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Influence of cold rolled surface structures with undercuts for interlocking joints on bending processes

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Abstract. Lightweight design is one of the methods to reduce CO_2 emissions and optimize energy efficiency in the transportation sector. The main motivation of this study arise from weight reduction through multi-material design with the materials commonly used in the automotive industry, steel and aluminum. Metallurgical bonding of steel and aluminum carries the risk of forming brittle intermetallic phases. Hence, new joining techniques such as joining by forming or casting are promising for these multi-material components. Previously, a hybrid component method was presented using channel-like surface structures with undercuts on a steel sheet created in a modified cold rolling process. In a subsequent high-pressure die casting, the channels were filled with aluminum melt, forming an interlocking connection as it solidified. As automotive components demand increased complexity, the bending of the structured sheet before casting was investigated. This study aims to analyze how the surface structure affects the bending process. Numerical simulations and experiments were used to investigate the effect on the maximum bending force, the resulting bending angle and springback. Therefore, the parameters bending angle, bending radius, and the lateral or longitudinal orientations of the channel structure on either sides of the bend were taken into account. The results showed a strong influence of the lateral and longitudinal orientation on the maximum bending force. Furthermore, a minor effect of the bending radius on the force and springback was found.

Introduction

To achieve the needed reduction of CO_2 emissions and improve the energy efficiency, changes in the transportation sector are needed. Lightweight design is an established method to optimize the energy efficiency, which has still a huge potential, especially for the automotive sector and in the targeted transformation towards electric vehicles. One way to reduce weight is by exploiting the advantages of different materials. Therefore, this research focuses on a multi-material design of two commonly used materials in the automotive industry. A steel is used for its high strength and ductility in combination with aluminum, which provides high specific strength and exceptional lightweight potential. A component of this combination can meet the automotive key requirements, i.e. performance, function and safety, while reducing weight.

State of the Art

The joining of different metal classes, in this study steel and aluminum, is challenging due to their dissimilar thermo-physical properties [1]. A metallurgical bonding brings the risk of the formation of brittle intermetallic phases and makes joining techniques such as fusion welding unsuitable. Therefore, multi-material components require new joining methods like joining by forming or casting [2,3]. Advanced processes like cold or friction stir welding can form a metallurgical bond under high interfacial pressure overcoming the problems of fusion welding. Mechanical joining processes like riveting or clinching interlock different materials by forming and avoid a metallurgical bonding [4]. Joining by casting brings the advantages of hidden joint areas and the possibility for more complex geometries. In hybrid casting, molten metal is cast around an insert of metal in solid state [3]. A metallurgical bond with a shear strength of up to 7.7 MPa was achieved for a combination of aluminum and coated steel [5]. Joining by casting with an interlocking connection has been investigated for steel with aluminum [6] but is very common for polymers (joining by molding) as well [7]. In both cases, the process usually contains a surface structuring and an assembly step. For the surface structuring, processes like micromachining [8], micro-stamping [9], electron beam sculpturing [10], or additive processes with ball-head pins [6] or nanospikes [11] are possible.

To develop an efficient process chain for interlocking on large areas, this research focuses on a cold rolling process to form channel structures with undercuts onto the surface of sheet metal (Fig. 1 a) [12]. In an initial pass, a structured roller imprints a rectangular channel and rib structure in a steel sheet (Fig. 1 b). The undercuts are formed in a subsequent pass by flat rolling (Fig. 1 c). This is achieved as the tips of the ribs spread in lateral direction resulting in a dovetail geometry. For larger flattening, the channel side wall can fold over the channel bottom and form an inner notch [13]. This sheet material was inserted into a high-pressure die casting process at the Foundry Institute of RWTH Aachen University. The liquid aluminum flows into the undercut channels and interlocks as the melt solidifies [14]. The compound strength is achieved by a clamping between aluminum and steel and is therefore decisively influenced by the undercut width.

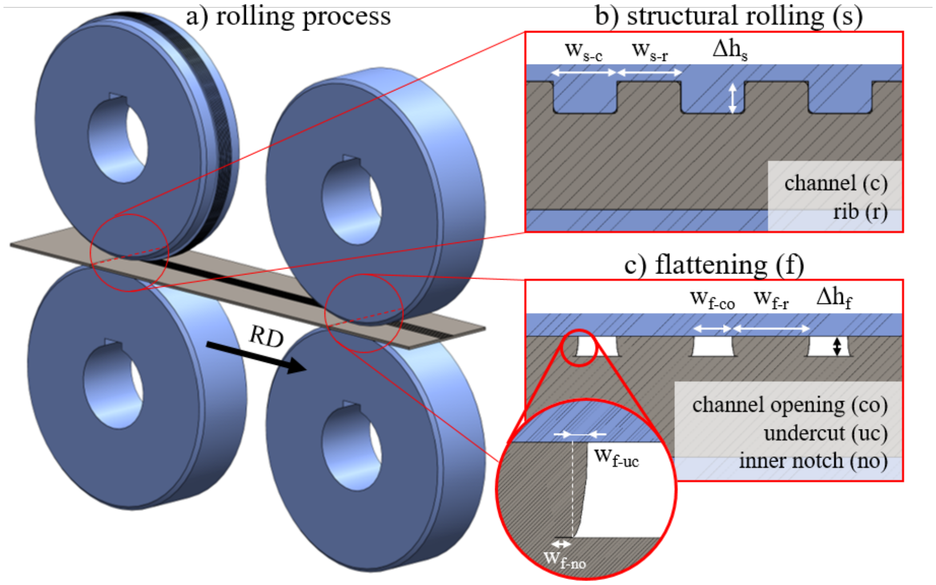


Fig. 1: a) surface structuring by cold rolling, b) structural rolling and c) flattening

In previous studies, hybrid casting tests with flat joining areas were performed, which achieved compound shear strengths up to 45 MPa [15]. As automotive components require an increased complexity of the parts, a section of an automotive roof cross beam was selected as a demonstrator part [16] (Fig. 2 c). Influencing factors of the die casting process have been analyzed and tensile strengths of up to 7.4 MPa were reached [17]. The complicated demonstrator geometry requires a bending of the structured sheet before casting (Fig. 2 a, b). It was assumed that the bending operation would affect the structure geometry. A narrowing of the channel opening would impede the filling with the aluminum melt and a reduction of the undercut width would reduce the compound strength. A previous study has revealed, that in the most unfavorable conditions investigated, the channel opening would decrease by 73% and the undercut width by 75% [18]. This study investigates how bending parameters like bending force or springback may depend on the imprinted surface structure. Similar to the previous study, the orientation of the structure to the bending axis might also have an influence. This knowledge is of interest as precise contour geometries are needed, when inserting the bent sheet into a die casting mold. Therefore, this study aims to analyze how the surface structure affects the bending operations.

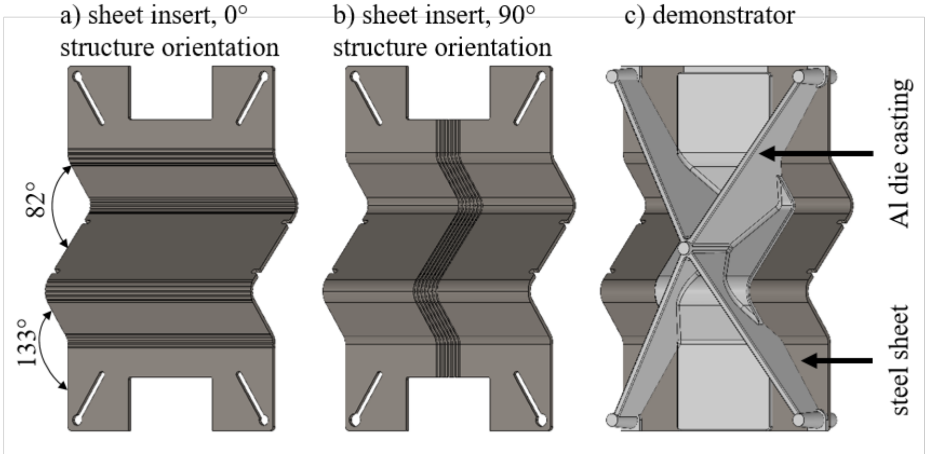


Fig. 2: Process for hybrid components, a) and b) steel sheet insert with different surface structure orientations (0°, 90°), c) demonstrator part

Materials and Methods

Materials. The steel sheet inserts of the previous studies were produced of DC04, which is therefore used for this study as well. The material properties of DC04 are defined in Table 1 and Fig. 3 for the upcoming simulation. The flow curve was measured in stack layer compression tests up to a true strain of 0.3 at IBF and extrapolated with a modified Hollomon approach up to a true strain of 0.6 (Fig. 3). The extrapolation was based on the data points at higher strains to receive a good continuity between experimental and extrapolated data. As the bending force is considered in this study, the extrapolation might influence the accuracy of the results.

Table 1: Material properties of DC04 at room temperature

Mass Density [t/mm³]	Young's Modulus [MPa]	Poisson's Ratio	σ_0 [MPa]
7.85E-09	210,000	0.3	265.2

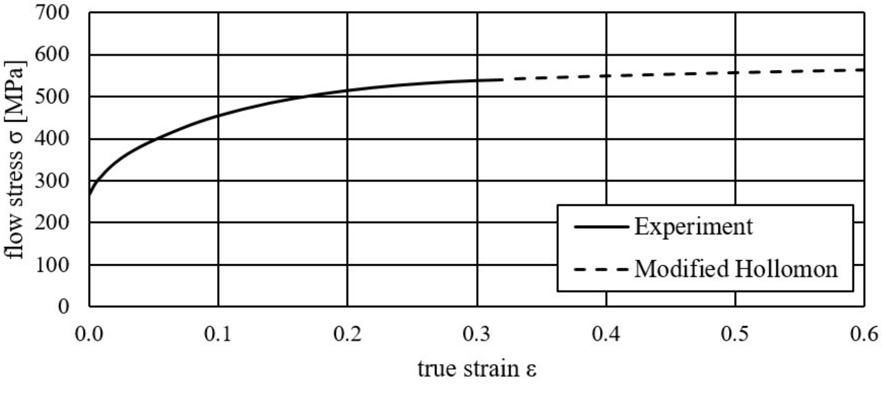


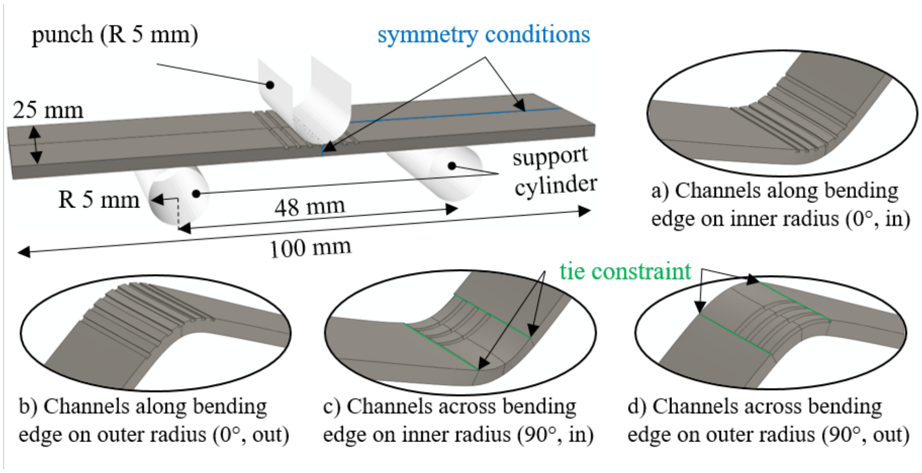
Fig. 3: Flow curve of 2.0 mm DC04 at room temperature

Structural rolling and flattening. Plates of DC04 were structured by cold rolling to create structured sheet material for the bending experiments. The plates were 2.0 mm thick, 200 mm wide and 245 mm long. The rolling was performed on a roll forming machine P3.160 by the company Dreistern GmbH & Co. KG with experimental parameters selected based on previous studies [13,15]. At the first rolling stand, a combination of an upper profiled roller (92.5 mm radius) and a lower flat roller (93.0 mm radius) were installed for the structuring. The profiled roller had seven ribs and six channels, each 1.0 mm wide, resulting in 13 mm structured width. The milled channels were 0.5 mm deep and had a fillet radius of 0.05 mm at the rib edges. Two flat rollers (93.0 mm radius) were used on the second stand for the consecutive flattening pass. A reference sample was selected after structuring and flattening and the geometry was measured by cross-section preparation. A channel depth Δh_s of approx. 465 µm resulted from the structuring. During flattening, the depth was reduced to $\Delta h_f = 343$ µm. For the simulation of the bending operation, an idealized structure geometry with the dimensions given in Table 2 was derived by averaging the measured values.

Table 2: Idealized reference structure geometry

channel opening width w_{f-co}	660 µm	rib width w_{f-r}	1346 µm
undercut width w_{f-uc}	57 µm	inner notch length w_{f-no}	93 µm

3-point bending. The bending test uses two support cylinders and a vertically moving punch with a load cell. The cylinders with a 5 mm radius are horizontally placed in a distance of 48 mm (center to center) and can freely rotate (Fig. 4). The structured sheet material from the previous cold rolling step was cut into specimens of 25 mm x 100 mm and placed on the support cylinders. The punch with a 5 mm radius moves vertically in the middle between the support cylinders to bend the sample. Depending on the displacement of the punch, a bending angle of up to 120° was reached.



a) Channels along bending edge on inner radius (0°, in)

b) Channels along bending edge on outer radius (0°, out)

c) Channels across bending edge on inner radius (90°, in)

d) Channels across bending edge on outer radius (90°, out)

Fig. 4: Bending simulation with different surface structure orientation, a) 0°, in, b) 0°, out, c) 90°, in, d) 90°, out

Simulation of the bending process. A 3D FE-model of the 3-point bending was set up in the software Abaqus (Fig. 4). The 3D approach was selected to model the bending behavior of the channels along (0°) and across (90°) the punch edge. Together with the channel structure on the inside (in) or outside (out) of the bend, four different configurations resulted (Fig. 4 a-d). As the alignment of the punch over a channel or a rib might affect the bending result, especially at small radii, the punch center was always positioned over the middle channel during the simulations. Two symmetry planes were used along the centerlines of the width and length of the specimen to reduce the computing effort. The sheet was given a fine mesh (approx. 0.05 mm) in areas of higher deformation like the bending apex to accurately display the formation of the structure. In areas of lower deformation such as the bending legs, a coarser mesh (approx. 1.0 mm) was selected to save computing effort. Furthermore, for the simulation of the channels across the bending edge (Fig. 4 c, d) the channels were truly modeled only around the bending apex. Thus, a section with the length of the punch diameter was given a surface structure. The bending legs, displayed by rectangular parts without surface structure, were tied to the structured section by a *tie constraint*. Hexagonal elements with reduced integration (C3D8R) were used for the mesh and a convergence study was performed regarding the fine-meshed areas. The punch and the support cylinders were assumed to be rigid surfaces. A reference point in the middle of the punch was used to extract the bending force. The contact between the sheet and the punch as well as the support cylinders was defined as *surface-to-surface* contact with a friction coefficient of 0.1 [19]. Higher friction coefficients of up to 0.3 were tested but this did not lead to any significant change in the bending force or springback. The process consists of a downward movement of the punch for the bending and an upward movement to relieve elastic deformation. In the simulation study, the punch displacement, the punch radii and the four orientations were varied. The punch displacement between 5 mm to 30 mm resulted in different bending angles. The simulations were validated with a punch radius of 5 mm. Further radii of 3 mm and 10 mm were simulated only.

Results and discussion

The resulting bending angle as a function of the punch displacement for the bending radius R = 5 mm is presented in Fig. 5 a). For all four orientations, a very similar behavior is observed. The error between simulated and measured values is less than 4%. Only for the “0°, in” orientation, the simulation overestimates the experimental values by approx. 6%. However, it can be stated, that for all orientations the springback behavior is very similar, which is evidence for a good reproduction of the behavior.

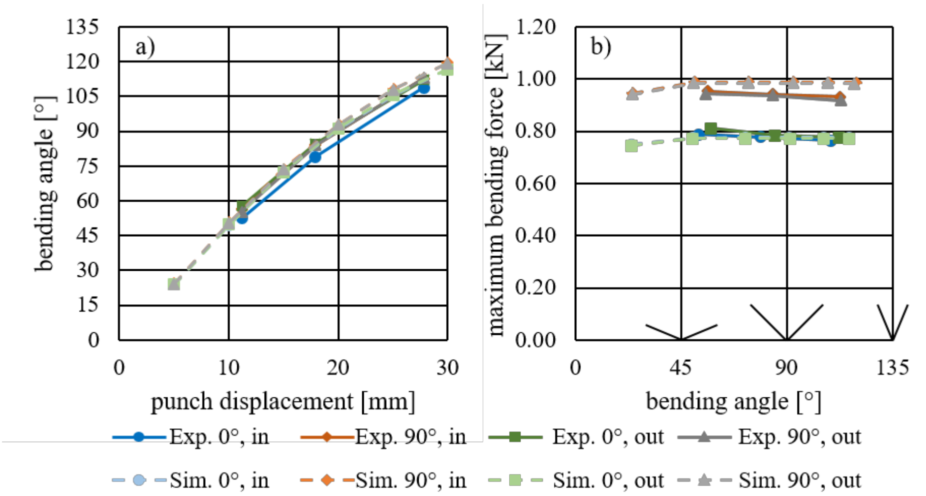


Fig. 5: a) resulting bending angle and b) maximum bending force for simulations and experiments with different surface structure orientations and a punch radius of 5 mm

The maximum force needed for the bending operation is shown in Fig. 5 b). The force is initially increasing with increasing bending angle up to approx. 50° and is stagnating afterwards. The orientations with the channels along the bending edge (0°) show a good fit between simulations and experiments at approx. 0.78 kN in the steady area. For the 90° orientations, the simulations overestimate the experimental values with 0.98 kN by approx. 5%. A comparison of the 0° and 90° orientations shows an approx. 27% larger maximum bending force for channels across the bending edge. An orientation of the structure on the bending inside or outside radius showed no significant effect regarding the maximum bending force. Therefore, the analysis of the effect of the punch radius is exemplary presented for the structure on the inner radius.

Fig. 6 shows the influence of the punch radius on the maximum bending force. For the “0°, in” orientation, the bending force for radii 3 mm and 5 mm is very similar. However, for the 10 mm radius the force increases above 45° bending up to 0.86 kN, which is an additional 11%. A contrary effect is found for the “90°, in” orientation as the maximum bending force slightly decreases with larger radius.

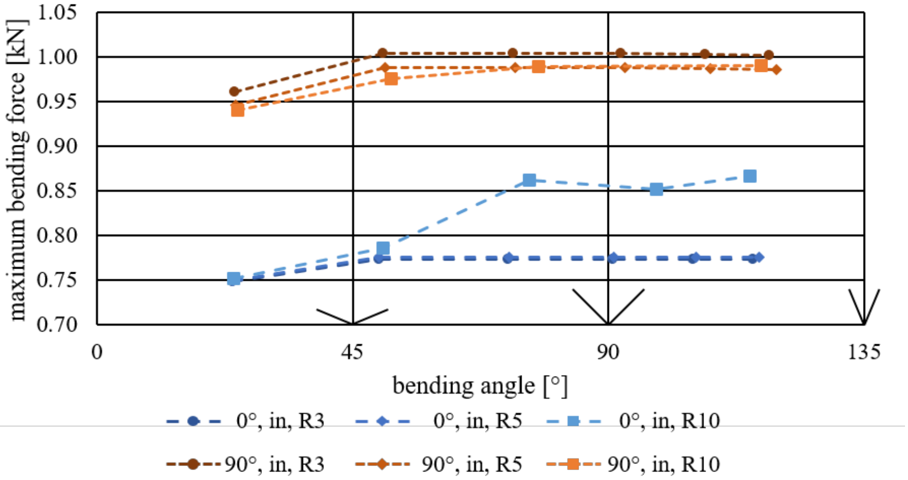


Fig. 6: Maximum bending force for "0° and 90°, in" orientation at bending radii of 3 mm, 5 mm and 10 mm

The effect of the punch radius on the springback is for the "0°, in" orientation (Fig. 7 a) minor. However, for the "90°, in" orientation, the 10 mm radius results in approx. 11% increased springback compared to 3 mm. This is a relevant difference to take into account for the process design.

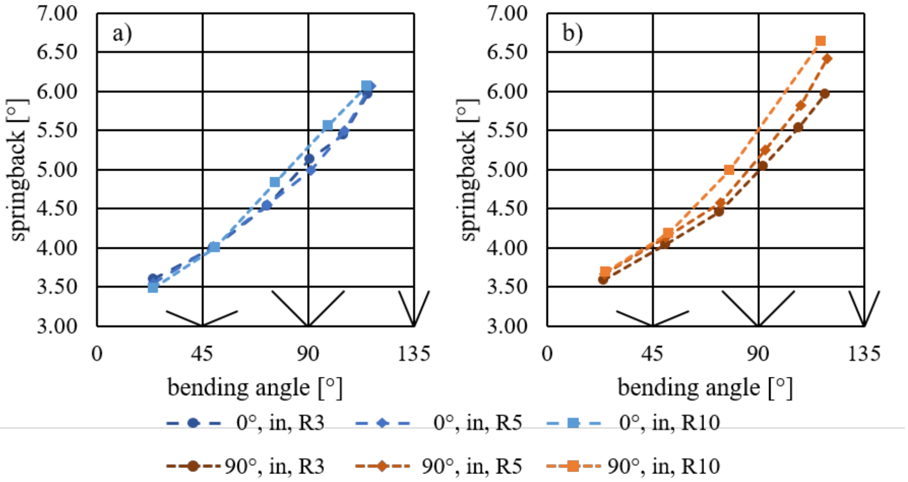


Fig. 7: Springback for 0° and 90°, in orientation at punch radii of 3 mm, 5 mm and 10 mm

Conclusion

The simulation and experimental values regarding the bending angle and maximum bending force for a 5 mm punch radius fit well. The springback seems to be influenced by the structure orientations only slightly. However, an increased springback behavior is found at larger bending radii. This is particular evident for the orientation across the bending edge on the inner radius ("90°, in" orientation) with an 11% increase.

The maximum bending force is influenced by the orientation of the channels across or along the bending edge of the punch. Channels across the bending edge results in approx. 27% larger force and the force is reduced by increasing bending radius. Contrary to that, the force increases when using larger punch radii for orientations with channels along the punch edge. An orientation of the structure on the bending inside or outside radius showed no significant effect. However, this knowledge will help with the design of structured and bent parts. For further study, it might be of interest to investigate how the alignment of the punch above a rib or channel influences the bending behavior.

Conflict of Interest

The authors declare that they have no conflict of interest.

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