysis of workpiece clamping ("iJaws"), the clamping force and the effects of the process forces on the jaw clamping forces can be quantified and assigned to their cause.

The safety of workpiece clamping will remain an important topic in the future. For example, a workshop will be organized by VDW at EMO in Hanover in September 2025 with the international suppliers of workpiece clamping devices represented there, see https://emo-hannover.com/. Also, further research projects are therefore already being prepared in Stuttgart and Chemnitz. Work can begin as soon as funding has been secured. Relevant results are going to be presented at future ESREL conferences.

Acknowledgement

During the long period of VDW research on workpiece clamping in machine tools, many experts have made valuable contributions. In addition to the authors named in the following list of references, special thanks are given to Dr. Alexander Broos from the VDW for making the basic research possible, and to Martin Stangl from Röhm for providing test equipment and internal results for the laboratory test with "iJaws".

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