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Approach to transferring force-based fatigue curves into stress-related fatigue curves for clinch joints

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Abstract. Cyclic strength is essential in many lightweight design concepts where the design is to be pushed to the limits of strength. While joining dissimilar metals such as aluminum and steel is a challenge of its own, fatigue life prediction for this joining type is all the more challenging. Here, clinching as a mechanical joining process offers many advantages. However, a generalized evaluation of the fatigue properties is complex since many influencing factors, such as the joint's geometry, the high plastic deformation, the proportion of bonding mechanisms, have to be considered. Force versus number of cycles (F-N) curves are the established basis to describe the fatigue behavior of clinch joints. However, a generalized evaluation of the service life requires stress versus number of cycles (S-N) curves. This research gives a first approach to transferring F-N curves to S-N curves on the basis of nominal stress determination in the damage relevant clinch cross section. The material combination used, EN AW-6014 and HCT590, offers excellent practical relevance since both materials are widely used in the automotive industry.

Introduction

Clinching is a mechanical joining process that has the potential to save immense amounts of energy. As a form-closure and force-closure process, clinching offers the advantage that it can be used for hybrid material combinations [1]. Especially in the mobility sector where clinching is used, i.e., in skin sheet applications. Here joining aluminum and steel can contribute to a significant weight reduction and thus help saving fuel consumption. Clinching also offers the advantage that materials can be joined without the need for auxiliary parts or high temperatures during the joining process.

Clinching is a versatile process allowing a vast variety of joining constellations. Clinching allows the joining of different sheet thicknesses, materials and surface conditions. Kalich and Füssel [2] have analyzed the influence of the surface condition on the properties and the binding mechanisms of the joints. In addition, joining more than two sheets is possible, and the corresponding layer architecture can be chosen individually. In another work, Kalich and Füssel [3] found that the joining direction however influences the mechanical behavior. In addition, the toolset geometry can change the mechanical properties of the joints, too, as was shown by Ewenz et al. [4]. The versatility of clinching makes a classical fatigue evaluation difficult since the stresses in the most critical area are unknown. Furthermore, it was shown in [5] that the failure mode is load-dependent. As a result, clinch joints are typically evaluated on a joint-to-joint basis by looking at the force versus number of cycles (F-N) curves.

However, a stress versus number-of-cycles curve (S-N curve) is required to enable a quantitative comparison between different clinch joints. In this work, an aluminum alloy EN AW-6014 and a HCT590X+Z dual-phase steel were used in different sheet thicknesses to

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produce clinch joints and evaluate the fatigue behavior and a first approach is presented, which allows a transfer from a F-N curve to a S-N curve.

Material and Method

The aluminum alloy EN AW-6014 and the dual-phase steel HCT-590X+Z were used for the experimental tests. A 2 mm thick sheet was used for the Al-Al clinch joint and a 1.5 mm thick plate for the St-St joint. The Al-St mixed joint consisted of a 1 mm aluminum sheet and a 1.5 mm steel sheet.

EN AW-6014 is a precipitation hardening alloy that has good formability in the T4 condition (solution annealed and quenched) and high strength after heat treatment to adjust the artificially annealing condition (T6). The clinch joints were designed to correspond to the established quality standards, i.e., no initial cracks, a symmetrical formation of the joint and no apparent gaps. Furthermore, all connections were processed with a conical punch, and an 8 mm fixed round point die to ensure good comparability. However, the punch diameters varied slightly between 4.8 mm and 5.6 mm to achieve a good quality of the joints. Fig. 1 schematically shows the clinching process. First, the sheets were fixed between the punch and the die. Subsequently, the punch moved towards the die until a predefined position was reached. This procedure achieves characteristic clinch point geometries according to the tool geometry (punch and die). The bottom thickness was used as a non-destructive quality parameter because this parameter can be used for a known geometry to conclude other geometric features such as undercut and neck thickness [6]. After the joining process, the joints containing aluminum are heat treated for 20 min at 185°C (T6) to increase the strength of the material.

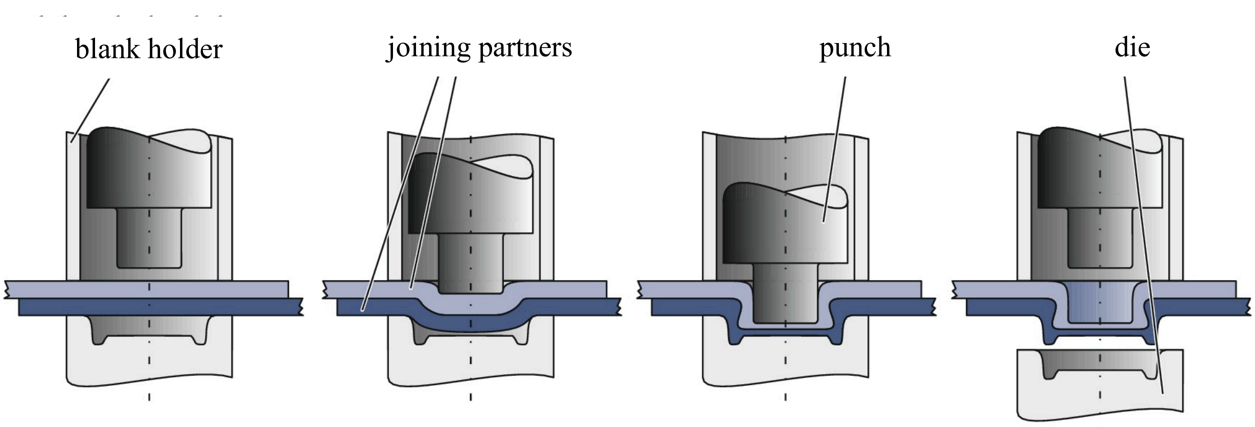

Fig. 1 Tool design and general process for clinching with closed die [7]

Metallographic cross-sections were prepared for the three different clinch joint geometries. For this, the clinch joints were cut, grinded and polished exactly to the middle of the joint. These cross-sections served to determine the geometrical features. Fig. 2 (a) shows a schematic cross-section with the geometrical features, neck thickness n, undercut u and the bottom thickness b.

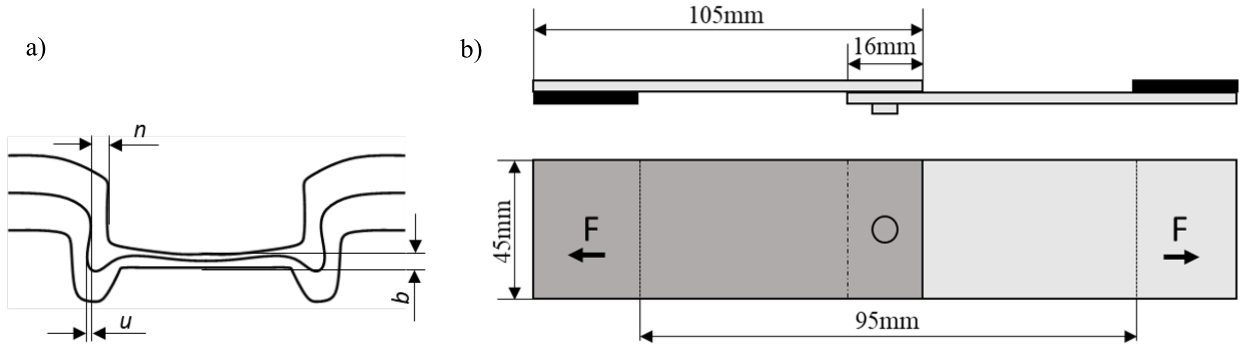

Fig. 2 (a) Schematic cross-section of a clinch joint with the geometrical features neck thickness n, undercut u and bottom thickness b, (b) geometry of single-lap shear specimens with alignment plates (black) as used for the mechanical testing

Flow curves were taken from the base materials using a layer compression test and are characterized by a biaxial stress condition. A Hocket-Sherby extrapolation was applied to calculate plastic strains higher than 0.5. Fig. 4 shows the flow curves of the base materials. The HCT590X+Z reaches higher stress levels than the AW-6014 in the T4 condition.

Fatigue tests were carried out using single lap-shear specimens made by two 105 mm x 45 mm sheets with a 16 mm overlap area (Fig. 2 (b)) using the resonance pulsation test system, Testronic by Rumul. About 20 specimens for each series were tested in a range of 10^5 to 10^7 load cycles. The load ratio applied was 0.1 in order to avoid buckling or bending of the specimens. The test frequency was about 70 Hz. When the specimens were broken or a frequency change of 5 Hz occurred, the test stopped. Specimens with more than 10^7 load cycles are marked as run outs. Visual inspection of the fracture surfaces in a scanning electron microscope revealed the corresponding failure modes.

Results

Cross-sections of the three different clinch joint geometries are shown in Fig. 3 and the corresponding values for the geometrical features can be found in Tab. 1. It can be seen, that each clinch series differs with regard to their geometrical features, which is a result of the different diameters of the conical punch applied. Nevertheless, they are all validated as joints with sufficient quality related to conventional standards. This means, no cracks could be observed after the joining process, the neck thickness-undercut ratio was acceptable and all connections were symmetrical.

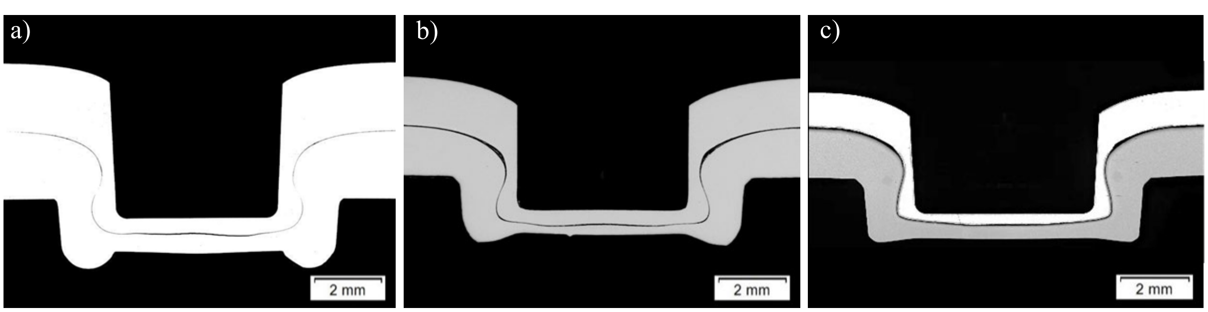

Fig. 3 Cross-section of the different clinch joints (a) Al-Al clinch joint, sheet thickness 2 mm; (b) St-St clinch joint, sheet thickness 1.5 mm; (c) Al-St clinch joint, sheet thickness Al-sheet 1 mm and St-sheet 1.5 mm

Table 1. Geometrical features of the different clinch joints

Parameter	Al-Al	St-St	Al-St
Neck thickness [mm]	0.42±0.03	0.36±0.01	0.23±0.04
Undercut [mm]	0.26±0.05	0.21±0.02	0.20±0.00
Bottom thickness [mm]	1.07±0.01	0.75±0.01	0.70±0.06

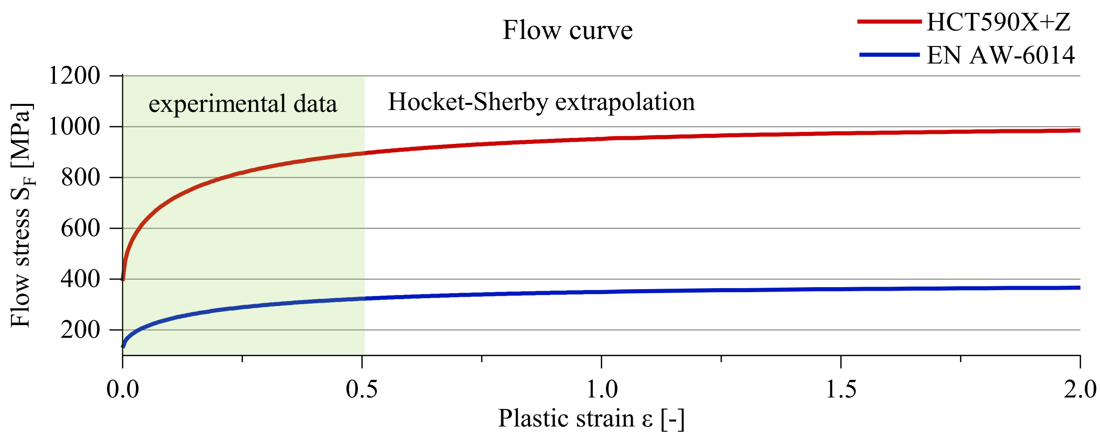

Fig. 4 Flow curve of the base materials

The results of the fatigue test show pronounced differences between the cyclic strength of the three clinch joint configurations. The St-St joints have the highest fatigue strength, while the Al-St joints show the lowest fatigue strength (Fig. 5 (a)). All clinch joint series display the same main failure mode, i.e. neck fracture, as depicted in Fig. 5 (b). Furthermore, it should be pointed that in the case of the Al-St joints, failure always occurred in the aluminum sheet.

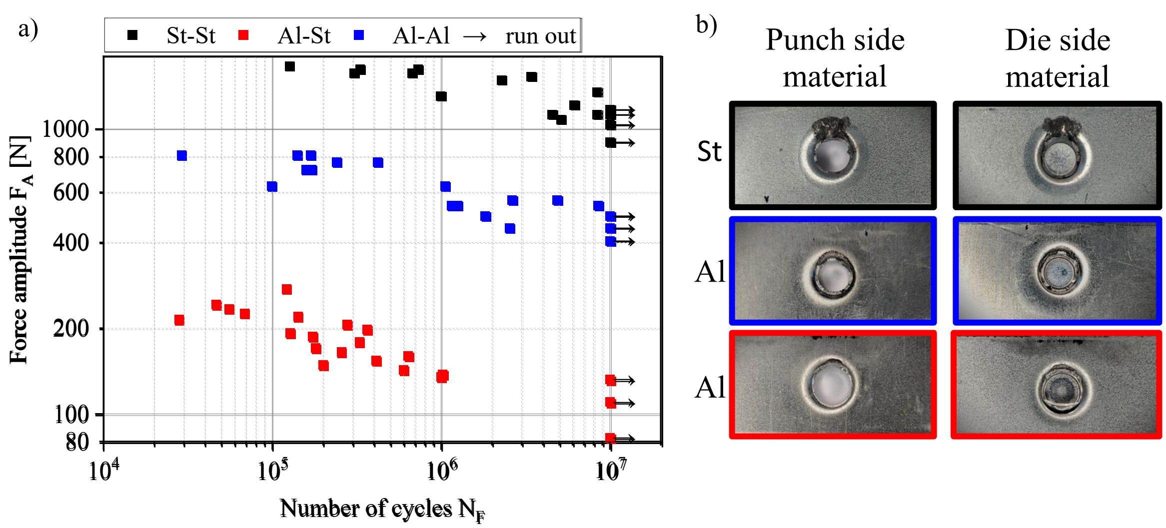

Fig. 5 a) F-N Curve of three different clinch joints and b) exemplary images of the main failure behavior of these clinch joints after fatigue testing

Development of an S-N-Curve

Two main factors significantly contribute to the fatigue behavior of the individual clinch joint configurations. On the one hand, an initial deformation is induced through the forming process during clinching, which can be interpreted as a kind of residual stress stored in the severely deformed microstructure. On the other hand, the cyclic load amplitude introduced during fatigue testing causes a local stress peak due to the complex geometry of the clinch joint.

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The post-mortem fractographic analyses of the fatigue test specimens showed that irrespective of the different cyclic strengths, all clinch joints show failure starting from the neck area. Based on the metallographic and the fractographic analyses the nominal area A assumed as ring area in the neck can be determined. As a consequence, the nominal stress introduced in this area through the fatigue loading can be calculated, too. To obtain the afore defined residual stress introduced by the plastic straining during the clinch process, the plastic strain was calculated at most critical area. These calculations resulted in plastic strain values of about 1.5 for all three series. The corresponding flow stress SFS is obtained from the Hocket-Sherby extrapolation. These values result in a normalization factor for the fatigue results according to the superposition principle (see Eq. 1).

$$S = \frac{F_A}{A} + S_{FS} \tag{1}$$

In Fig. 6 the fatigue results from Fig. 5 are transferred to the stress versus number of cycles format, applying the aforementioned superposition principle to define the correlating stress amplitudes. While the St-St joints still show a much higher fatigue strength, the Al-Al joints and the Al-St joints no longer show such a pronounced difference than is the case of the F-N curves. Hence, the transfer of the F-N curves to S-N curves clearly corresponds to the expected cyclic strength of the failure relevant base material, the aluminum sheet. However, a remaining discrepancy in fatigue behavior can neither be explained by the clinch joint geometry nor the predeformed and hence strengthened material.

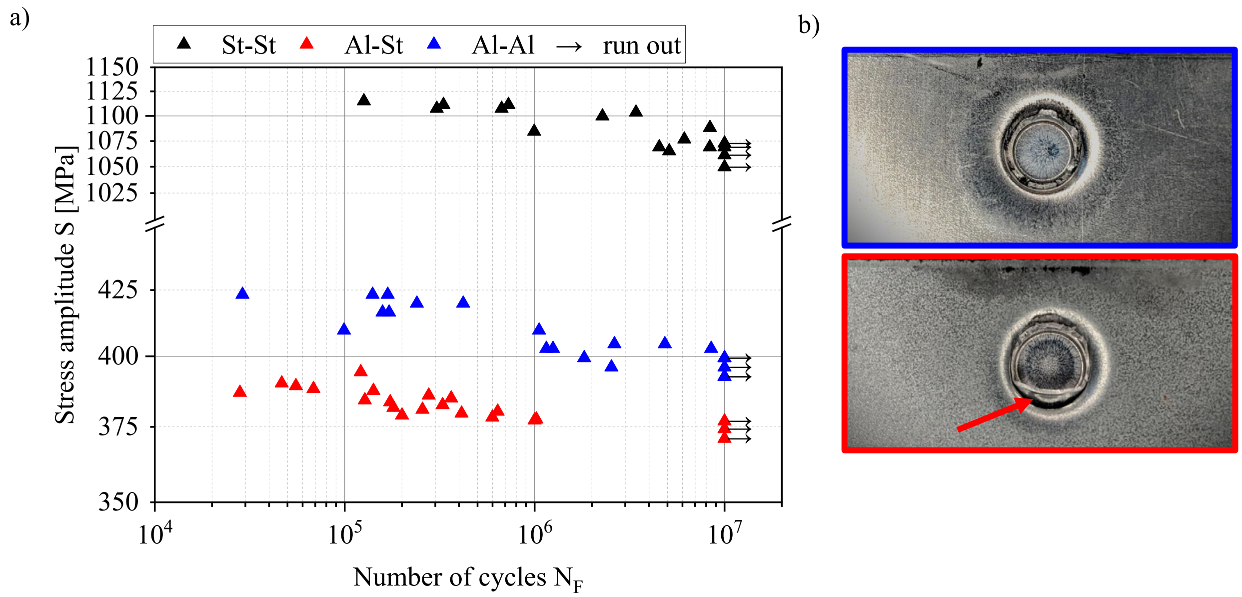

Fig. 6 a) S-N curve of all clinch joint constellations, b) detailed image of the main failure behavior of Al-Al (blue) and Al-St joint (red) the arrow marks the plastic deformation on the remaining cup.

Fig. 6 (b) shows that the remaining aluminum cup in the lower steel sheet of the Al-St joint has a pronounced plastically deformed zone (marked by an arrow) compared to the Al-Al joints. This difference in failure mode proves that the local loading situation must be influenced by additional factors. As a matter of fact, the current approach did not consider the likely influences of the binding mechanisms which will be the focus of future research. However, the investigations presented, provide a first approach to obtain S-N curves for clinch joints and thus pave the way for a more generalized lifetime prediction of clinch joints considering the particular needs of versatility.

Summary

St-St, Al-Al and Al-St clinch joints were manufactured. Fatigue tests of the joints were carried out, and the fracture surfaces were analyzed, subsequently. An approach to transfer the force versus number of cycles (F-N) curve into a damage-relevant stress versus number of cycles (S-N) curve was established for a neck fracture failure mode. The approach considered the damage-relevant nominal stresses calculated for the neck area based on the fatigue tests' forces and the clinch process's initial stresses.

Acknowledgement

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