Influence of process parameters on mechanical properties of lamination stacks produced by interlocking

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Abstract. Interlocking is mainly used in the manufacture of lamination stacks for the cores for electrical energy converters. The process involves the embossing of nubs, which are subsequently stacked and joined by an interference fit. For an optimal design of interlocked joints, sufficient knowledge of the relationships between various influencing parameters in the manufacture and the resulting stack properties is essential. In addition to the design parameters nub geometry, size and embossing depth, the process parameters embossing clearance, counterpunch and blankholder force influence the joint strength. In addition to these fixed parameters, continuously varying uncertainty such as wear, which can lead to a rounding of the tool edges, affects relevant stack properties like the joint strength. The mechanical loads in the area of the tool edge which are responsible for this rounding mainly act immediately before material separation and have to be considered in the embossing process. However, the influence of punch edge radii on the joint properties during the interlocking process has not yet been investigated. In order to describe the interdependencies between different influencing parameters on the achievable mechanical strength, experimental investigations are carried out. Therefore, cylindrical nubs are interlocked with varying embossing depth, clearance and edge radii. The joint strength is determined via tensile tests. Key findings are that the joint strength of nubs with increasing abrasive wear on the cutting edge of the embossing tool are compensated by a higher embossing depth. The minimum embossing depth required for stacking and the embossing depth at which the optimum strength is achieved depend on the embossing edge radius and thus on the current abrasive wear state.

Introduction

Interlocking is a process for manufacturing iron cores in the stators and rotors of electric motors. These are assembled from thin sheets that are electrically insulated from each other in order to minimise iron losses. To build up a lamination stack, interlocking nubs are introduced into the sheets by an embossing operation and then pressed into each other, creating a force-fit joint. For electrical insulation, the sheets are coated in advance. Various coating materials are used for this purpose, which are classified according to their chemical composition, insulating capacity and the area of application [1]. Common coating types are organic coatings of type C3 and the completely or predominantly inorganic C5 coatings. C3 coatings can contribute to an improvement in punchability compared to uncoated materials. The same applies for C5 coatings depending on the fillers and additives. Therefore, both are in principle suitable for use in punch-stacked components [2]. Since the working principle of interlocking is based on friction and is therefore dependent on the tribological conditions, the choice of the coating material potentially influences the joint quality.

Fig. 1(a) shows the schematic sequence of the punch-stacking process chain consisting of punching, embossing and stacking. For use in electric drives, both the magnetic and the mechanical properties (joint strength) have to be taken into account when designing interlocked lamination stacks. In order to achieve a high torque density and low power losses, the magnetic properties must be optimised and additional losses caused by the manufacturing process minimised [3].

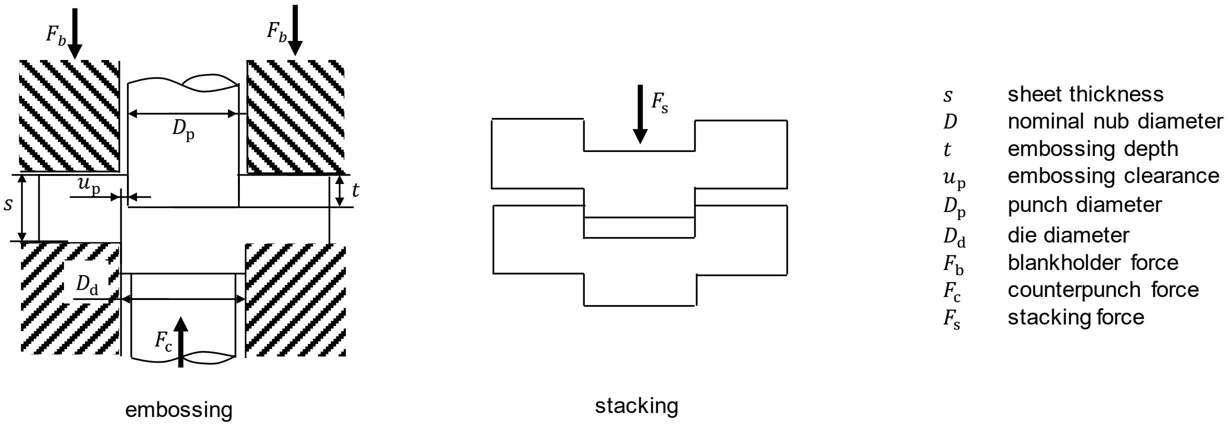

Fig. 1. Schematic illustration of the interlocking process chain.

From a mechanical point of view, the joint strength between the sheet metal lamellae plays a decisive role. To ensure a reliable connection of the lamination stacks in the subsequent assembly steps, a minimum strength is required for robust process handling. The resulting strength of the punch-stacked joint depends on a complex interaction of a multitude of parameters. The geometry, position and number of nubs as well as the material properties (sheet thickness, alloy combination, coating material) are determined during product design of the electric drive. Parameters such as the embossing clearance, the blankholder and counterpunch force as well as the stacking force are determined by the tool design and can be varied within a specific range. The tool parameter embossing clearance and the process parameter embossing depth have been shown to have the greatest influence on the joint strength in previous investigations [4,5]. As an uncontrollable parameter, wear causes alterations in the tool configuration and thus directly affects the mechanical properties of the embossed nubs. Since the embossing process is a punching process that is stopped just before cracks are initialized into the material, wear on the edge of the embossing tool plays an important role.

From the literature it is known that the so-called punch phase in which the blanking tool separates the products from the sheet metal strip causes abrasive wear on the cutting edge of the tool [6]. This abrasive wear is influenced by the acting contact normal stresses, which correlate with the maximal punch force $F_{\max}$. The maximal punch force is defined as the cutting force $F_{\max} = l \cdot s \cdot k_s$, with the cutting line l, the sheet thickness s and the shear strength shear strength k_s, according to Lange [7]. The shear strength depends on a various number of variables such as tool parameters (clearance, tool wear, surface conditions of the active elements), material parameters (tensile strength, elongation at break, alloy composition) and other process parameters (lubrication, temperature, cutting speed) [8].

Due to high accuracy requirements in the cutting step and the influence of the embossing gap on the joint strength, very small clearances between punch and die are selected for both the cutting step and the embossing step in interlocking, which leads to high contact normal stresses and promotes the occurrence of abrasive wear. As mentioned above the embossing step corresponds to a shear cutting process in which the slug is not sheared off completely until it breaks, but remains connected to the base sheet due to a sufficiently small immersion depth of the punch. Because the maximum force occurs shortly before the material fails by tearing off the slug, it can be assumed that only abrasive wear in the form of rounding of the punch edge has to be considered. Further wear phenomena such as adhesions, scratches and chipping are found on the lateral surface and can be neglected during the embossing process. Literature in area of shear cutting demonstrates that abrasive wear directly affects the properties of the manufactured part.

Former studies prove that the occurring tool wear plays a significant role in the shear cutting of electrical sheet and can also have an effect on the magnetic properties [9,10] in addition to the influence on the mechanical properties and the cutting contour [10,11]. Although this correlation for punching tools is present in recent studies, abrasive wear on embossing tools and its effect on the stack properties have not yet been investigated.

An established method of monitoring the wear condition of punching tools is the measuring of force signals during the process [12]. Previous studies have shown that it is possible to estimate the current punch edge radius [13] and the resulting workpiece characteristics [14] based on time series, for example using machine learning algorithms. This methodology can potentially be used to monitor the current wear condition during punch stacking and to adapt to it by appropriate countermeasures. The hypothesis put forward in this paper is that by monitoring the wear condition in-situ, the optimum range in the process window in terms of joint strength can be determined in real time and abrasive wear can be counteracted by adjusting the process parameters. In order to lay the foundation for this, the correlations between the parameters embossing depth, embossing clearance and punch edge radius and the resulting joint strength are to be investigated experimentally in this paper.

Approach

In order to investigate the influence of the main process parameters and the tool wear state on the joint strength, experimental investigations are carried out. For the experiments electrical steel sheets of grade M270-50A according to DIN EN 10106 [15] are used with two different coating materials (C3 and C5). The sheet thickness is 0.5 mm and the specimen have a size of 35x35 mm containing one cylindrical nub per layer. The nubs have a circular cross section with a diameter of 6 mm. The single sheets where stacked using a punch with the same diameter. For the investigation the parameters blankholder force and counterpunch force are kept constant. The embossing depth is varied in the range 60 % to 125 % in relation to the sheet thickness. The embossing gap is 2 % or 1 % of the sheet thickness. Table 1 gives an overview over the experimental parameters.

Table 1. Dimensions and parameters used in the experimental investigation.

material and design parameters		constant process and tool parameters		varied properties and parameters	
sheet thickness s	0.5 mm	stroke height	35 mm	coating type	C3, C5
specimen size	35 x 35 mm	stroke speed	15 strokes/min	embossing depth t	60 % - 125 %
material	M270-50A	blankholder force F_b	3,000 N	embossing clearance u_p	2 %, 1 %
punch diameter D_p	6 mm	counterpunch force F_c	800 N	punch edge radius	sharp (R00), 0.1 mm (R01), 0.2 mm (R02), 0.3 mm (R03)
		stacking force F_s	5,654 N		

Fig. 2(a) shows the test tool used for the embossing step and the test set-up for stacking the nubs. The tool used for embossing is a test tool for simple shear cutting operations with a closed cutting contour. A round punch with a diameter of 6mm is used. To investigate the influence of tool wear in the form of abrasion, punches with an artificially rounded embossing punch edge (indicated in Fig. 2(a)) with different radii (see Table 1) are used for embossing in addition to a punch with a sharp edge. The tool is equipped with a piezoelectrical force washer (Kistler 9015A) to acquire the embossing force and an eddy current sensor (µEpsilon EU8) to acquire the motion sequence of the tool.

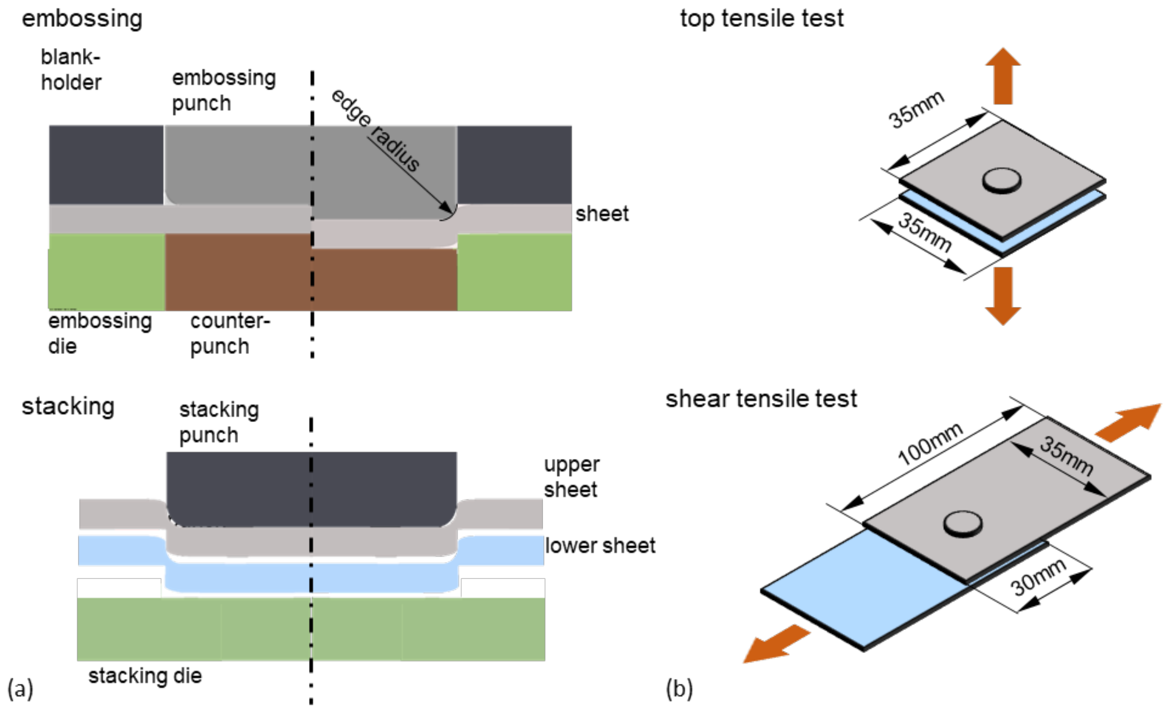

Fig. 2. Experimental setup for embossing, stacking and tensile testing.

The samples are stacked on a tensile-pressure testing machine, whereby the lower sheet is placed on the convex side of the nub on a flat pressure plate and a punch with the same geometry as the embossing punch presses the nub of the upper sheet into the lower nub. The punch movement is force-controlled at 500 N/s until a defined upper force limit is reached, for which a value of 5,654 N was empirically determined, which corresponds to a compressive stress of 200 MPa in relation to the nub cross-section. In order to prevent the lamination stack from sticking to the punch due to radial clamping forces caused by elastic deformation, the stacking punch has an edge radius that is 0.1 mm larger than that of the embossing punch.

Fig. 3 shows the curves of the punch force over time for both materials as a function for different embossing depths using a sharp punch (R00) and for a slightly rounded punch with an edge radius of 0.1 mm (R01). The graphs are synchronised so that the times of impact of the blankholder coincide. Since the embossing depth is varied by adjusting the bottom dead centre of the press, the punch speed changes with the embossing depth, therefore the time at which the punch hits the sheet also changes, as can be seen from the rapid increase at between 0.5 s and 0.6 s. With the rounded edge, the punch consistently hits the sheet a little later, as the length of the punch is slightly shorter with the artificially worn rounded-edge punches, but the hold-down is set the same. In the embossing phase, different characteristic progressions can be seen depending on the embossing depth. At high embossing depths, the typical force curve of shear cutting results with an abrupt drop in force after reaching the critical breaking stress. Using a sharp punch, this can be observed at embossing depths of 100 %. In this case, fracture initiation already takes place at embossing depths in the range of 80 % to 85 %. Below this, the curve of the punch force is decisively dominated by the punch travel and the corresponding counterpunch and blankholder forces.

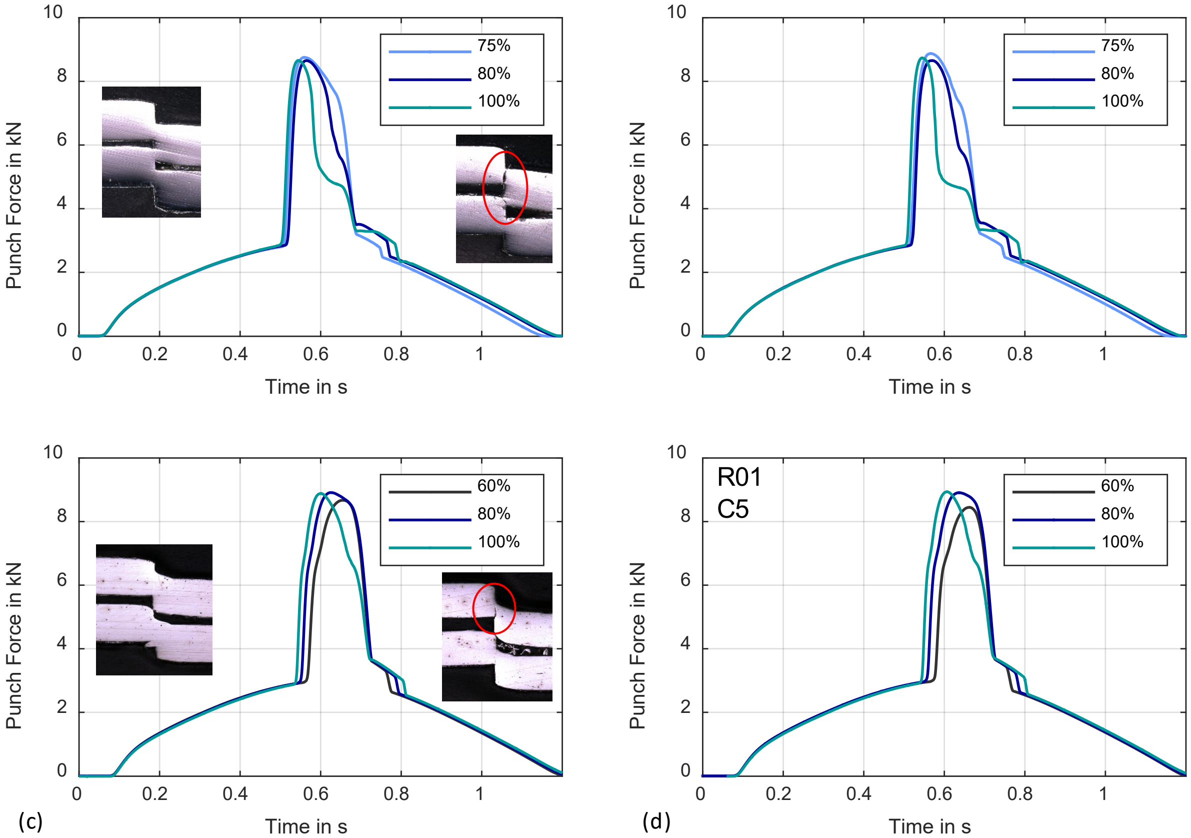

Fig. 3. Punch force curves for different embossing depths (in relation to the sheet thickness) with sharp (R00) embossing tool, (a) and (b), and rounded tool (R01) with edge radius 0.1 mm, (c) and (d); (a) and (c) show the curves for the material with C3 coating, (b) and (d) the material with C5 coating.

When using a worn punch, the material breaks at higher embossing depths. In this state, tensile and compressive stresses are superimposed in the forming zone, local stress peaks are reduced, and the material allows greater plastic deformations. As a result, the embossed nubs do not tear off at embossing depths of 90 % and below.

Fig. 4 demonstrates how the punch force changes with different edge radii at the same embossing depth (100 %). It can be seen that the maximum force increases with increasing edge radius. This is consistent with investigations of force signals during shear cutting [16]. Since the edge radius increases, the effective clearance decreases depending on the depth the tool penetrates the die. As a result of a smaller clearance, the maximum cutting force is reduced. This effect is counteracted by an increasing radius, due to the greater load which must be applied to the tool system to induce cracks in the material. According to Kubik et al., the effect of superimposed tensile and compressive stresses dominates, resulting in an increased maximal force [16].

Furthermore, it can be observed that in the case of a slight fillet, the shape of the curve changes significantly. There is a sharp drop in the force and a kink in the curve immediately before reaching the bottom dead centre (which is passed through at approximately 0.63 s), which indicates that the tensile strength of the material has been reached locally and damage and possibly initial cracking occurs in the area of the tool edges, so that a further increase in the embossing depth can be expected to cause the punching nub to tear off. It is noticeable that the curves for R01 and R02 are very close together. Only a further increase of the edge radius to 0.3mm causes the critical embossing depth to shift upwards until breakage occurs to such an extent that cracking does not yet occur at 100 % embossing depth. Due to these characteristic changes in the force curve, it is possible to predict the state of wear, expressed by the edge radius for the case at hand, using known methods [6].

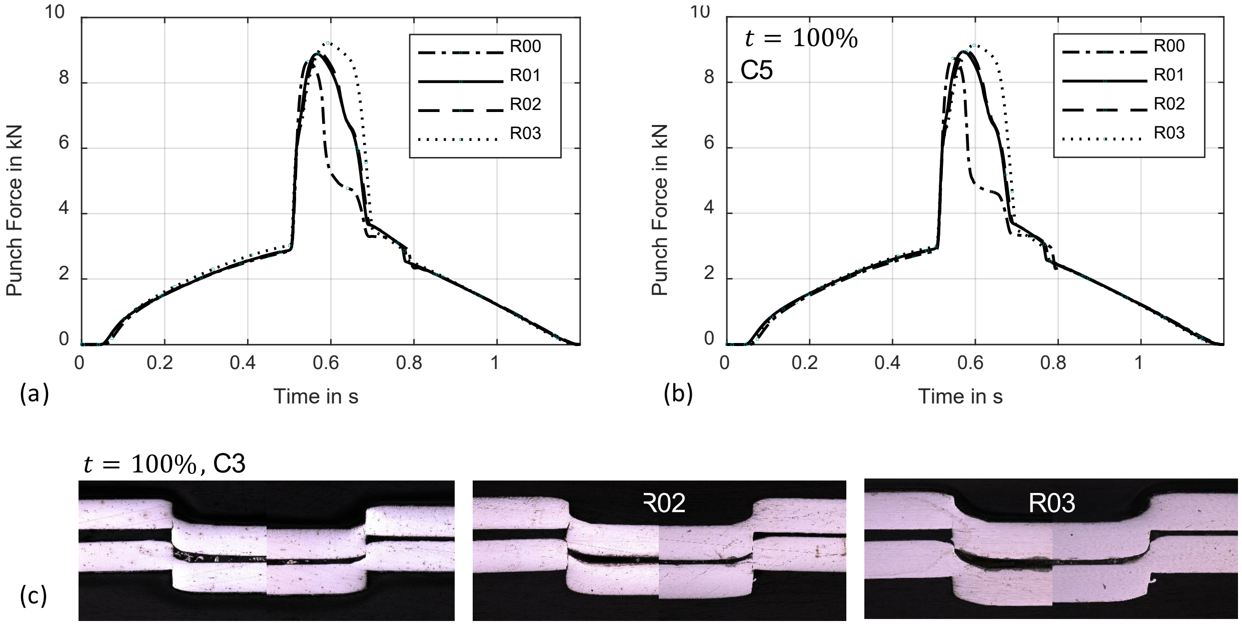

Fig. 4. Punch force curves for different edge radii of the embossing tool for the materials with C3 coating (a) and C5 coating (b) at a stamping depth of 100%.

The joint strength was determined by quasi-static tensile tests, as illustrated in Fig. 2(b) with five repetitions per process parameter set whereby the focus is on the maximum force achieved in the load direction until separation of the stack. For the case R01 shear as well as top tensile tests were performed and evaluated. The results for stamping depths of 80 %, 90 % and 100 % show that the shear strength is significantly higher than the pull-off strength in top tensile test in all cases (see Fig. 5), which can be explained by the fact that in the direction of loading in the sheet plane, in addition to the force-fit connection, they are also joined by a form-fit force component. Nevertheless, both tests show the same qualitative correlation when varying the embossing depth. In the following, only the results from the top tensile tests are used to simplify the investigation of the influence of edge radius, embossing depth and embossing clearance.

Results

In order to find out how the relationship between embossing depth and joint strength changes with increasing tool wear, investigations are carried out with one sharp and three rounded embossing tools. Nubs with different embossing depths are introduced into the samples and then two sheets are pressed together. In the following, the maximum forces achieved in the top tensile test are used to evaluate the joint strength.

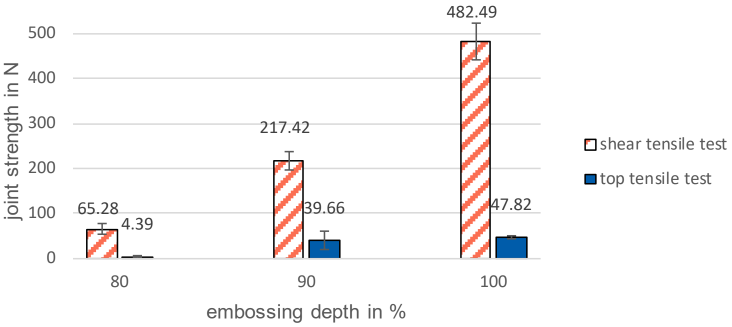

Fig. 5. Comparison of shear and top tensile test for an embossing radius of 0.1 mm.

The results are intended to provide the basis for making a real-time prediction of the joint strength by monitoring the wear condition on the basis of force signals. In addition, it will be investigated whether a targeted rounding of the tool edge can have a positive effect on the joint strength.

Fig. 6 shows the results of the tensile tests for the materials with C3 and C5 coating. Using a sharp tool (R00), a stacking with the present configuration is possible from an embossing depth of 70% (with C3) or 75% (with C5). Below this, no permanent joint can be created. The strength values for R00 of 13.75N at 70% and 14.09N at 75% are at an almost constant, low level in this range. Further increase of the embossing depth to 80% leads to a slightly decreased joint strength. For C5, the lowest embossing depth with which a successful package was produced is 75%. The strength values of 9.45N and 9.69N for 75% and 80% are also very close to each other, whereas the maximum strength value of 12.5 N is measured at 85%. The maximum achievable embossing depth before the nub breaks off is 80% for the C3 material and 85% for C5.

In the tests with rounded tool edges, three main observations can be made:

1. Both the minimum embossing depth at which a laminations stack can be joined and the maximum embossing depth before nub breakage occurs increase significantly compared to a sharp tool. The increase in the minimum embossing depth is due to the fact that, because of the rounded tool edge, there is a significant radius on the inside of the dimple as well as on the underside of the sheet in the rollover zone of the nub, which increases with increasing tool edge radius. This reduces the remaining actual contact area on which the contact normal stress can act in the radial direction. The maximum stamping depth increases because with a rounded punch, the stress peaks at the sharp edges are lowered, causing cracking to occur later. For C5, in all cases with a rounded tool, regardless of the edge radius, a joint can only be made from an embossing depth of 90%. With the largest radius of 0.3mm (R03), nubs with a maximum embossing depth of 125% can be successfully stacked for both C3 and C5.
2. After reaching an optimum, the strength decreases again with a further increase in the embossing depth. This could indicate that if the embossing depth is increased too much, the crack formation is already initiated at least locally and the thus pre-damaged nub no longer has the necessary strength in the subsequent stacking process to build up a press-fit with the same joint strength.
3. The maximum achievable strength with optimal choice of embossing depth increases significantly compared to the case with sharp embossing tool. It can be clearly seen that the maximum achievable joint strength in all cases with a rounded tool edge is above the strength with a sharp tool, regardless of the radius. The optimum is achieved at 100% embossing depth with a slight rounded tool with a radius of 0.1mm and is 47.82N with C3 coating or 44.42N with C5 coating. With further increase, the maximum strength decreases again and tends to occur at higher embossing depths.

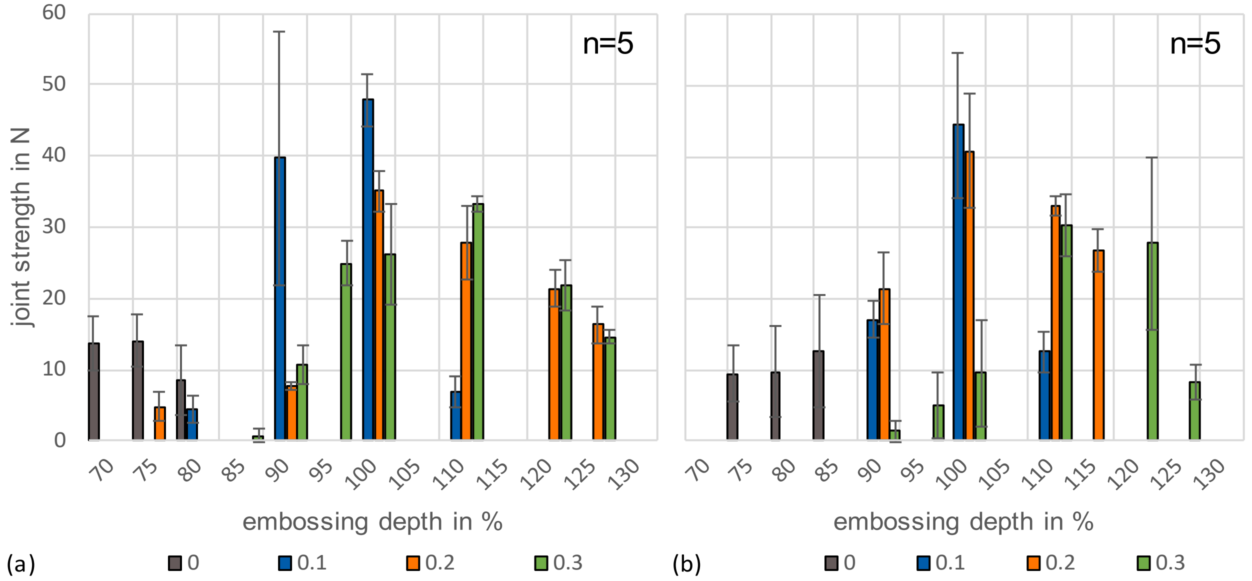

Fig. 6. Results of top tensile tests for different embossing depths and embossing tool radii at samples with C3 coating (a) and coating of type C5 (b).

Based on the tests carried out, the process window for the present joint configuration with a cylindrical nub of 6mm diameter can be determined empirically using an embossing clearance of 2%. In Fig. 7 this is shown as a function of the punch edge radius and the embossing depth. On this basis, both an upper and a lower limit can be read off for the respective radius. These differ only slightly for the two materials examined with different coatings.

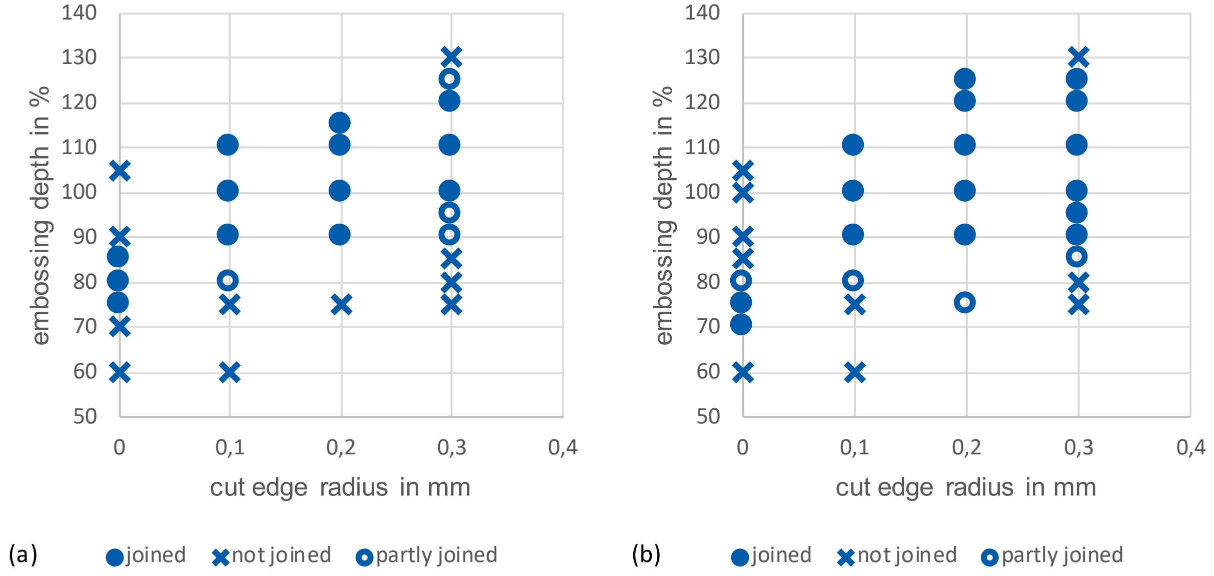

Fig. 7. Process windows for the investigated interlocking setup for test stacks of C3 (a) and C5 (b) coated sheets.

For achieving high-quality lamination a small clearance between the embossing punch and die is favorable [4]. Therefore, the influence of the embossing clearance is further investigated. Fig. 8 shows that the joint strength increases when the embossing clearance decreases from 2 % to 1 %, which is in accordance with studies by Lin et al. [4], where the same relationship between the embossing clearance and the joint strength was established with a sharp punch of 2mm diameter. In addition, the results indicate that the maximum embossing depth at which successful stacking is possible is about the same as with a smaller gap, although higher local stresses are expected in the embossing step. Furthermore, the lower process limit for the embossing depth is lower with a smaller embossing gap, which leads to a significantly larger process window. This is valid for both C3 and C5 coated material.

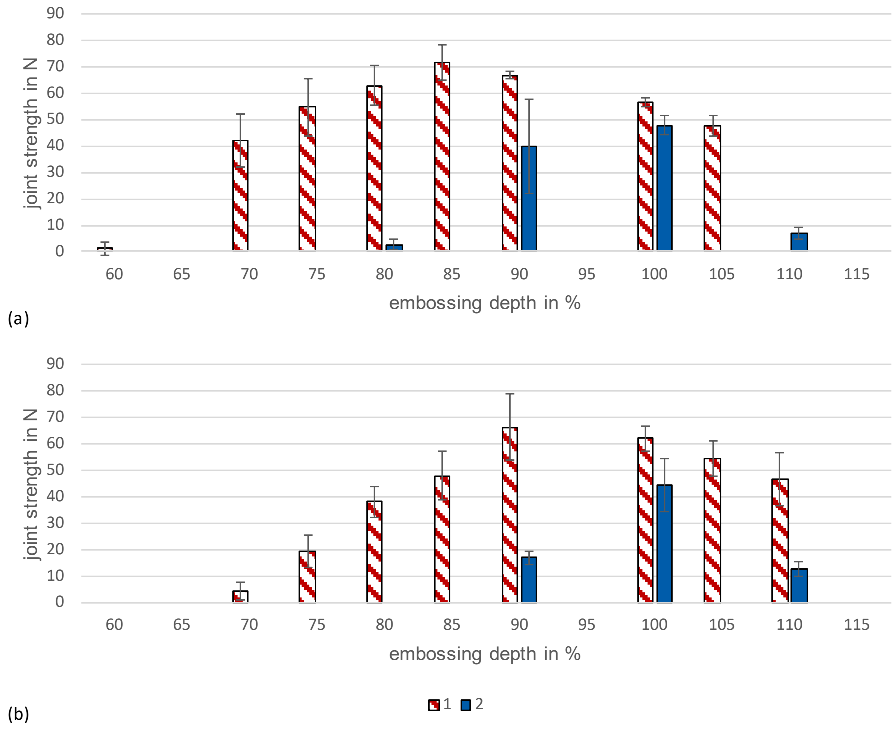

Fig. 8. Joint strength determined in top tensile tests for different embossing clearances 1 % and 2 % at various embossing depth with (a) C3 and (b) C5 coating.

Summary

In this work the influence of tool wear expressed by a rounding of the embossing tool edge on the joint strength of interlocked lamination stacks with cylindrical nubs was investigated.

It can be found that the achievable embossing depth increases when using an embossing punch with a rounded tool edge. Coincidently, the minimum embossing depth required for stacking and the embossing depth at which the optimum strength is achieved depend on the punch edge radius. If the embossing depth is regarded as a control variable, this knowledge can be used to react to wear occurring on the tool edge by adjusting the process parameter embossing depth. Another approach, which is obvious in order to design the interlocking die with regard to optimum mechanical joint strength, is to design the tools for stamping from the outset in such a way that an edge radius is provided in order to achieve the optimum of the achievable joint strength.

The comparison of the two different coating types C3 and C5, which are commonly used for blanking of electrical sheets shows no clear difference in the suitability for interlocked lamination stacks.

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