Enhancing Reliability and Service Life Predictions through Friction Monitoring during Assembly Process

Bolt Tightening Process Independent of Coefficient of Friction

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1 Introduction

Electrification leads to a high interest in electrical contacts. Battery or Hydrogen **Electric Drivetrains, E-Scooters and E-Bikes** become increasingly popular. In December 2022, the share of battery-electric and plug-in hybrids in newly registered cars in Germany rose to more than 55%.

Every electric vehicle relies on numerous electrical high current contacts. Therefore, appropriate design with **energy efficiency, performance**, and the highest reliability, especially in high current contacts, is essential.

However, there remain areas for the use of green synthetic fuels. **Hydrogen** is considered one of the most promising energy sources of the future. Green Hydrogen generation and Fuel-Cells are based on electrochemical processes and on many **electrical contacts**.

Furthermore, trends toward **automation** not only aim to enhance energy efficiency but also demand enhanced **reliability** in tribological contacts. In autonomous systems, these contacts must perform their functions seamlessly throughout their lifecycle or autonomously **detect and communicate** any deviations. Anomalies previously detected by the observing operator.

This manuscript delves into systematic decision-making by highlighting and rating different solutions. The focus is on tribology in electric vehicle connections and ensuring robust performance and reliability. Based on these and other requirements, the **best type of contact** must be chosen.

2 Requirements and Design-Possibilities

In engineering, decisions about the best design solution are made very early in the design process. The importance of making robust design decisions early in the engineering process is emphasized due to the costly and risky nature of late changes or failures. This is often visualized using the cost rule of 10. As a first step, key electrical contacts are shown in Figure 1.

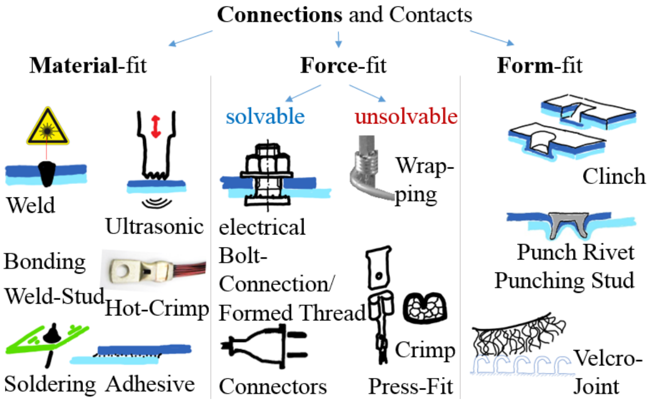


Figure 1: Connections and Contacts grouped into material-fit, force-fit, and form-fit. In the case of electrical contacts, form-fit connections also require force or even better, material-fit, e.g. by cold welding.

Based on the requirements, initial decisions can be made, e.g. whether a solvable contact is required. A detachable contact is more complex and therefore heavier and usually more expensive.

Contact Resistance and Reliability of contacts are a common concern, prompting inquiries and extensive discussions. **Contact resistance** affects **temperature, aging** and energy **efficiency**. Power loss P and resulting heating during operation depend on current flow I and resistance R ($P = I^2 \cdot R$).

Other criteria often discussed are costs, process ability/process deviations, assembly/possible damage during assembly, or diagnostic ability.

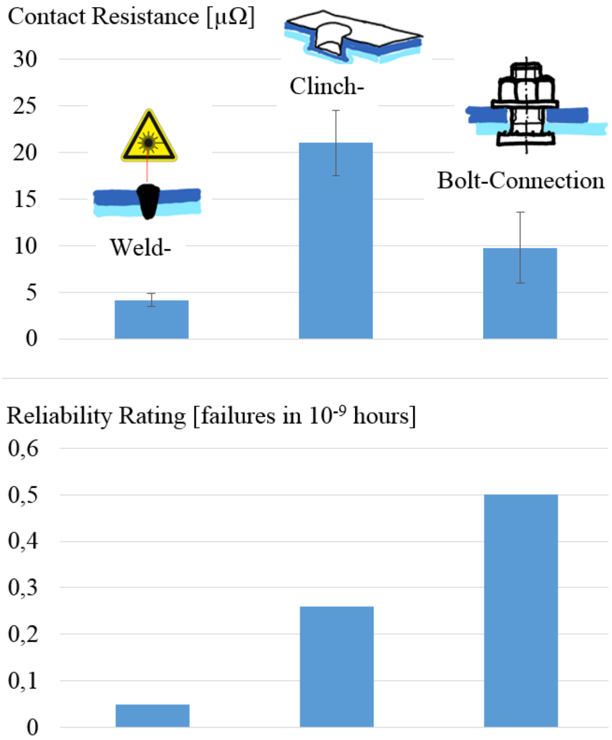


Figure 2: Measurements of Contact Resistances. Lower diagram shows Reliability Ratings of Weld, Clinch, and Bolt Connections. Reliability figures are according to MIL-HDBK 2017 and IEC 61709.

Welding/Bonding allows high strength and the lowest resistance, and high reliable joints. The same materials avoid the formation of intermetallic layers. A disadvantage of material-fit connections is the relatively high energy consumption when producing the connection. For this reason, the mechanical joining processes, such as pressing or clinching, are being further developed and examined in more detail.

Clinch joints use their own material; therefore, no additional joining element is required. Advantages of clinch joint are an established process for copper material. Clinch joints have been used for years in many electrical applications, for example in building automation and automotive fuse/distribution boxes or heaters.

The process needs only mechanical energy and, therefore, low energy consumption during manufacturing. No additional joining element allows an easier assembly process compared to welding or bolting. For the clinch process, the control distance and force of the punch tool are recorded. Furthermore, the thickness of the bottom material, "Control dimension X," is an important quality characteristic.

There is no heat influence, nor intermetallic phases (in the case of aluminum and copper weld, there are not very conductive intermetallic phases).

During the assembly process, relative movement of contacting materials breaks oxide-layers. Contact generates large contacting areas and provides low contact resistance and high short current carrying capacity. Nevertheless, Clinch joints are still the topic of deeper investigations. Further investigations and tests are planned in upcoming years.

Bolt-Connections have been extensive investigated [1], [2], are used in countless joints and are still very common for solvable connections. Many high current hardware components like fuses, contactors or connectors are provided with bolt joints. Nevertheless, because of assembly, process effort and weight, bolt joints are in competition with plug-in, Clamp-Connections, or Connectors.

Connectors allow comfortable tool-less exchange and service. However, more interfaces press-contact, connector and therefore higher resistances. Mating cycles and degradation need to be considered. A spring force is required to get low pretension loss, and the material needs to have low relaxation under operational loads. Therefore, cold working, alloys, micro-alloys are common, which are a compromise between conductivity and low relaxation. Connector **reliability** starts in the reliability area of the screw connection. It's very dependent on the type and design of connector, the materials used, the ambient temperature, the current load, mating/unmating cycles, number of pins, and environment. High current multi contact connectors starting at Contact Resistances at about 23.5 µOhm. However, some connectors have a much higher resistance. Because of many influences like coating, spring load, number and shape of contacts, connectors are not considered in the above Figure.

In an overall comparison energy consumption required in manufacturing needs also to be considered. Welding processes require the multiple process energy compared to mechanical joints. On the other hand, material-fit joints provide lowest contact resistances.

In operation, the contact resistance is proportional to the power loss in the system, $P=I^2 \cdot R$. Resistance is proportional to power loss and must be considered over lifetime. In battery electric vehicles energy/capacity of the batteries is limited (range). In addition, due to higher efficiency of electric drives, power losses are more significant, in worst case even requiring additional energy for cooling. Low contact resistance is therefore essential.

3 Focus on tribological failures/failure mechanisms

The main goal of contacts is to fulfill required functions. In an appropriate and optimized design, most failure mechanisms can be avoided [3]. Figure 3 shows electrical, mechanical, and chemical failure and aging mechanisms. Because, in current-carrying connections, the mechanical, electrical, chemical, and thermal contact properties are coupled/interact with one another. For example, temperature leads to higher resistance and accelerates oxidation processes, which increases resistance further. Influences which are in this document deeper addressed are **frictions and wear**.

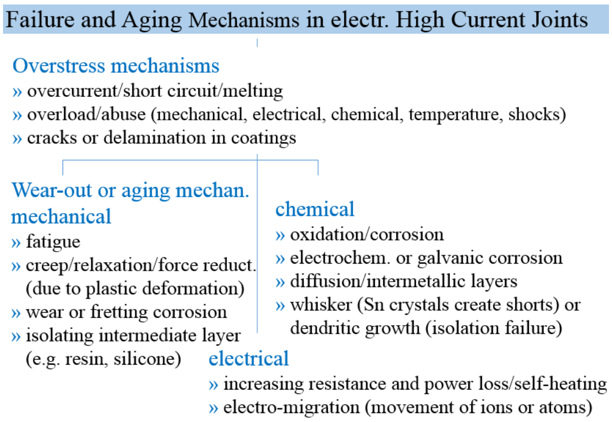


Figure 3: Overview of influences, failures, and failure and aging mechanisms of high current contact.

3.1 Friction monitoring in electrical bolted joints

Bolted joints are detachable and have lower contact resistance than connectors. However, assembly and tightening are often cited as disadvantages. The coefficient of friction has a significant influence on the assembly force/clamping force in the connection, which in turn has a significant influence on the resistance of the connection. Low clamping forces lead to an increase in contact resistance.

Additional, highly conductive materials tend to creep. Creep/Relaxation reduces clamping force. Materials have a limited allowed surface pressure in highly conductive materials limits torque. In some cases, hardware also limits torque.

Finally reached clamping force and friction between contact partners also influence transverse force and sliding, partial sliding, or fretting in the contact area. A general rule is to **avoid sliding or micro-movements** in an electrical contact.

However, friction coefficients spread. Especially if bolts are in delivery state provided from different suppliers, what usually is required in mass production, to stay independent. Controlling only torque, friction causes distribution in clamping force.

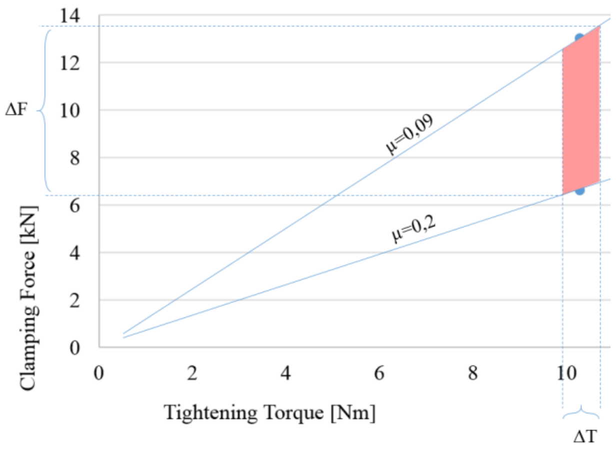


Figure 4: Clamping force vs. tightening torque for a bolted joint. In particular, the distribution of the coefficient of friction leads to a distribution of the clamping force in the joint. However, clamping force is required for a reliable joint.

To reduce distribution of coefficient of friction slide coatings are used. Anti-**friction coatings** on the connecting elements are used to reduce the distribution of coefficients of friction, to set a defined coefficient of friction window, for example from μ=0.09 to 0.14. This reduces the spread of the contact force achieved and thus also the spread of the contact resistance/electrical values of the connection.

Determining the coefficients of friction according DIN EN ISO 16047 requires measuring the clamping force. However, the force sensor also changes the screw connection. A longer screw is usually required. Accordingly, friction measurements can neither be carried out as part of a series production, nor with in series used bolts. In order to minimize this change, a very flat strain gauge sensor was manufactured in our laboratory for verification purposes and screw joint analysis.

Known are gradient based model as well. However, the settlement of joints and also the torsional rigidity of the tightening tools are challenging.

To address objective to measure coefficients of friction in serial production line, in addition, the determination of the coefficients of friction from the measured torques is shown in Figure 5. The big advantage is now that this can also be done as part of series production. A relative comparison of friction values during assembly processes is possible. Deviations in assembly process are quantified.

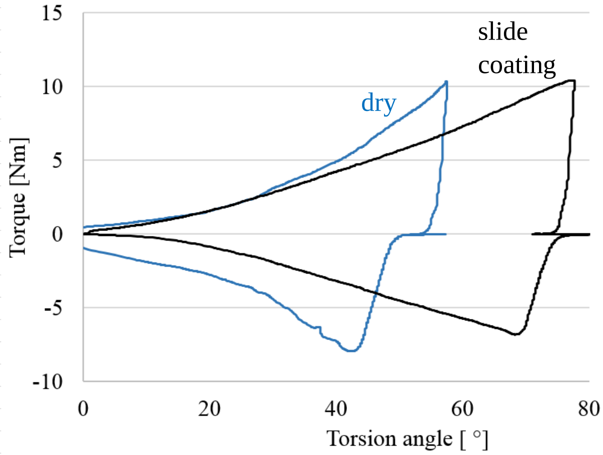


Figure 5: Torque vs. Torsion angle for a Bolt Connection with slide coating (black line) and dry/without (blue line). In assembly Process measured coefficients of friction are 0,09 and 0,2. The corresponding clamping force differs from 13 kN to 6,6 kN accordingly.

Table 1: **Consequences on Clamping Force due to distribution in coefficient of friction**

	Joint-1	**-2**
Measured Coeff. of Friction µ	0,09	0,2
Tightening Torque in Nm	10,3	10,3
Resulting Clamping Force in kN	13	6,6

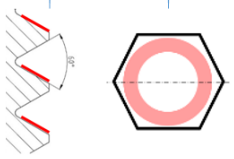
Finally, as an alternative, the ratio of tightening and loosening torque was determined, and the coefficient of friction was calculated from these. This approach delivers very satisfactory friction values results. Finally, deviations in the friction values can be **calculated and identified during series production** based on measured torque. This reduces the effort of traditional bolt case analysis. All influences on friction are taken into account 100% and on serial parts.

Several possibilities have been discussed in the literature, as already mentioned, including a force sensor or torque-angle gradient models. However, the best results were obtained using the developed and presented tightening and loosening approach:

(Eq. 1.1) [1]

$$M_T = F_G \left[\frac{d_2}{2} \tan(\alpha + \varrho') + \mu \, r_a \right] \quad \text{Tightening}$$

$$M_L = F_G \left[\underbrace{\frac{d_2}{2} \tan(\alpha - \varrho')}_{} + \underbrace{\mu \, r_a}_{} \right] \quad \text{Loosening}$$



$$\text{with} \quad \varrho' = \arctan \mu' = \arctan \frac{\mu}{\cos(\beta/2)}$$

If tightening torque M_T and loosening M_L are measured, we get two equations. Accordingly, the unknown clamping force F_G can canceled out. A coefficient of friction can be calculated.

From a tribological point, Friction Monitoring of bolted joints in tests and during serial production is very helpful. Available process data are used for calculation and control of friction values. By **monitoring** the coefficient of friction during the assembly process in joints anomalies, such as a bolt with different coefficient of friction or a bolt missing slide coating and therefore higher friction can be easily be detected.

In addition, with the coefficient of friction measured in first step, the tightening **torque can be adapted to measured friction value** and a tightening independent of coefficient of friction is possible. The influence and distribution of friction on the clamping force can be simply canceled out. Material efficiency can be improved.

3.2 Relaxation, reduction of spring or contact force

Challenging **relaxation**/loss of preload force, especially with **highly conductive materials**. For this purpose, relaxation tests and hot aging tests are usually carried out.

For plug-in connections, we explored fretting **wear** optimization and wear prediction of coatings in electrical contacts. Optical measurement techniques enable the measurement of wear rates after a short test duration, while service lifetime models allow for estimating the service lifetime of the contacts.

3.3 Fretting/Friction Corrosion and Friction Wear

Frictional wear describes the aging of current-carrying connections due to relative movements. Spring forces/mating forces limit contact pressure and therefore friction force. Micro motions in contact can be caused by thermal expansion, by shocks or vibrational loads. Sliding goes with Oxidation, Corrosion, Wear, and an increasing Contact Resistance. Figure 6 shows results on our fretting test rigs. Test conditions are according to testing standard LV214, reversing friction distance of 50 µm, cycle time 1 Hz. As the test was not passed, design improvements were required.

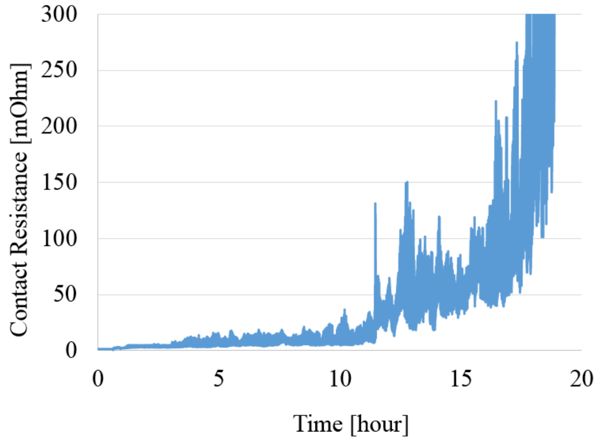


Figure 6: Increasing Contact Resistance and Distribution on a Connector due to Fretting. Even intermittent contact was observed. Contact was improved by minimizing relative movements, friction and therefore temperature in contact. With these improvements, tests run through and were passed easily.

4. Testing and Monitoring

Besides mentioned force, resistance/voltage drop, electromagnetic field measurements or electronic sensing, temperature is an easily accessible factor in electrical contacts. **Monitoring** supports:

a) Verification of results e.g. at other/system levels
b) Actual operating limits, e.g., to avoid overloading/overheating of components during operation
c) Operating Condition and Anomaly detection. Detection of early signs of failures, early warning, Mitigate potential risks associated with high current contacts, avoid subsequent errors.
d) Derating, Service Lifetime Prediction, Predictive maintenance, planned maintenance

Multi sensor approaches, **Temperature** Measurements are implemented during testing, but can also implemented in serial production accompanying testing/prototypes, to further enhance reliability and ensure long-term performance.

Thermal expansion/bimetal-based mechanisms. **Positive Temperature Coefficient** materials acts as a reversible thermal shutdown mechanism in case of extensive current load e.g. PTCs in consumer cells. Measurements use again temperature-dependent resistors like PT100 or **thermoelectric effects** are e.g. thermocouples. **Thermochromic** labels/materials are a simple and effective way to see if a certain temperature/maximum temperature that was reached.

Additional contactless diagnosis is possible. The **microbolometer** membrane absorbs emitted infrared radiation, heats up and chances resistance. **Infrared** sensors or cameras can be used. Infrared is not influenced by electromagnetic/EM noises. A very elegant and cost-effective solution is to integrate a miniature infrared thermometer on a circuit board/PCB, shown in Figure 6.

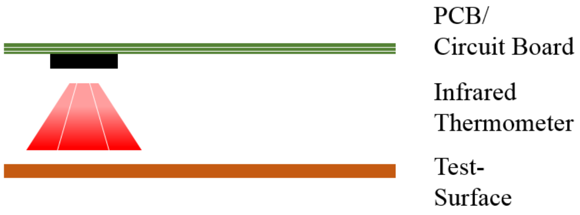


Figure 6: Miniature Infrared Thermometer (e.g. MLX90632) stacked on top of Test-Surface. Infrared Thermometer measures surface temperature of an electrical contact surface, of a cooling media or lubricant.

5. Conclusion

The document provides an overview of important high current contacts. Strengths and challenges of different designs are presented and help in making design decisions.

Furthermore, consideration and results of important influences and reliability rating help in making decisions and designing a robust design. Important influences that are in more detail investigated are friction and fretting wear. Multi-sensor approaches and monitoring solutions are discussed to support testing, automation and to increase reliability.

Friction monitoring during bolt assembly process controls the important influence of friction in a bolted joint and enables even adjustment of applied torque.

By using a multi-sensor approach, or even embedded sensors, we can significantly accelerate design optimization, improved reliability, service lifetime prediction, proactive/predictive maintenance and mitigate potential tribological or high current contact risks.

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