 doi:10.20944/preprints202107.0500.v1

Type of the Paper (Communication)

Influence of the Production Process on the Binding Mechanism of Clinched Aluminum Steel Mixed Compounds

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Abstract: The multi-material design and the adaptability of a modern process chain require joining connections with specifically adjustable mechanical, thermal, chemical or electrical properties, whereby previous considerations have focused primarily on the mechanical properties. With clinching, the multitude of possible combinations of requirements, materials and component or joint geometry makes it impossible to determine these joint properties empirically. As a result of the established and empirically based procedure, no model exists to date that considers all questions of joinability, i.e. the materials (suitability for joining), the design (joining safety) and the production (joining possibility) and allows a calculation of the achievable properties. It is therefore necessary to describe the physical properties of the joint as a function of the three bonding mechanisms force closure, form closure and material closure in relation to the application. This approach enables the illustration of the relationships along the causal chain "joint requirement - binding mechanism - joining parameters". In this way the adaptability of the mechanical joining technology can be improved. A geometric comparison is made using metallographic cross sections, of clinched joints of the combination of aluminum and steel. The torsional testing of the rotationally symmetric clinching points for detection of the mechanical stress state are qualified as examination method and technological test. By measuring the electrical resistance in the base material, in the clinch joint and during the production cycle (after clinching, before precipitation hardening and after precipitation hardening), this change in the stress state can also be detected.

Keywords: Clinching; binding mechanism; process chain, torsion test, electrical test

1. Introduction

The technical task of joining materials to one another leads to extended or new demands on joining technology against the background of constantly increasing functional integration in production. Joining connections of the most diverse materials are becoming increasingly important. To allow a function- and cost-related mixed design being used on a larger scale, it is necessary to further develop the joining technologies and to coordinate the materials used for these mixed designs. This means increased planning effort in design and logistics, but offers the possibility of using the materials in a more demand-oriented way. Furthermore, with today's safety requirements and standards, seamless monitoring and documentation of the entire manufacturing process must be ensured. As established joining processes for overlapped sheet metal and profile parts, forming technology has a wide range of applications. For example, clinching can be used to join semi-finished products of different thicknesses as a joint of identical materials [1] or as a mixed joint of aluminum and steel [2], or of copper and aluminum [3]. For the clinching process, it is necessary to meet the requirements for clinchability. The clinchability of a component is given if, by local forming of a material, a form- and force-closure can be produced in the first instance and a material-closure in the second. The properties of the joint as well as the connected structures must satisfy the requirements specified for them. Like weldability in

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[4], clinchability results from the influencing variables material, design and production, which are assigned to the process chain. A characteristic production process for clinched joint with joining partners of aluminum and steel is shown in **Figure 1**.

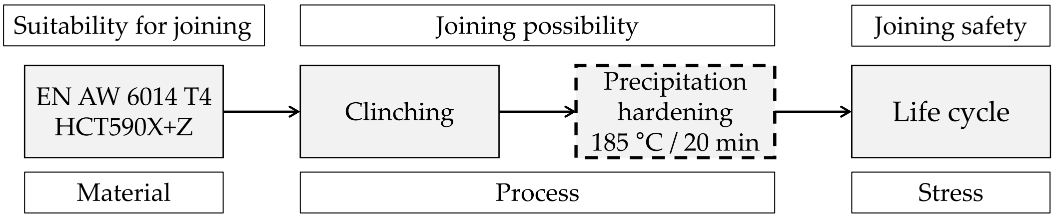

Figure 1: Production process Clinching of Al – Steel- components

One advantage of the clinching joining process is that the joined components can be further processed immediately after the joining process. The binding mechanisms generated in clinching provide the necessary prerequisites for this. Clinched joints are based on the principles of form and force-closure [**Figure 2a**], although material-closure may also be present, as described in [5], or can be introduced in a targeted manner [6].

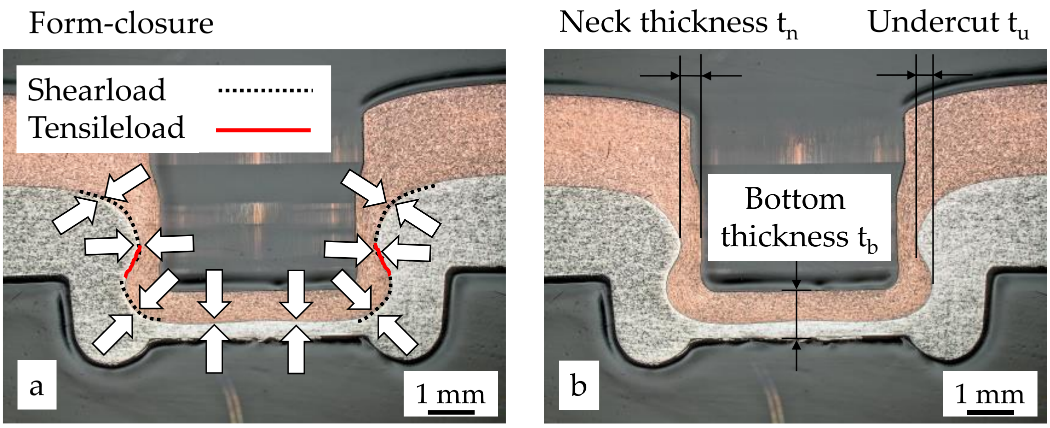

Figure 2: geometric features and local binding mechanisms at clinch points

The amount of form-closure generated within the clinch point depends on the direction of loading. If the clinch point is subjected to a shear tensile load or a head tensile load, the form-closure components correspond to the areas shown in **Figure 2a**. The force-closure component and a possible material-closure component are independent of the loading direction. The force-closure component acts along the boundary line between the formed parts, which is marked with arrows [**Figure 2a**]. The dimensioning of clinched joints is based primarily on the geometric characteristics of neck thickness and undercut (**Figure 2b**) as well as the main load case in the later life cycle. In this design according to the state of the art, the force-closure component has not yet been taken into account in the dimensioning. When using different joining part materials, the mechanical stress states [7] and thus the proportions of the bonding mechanisms form-closure and force-closure differ considerably according to the joining part arrangement due to the inhomogeneous shape changes introduced by the clinching process.

When using age-hardenable aluminum alloys, precipitation hardening of the aluminum material takes place after the joining process and before the subsequent life cycle (**Figure 1**). The necessary process heat introduced during this step increases the strength of the aluminum alloy. Due to the large local deformations of the joining parts during the clinching process [3], the recrystallization temperature is reduced [8]. This results in a reduction of force in the joint between the parts to be joined, which causes a change in the surface pressure between the parts to be joined and thus influences the existing binding mechanism of the force –closure component.

The subject of the work carried out is the description of these existing form- and force-closure components in the course of the production process. With regard to the joinability, the factors influencing the formation of the form- and force-closure components can be defined. By knowing these influencing factors, it is possible to produce a functional and function-related clinch connection.

2. Materials and Methods

2.1 Materials

Based on the joining task of producing a steel-aluminum mixed joint using the age-hardenable aluminum alloy EN AW 6014 in the T4 heat treatment condition (solution annealing) with a component thickness of t = 2. 0 mm and the dual-phase steel HCT590X+Z (hot dip galvanized) with a component thickness of t = 1.5 mm and a zinc coating of thickness t_{Zn} = 7.82 µm (S_D = 1.20) by clinching, the effect of the manufacturing process on the individual parts of the bonding mechanisms is to be detected. The chemical composition and the mechanical properties of the materials used are shown in [9] for the aluminum EN AW6014 and in [10] for the steel HCT 590X+Z.

2.2 Design of joints

The clinch points were first dimensioned by using a single step round joint with a closed die and a nominal diameter of 8 mm. The materials to be joined were joined in a displacement-controlled clinching process. The tool geometries of the punch and die, the blank holder or stripping force and the punch penetration depth define the form closure of the clinch connection. The force-closure component within the clinched joint is defined by the joining partners, the friction between the joining partners, the local degree of forming and the springback effect of the joining part materials.

For the investigations carried out, two different surface conditions were used for the components to be clinched. In the "Cleaned" (O1) condition, a defined surface condition was achieved by cleaning with isopropanol. Impurities and inhomogeneities present on the surface were removed. The oxide layer on the aluminum components, as characterized in [14], was not affected. The "Delivery condition" (O2) represents a non-defined surface condition, which exists due to the manufacturing process, the semi-finished product transport and the handling during specimen production at the joining process. These two surface states characterize a change in the tribological system and can initially affect the geometric formation of the undercut and neck thickness quality criteria. This condition can be taken from the micrographs at **Table 1**. In addition to geometric changes, a change in friction also leads to a change in the mechanical stress state between the joining partners, which cannot be detected in terms of dimensions, and thus to a changed force-closure component.

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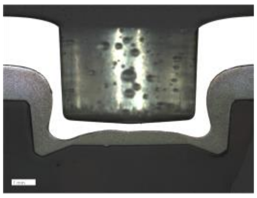
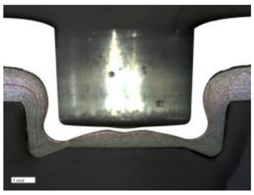
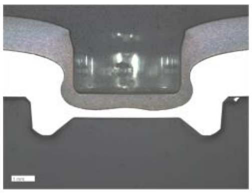
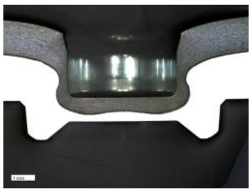
Table 1: Design and dimensioning of the clinch joints investigated (7 specimen per series)

Sheet thickness in mm	Surface condition	Micrograph	Tools A - Punch B - Die	Neck thickness t_n in mm	Undercut t_u in mm	Bottom thickness t_b in mm
Series 1 $t_1 = 2.0$ $t_2 = 1.5$	Cleaned		A56100 / BD8016	0.42 ±0.03	0.23 ±0.01	0.87 ±0.01
Series 2 $t_1 = 2.0$ $t_2 = 1.5$	Delivery Condition		A56100 / BD8016	0.44 ±0.03	0.24 ±0.02	0.79 ±0.01
Series 3 $t_1 = 1.5$ $t_2 = 2.0$	Cleaned		ABY461850100 / BB8008	0.39 ±0.01	0.14 ±0.02	1.00 ±0.01
Series 4 $t_1 = 1.5$ $t_2 = 2.0$	Delivery Condition		ABY461850100 / BB8008	0.36 ±0.02	0.14 ±0.02	0.99 ±0.01

2.3 Mechanical test

After clinching, the joined components are subjected to heat treatment. This precipitation hardening takes place according to the manufacturer's specifications [9] for 20 min at 185 °C. The changing mechanical material properties are shown in **Table 2** by using data from [9].

The introduced process heat as a result of this precipitation hardening and the different thermal expansion coefficients of the joining partners aluminum initially influence the proportion of the binding mechanism force-closure within the clinch point due to a change in the mechanical stress state. The change of the mechanical stress state depends on the component arrangement and the surface conditions. The form closure, on the other hand, is not affected.

Table 2: Mechanical properties of EN AW 6014 [9]

	$R_{p0.2}$ in MPa	**Rm in MPa**	**A_G in %**	**A_{80} in %**	**$R_{p0.2}$ / Rm**	**n_5**	**r_{10}**
T4	≤ 130	≥ 175	≥ 20	≥ 23	≤ 0.55	≥ 0.26	≥ 0.6
T6	≥ 200	≥ 260		≥ 14			

This changed force-closure component can be verified mechanically for rotationally symmetrical clinch points by means of a torsion test. The test rig consists of a tightening spindle with integrated torque-angle detection [**Figure 3a**]. The test result is the testing

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torque, which is measured during the torsion of the two joining partners against each other. A large testing torque indicates a large force-closure component.

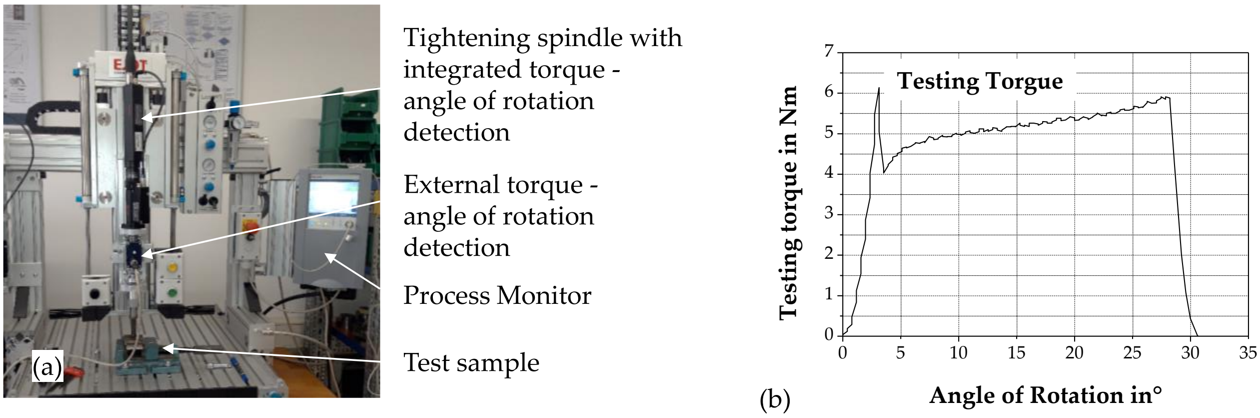

Figure 3: Test setup Torsion test an characteristic testing

Figure 3b shows the plotted characteristic test curve. The first local maximum after the monotonic increase of the graph represents the testing torque. When this peak is reached, the two joining partners start to twist against each other. The subsequent increase in torque is due to the leveling of the roughness peaks and the associated change in the coefficient of friction between the components in the interface as a result of further rotation.

The diagram [**Figure 4a**] shows the testing torques for the component arrangement of the aluminum as the die-side joining partner. Here it can be seen that initially the surface condition exerts nearly no influence on the torsional torque. On average, the samples cleaned with isopropanol exhibit a 6.3 % higher torsional torque in the T4 condition and an 8 % higher torsional torque in the T6 condition but the average values are covered by the scatter bands. These minor increased values for the cleaned surface condition, compared to the as-delivered condition, exists due to the increased friction between the joining partners during the relative movement at the clinching process. This increased friction leads to an increased frictional component in the joined joint. If, in addition to the surface condition, the values achieved for the breakaway torque after precipitation hardening are also compared [**Figure 4a**], no significant difference in the mean values can be detected here, and the maximum and minimum values also lie in almost similar ranges. This is due firstly to the component arrangement, secondly to the different springback behavior and thirdly to the shape change introduced. In this combination, the more thermally sensitive aluminum material is located on the die side, i.e. the different coefficients of thermal expansion of the component materials initially reduce the surface pressure between the components during heat treatment. After completion of the heat treatment and elimination of the thermal load, the surface pressure is increased again as a result of the different thermal expansion of the joining partners. The second influencing factor is the springback behavior. Due to the greater springback of the aluminum material, a larger force-closure component is achieved irrespective of the surface condition. The third influencing factor is based on the lower deformation of the die-side component and thus on a low thermal sensitivity with regard to recrystallization as a result of precipitation hardening.

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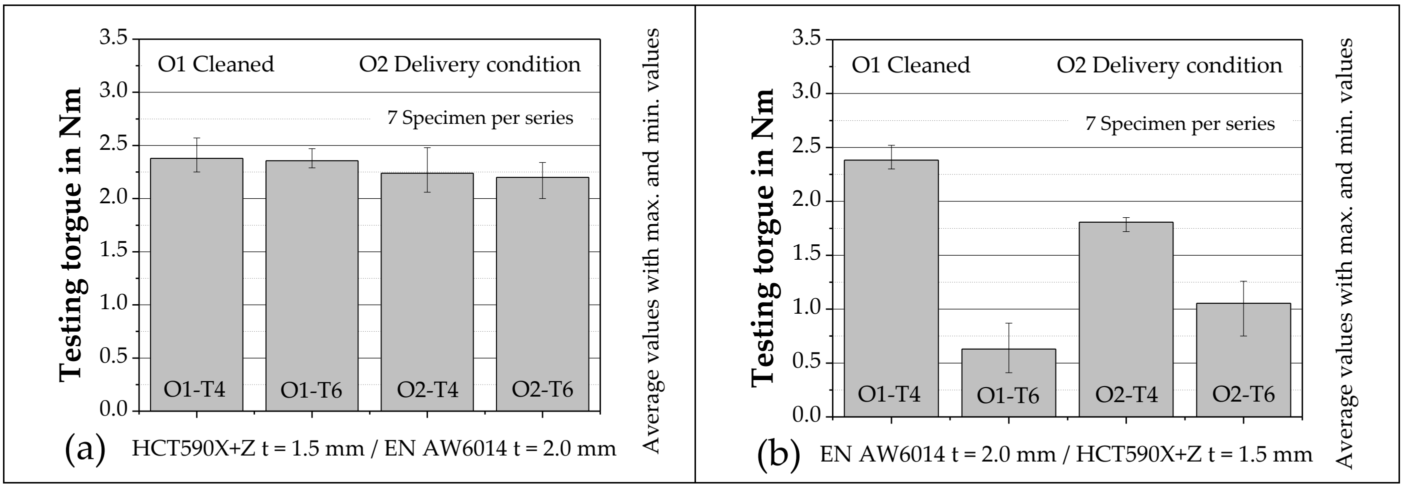

Figure 4: Torsion test by variation of joining direction and surface condition

If the aluminum material is arranged on the punch side, significant differences can be detected in the torsional test with regard to both the influence of the surface condition and the precipitation hardening process [**Figure 4 b**]. With respect to the surface condition, cleaning with isopropanol in the heat treatment condition T4 results in an increase of the torsional torque by 17.5 %. This increase can be attributed to the increased friction coefficient caused by the cleaning. A comparison of the same surface but different heat treatment conditions shows a significant reduction in torsional torque. For the series with cleaned surface, this torque loss amounts to 71 %. The torsional torques of the as-delivered series differ by 39 %. This indicates a reduction in the frictional component associated with the lower torsional torque. When the more thermally sensitive aluminum material is arranged on the punch side, the recrystallization temperature is reduced as a result of the maximum deformation occurring in the neck area [15]. This process is superimposed by an expansion restraint of the aluminum material due to the larger coefficient of thermal expansion as a result of the process heat during precipitation hardening and leads to a further change in the mechanical stress state at the clinch point. The influence of the different springback behavior of the component materials is independent of the heat treatment performed. Due to the greater springback of the aluminum cup compared with the steel on the die side, there is a reduced surface pressure between the joining partners.

2.4 Electrical test

The values measured in the torsion test are to be verified using a second independent physical quantity. A clinch point represents not only a mechanical but also a stationary electrical contact system [6]. An electrical contact system can be described by the connection resistance R_V [16]. This connection resistance depends on the constriction resistance R_e, the impurity resistance R_f and the intrinsic resistance of the contact partners R_b [**Equation 1**].

$$R_V = R_e + R_f + R_b \qquad \textbf{Equation 1}$$

In this relationship, the constriction resistance R_e represents the contact pressure-dependent variable. In a clinch connection, this contact pressure represented by the force-closure component. A change in the force-closure component causes a change in the connection resistance. According to Böhme [16], the larger the contact force, the larger the contact area of the contact partners and, consequently, the smaller the constriction resistance. The contact pressure is influenced by temperature, time and the conductor materials [17].

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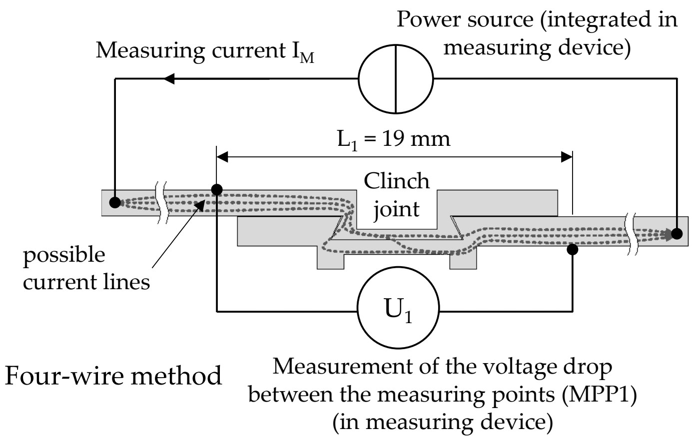
The measurement of the electrical connection resistance therefore offers the possibility to prove a changed force-closure due to a thermal load [3]. In [3], the suitability of clinch points for contacting electrical conductors was investigated and their properties characterized. For the electrical contact behavior of clinch points, the force-closure component between the joining partners after joining and, in the case of the aluminum materials used here, after precipitation hardening is primarily decisive, since this ensures the integrity of the micro contacts [18]. Based on these studies, measurement of the electrical resistance of a clinched joint can reveal the altered force-closure component due to precipitation hardening [6].

The connection resistance is determined using the four-wire measurement method shown in **Figure 5** [19]. A defined current I_M flows through the clinched components via two cables. The voltage drop U_1 across the clinch point is measured over a defined distance using two further cables. The resistance is calculated using Ohm's law. Due to the measuring principle, the influence of the measuring cable resistance on the resistance to be measured is greatly reduced. Only a very small, negligible current flows in the test leads. The voltage drop across the low-impedance test leads is negligible (compared to the voltage drop in the high-impedance voltmeter) [3]. According to [20], the measurement of electrical conductivity can be used as a check for the heat treatment condition. Jiang [21] uses the measurement of the electrical resistance with the four-wire-method at clinched joints as a quality inspection method.



Symbol	Name	Unit
I_M	Measuring current	A
U_1	Voltage at MPP1	V
R	Resistance	Ω
L_1	Measuring distance	mm

Figure 5: Test setup electrical test

A comparison of the electrical resistances of the homogeneously flowed-through test material in the material states T4 and T6 with the same conductor cross sections and gauge lengths is shown in **Figure 6**. While the material resistance R_M in the T4 state is 26.43 µΩ, the electrical resistance decreases to 25.93 µΩ in the T6 state due to precipitation hardening. Thus, there is a 7.9% reduction in electrical resistance compared to the T4 condition. The measurements in [6] for the material EN AW6016 show a similar percentage decrease in resistance.

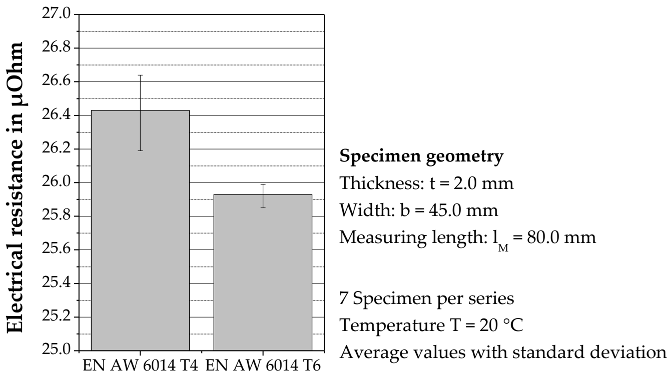


Figure 6: Material resistance of the test material before and after precipitation hardening

This means that the electrical conductivity of the base material is improved by heat treatment, as also explained in [22] using the aluminum layup EN AW 2024 and [23] for 6xxx aluminum conductors. Zhang et. al. [23] state in their investigations that heat-treated conductors have a higher electrical conductivity compared to the non-heat-treated conductors made of Al-Mg-Si alloys. This improved conductivity should also affect the electrical resistance values of the clinch points.

When comparing the electrical resistances, a higher electrical resistance is measured for all clinched samples after precipitation hardening than in the initial condition T4. In **Figure 7a**, when the aluminum is arranged as the die-side joining partner, a small influence is initially measurable when comparing the surface states. When comparing the heat treatment condition and in the cleaned condition (O1), an increase in the electrical resistances from R = 79.5 µΩ in condition T4 to R = 99.2 µΩ in condition T6 can be seen. Similarly, for the series joined in the as-delivered condition (O2), the electrical resistance increases after precipitation hardening from R = 75.3 µΩ in the T4 condition to R = 88.1 µΩ in the T6 condition. The increase in electrical resistances is due to the decrease in surface pressure between the joining partners is caused by the thermal load during precipitation hardening.

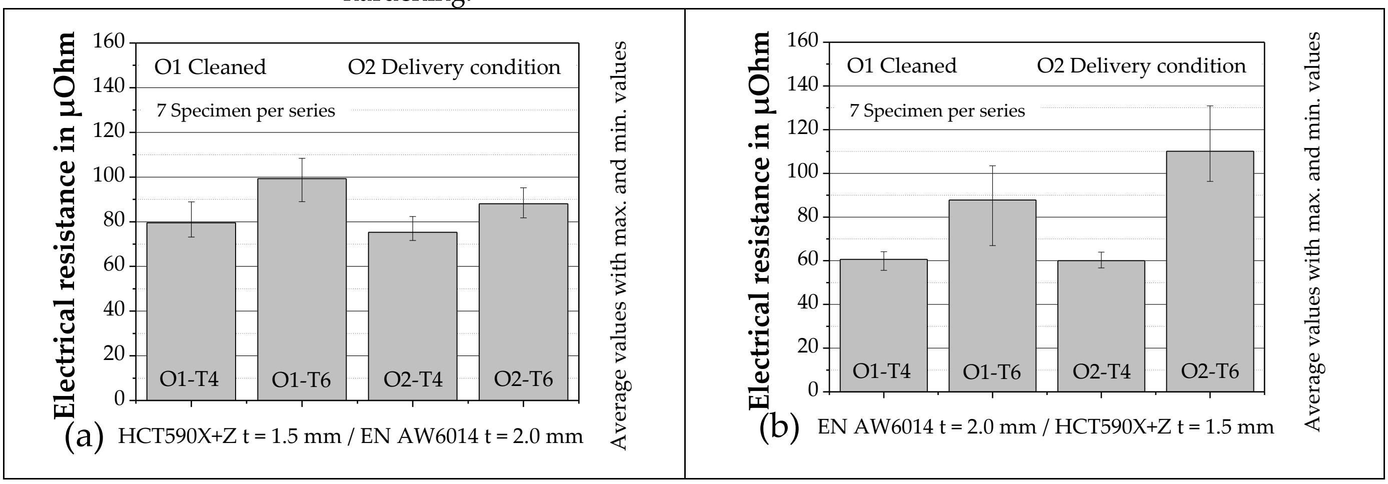


Figure 7: Electrical resistance by variation of joining direction and surface condition

When the joining direction is reversed with the aluminum material in the punch-side arrangement, the surface condition exerts only a minor influence on the contact behavior [**Figure 7b**]. The influence of precipitation hardening, on the other hand, dominates the electrical contact behavior more clearly than in the series with the aluminum material arranged on the die side. The electrical resistance increases by 27.1 µΩ after precipitation hardening for the series with cleaned surface (O1), which corresponds to an increase of

44.9%. This is similarly true for the specimens with the surface condition (O2) "as-delivered", with resistances increasing after precipitation hardening from 60.0 µΩ to 110.1 µΩ, corresponding to an increase of 83.5%. The scatter bands also increase after precipitation hardening of the aluminum material. In evaluation of the electrical resistances, it can also be found here that the process of precipitation hardening affects the force-closure component of the bonding mechanism. The mechanical stress reduction increases the electrical resistance, which corresponds to a reduction in the fraction of the force-closure component. The change in the inherent resistance of the aluminum material is negligible for the measured increases in the bond resistances.

3. Discussion

These comparison series were created in order to show the influence of the different mechanical stress states at the clinch point, which in the case of mixed joints leads to different formation of the binding mechanism force-closure as a result of the precipitation hardening process, depending on the joining direction. In the case of the mixed joints investigated here, a resulting material-closure can be ruled out on the basis of the resistances measured.

The deformed state of a material is basically unstable [8]. The strain hardening generated by the clinching process, which is inhomogeneously distributed in the clinching point, affects the residual stress state of the joint. This residual stress state is superimposed with load stresses and, in addition to the mechanical properties, also influences the thermal and, as a result, the electrical properties as a function of the degree of deformation, the joining part material and the temperature. Gibmeier [7] shows that residual compressive stresses are present in both base materials when closed dies are used in the range up to a distance of approx. 4-6 mm from the clinch joint. The applied process heat of 185 °C over a period of 20 min during precipitation hardening influences this residual stress state and, consequently, the force-closure component in the joint. The stresses arising at the clinch point, which are caused by the difference in the coefficients of thermal expansion of the individual joining partners during precipitation hardening, superimpose these residual stresses.

For the work carried out, it is first necessary to integrate the process chain running through during component manufacturing [**Figure 1**] into the investigations. By evaluating the tests carried out and taking into account the process chain [**Figure 1**], the influencing factors and dependencies shown in **Figure 8** can be used to indicate the changed force-closure component proportions within the clinched joints.

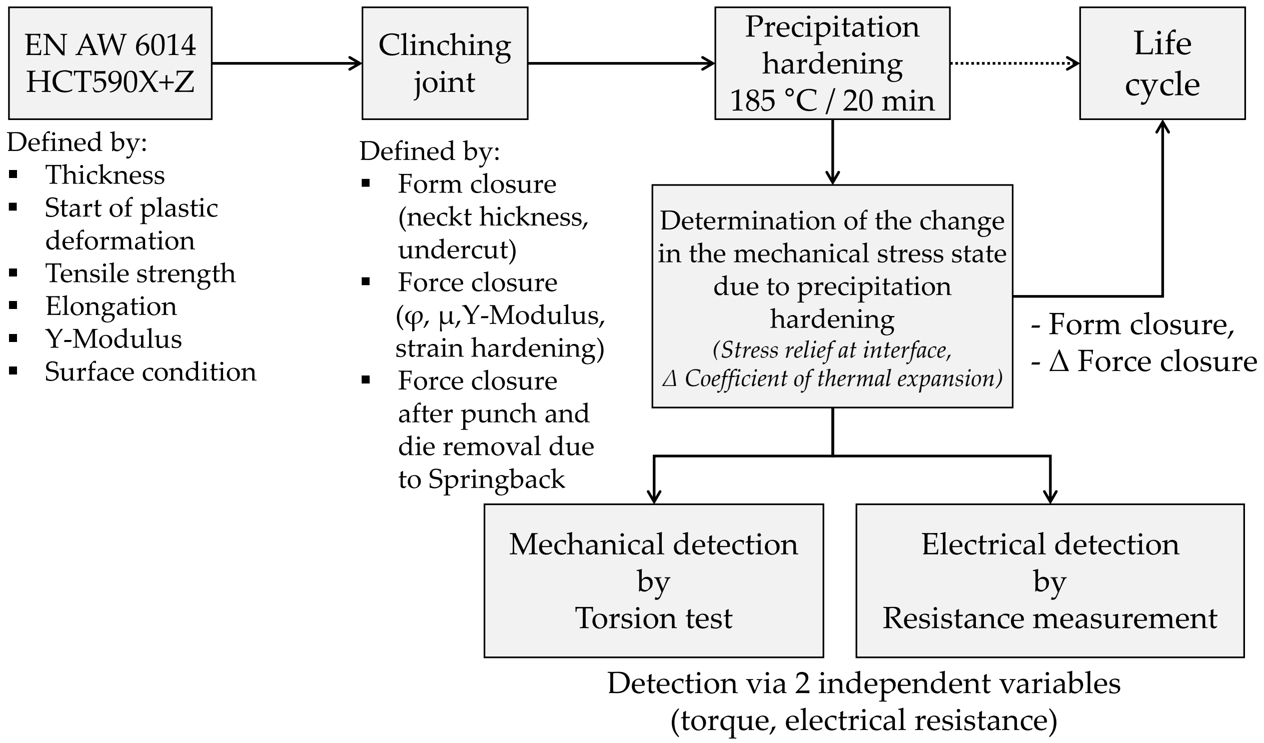


Figure 8: Factors influencing the clinch connection along the process chain

The process heat introduced as a result of this precipitation hardening influences the proportion of the bonding mechanism force-closure within the clinch point. The form-closure component, on the other hand, is not influenced. The form-closure and force-closure binding mechanisms in clinched joints can be analyzed by taking a holistic view of the production process (joinability). Using the test methods of torsion testing and measurement of the electrical connection resistance, a change in the force closure component can be quantified via two mutually independent variables. On the basis of the tests carried out, the binding mechanism of force-closure can be taken into account in a future clinch point design or an FEA simulation of the process chain.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, U.F. and J.K.; methodology, J.K.; validation, U.F.; investigation, J.K.; data curation, J.K.; writing—original draft preparation, J.K.; writing—review and editing, U.F.; supervision, U.F.; project administration, U.F.; funding acquisition, U.F. All authors have read and agreed to the published version of the manuscript."

Funding: This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – TRR 285 – Project-ID 418701707, subproject A04.

Data Availability Statement: All data generated in this study were included in this article.

Conflicts of Interest: The authors declare no conflict of interest.

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