

Influences of the Rolling Parameters on Multi-Material Copper-Aluminum Composites via Compound Casting

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Abstract. Multi-material components that consist of copper and aluminum enable the combination of advantageous mechanical, thermal, and electrical properties at competitive cost. While roll bonding is an efficient-solid state joining technique, its implementation requires fully processed, cold-rolled strip material from two process routes. Continuous compound casting in contrast offers a more efficient approach by combining aluminum and copper during casting, followed by flat rolling in a single process route. However, the differences in flow stress between the metals can cause non-uniform elongation and therefore significant shear stresses at the interface during rolling. These stresses may lead to a delamination of the compound if process conditions are not well controlled. This study investigates whether a geometrically structured interface, introduced during compound casting, can contribute to withstanding interfacial shear stresses through mechanical interlocking. In finite element simulations varying process parameters including height reduction, initial temperature, rolling speed ratio, and pass schedule were examined. Results show that a structured interface can effectively resist shear stresses at the copper-aluminum boundary, thereby improving joint stability during deformation. Furthermore, the strain distribution as well as the fluctuation of the shear stresses can be controlled by the process parameters. The findings indicate that the mechanical interlocking by a geometric interface combined with optimized process parameters can enhance the rolling of compound-cast copper-aluminum composites.

Introduction

The integration of different material classes in multi-material components allows for the advantageous combination of their respective mechanical properties. Joining copper (Cu) and aluminum (Al) results in an attractive combination of high mechanical strength, corrosion resistance, and favorable thermal and electrical conductivity, all at a competitive cost [1]. However, joining Cu and Al using classic welding techniques, i.e., fusion welding, is problematic due to significant differences in their physical and chemical properties. Furthermore, the formation of brittle intermetallic compounds (IMC) can significantly reduce joint strength. A common alternative is explosive welding, which is typically employed for batch production and introduces safety risks due to the need for individual preparation and handling of explosives for each weld [1].

In contrary, roll bonding offers a high-throughput, continuous manufacturing while avoiding these safety hazards. The joint formation mechanism can be described by the film theory: During deformation, the contaminant layers present on the surfaces fracture. As a result, the base material extrudes through these cracks and coalesces with the opposing base material [2]. This mechanism implies that metallurgical bonding occurs only after surpassing a threshold deformation level. Beyond this threshold, the bond strength increases with further deformation until reaching the strength of one base material [3]. Reported threshold height reductions in roll bonding vary depending on the

materials and the process parameters: values range from 40% [4], over 60% [5], up to 80% [6] height reduction during the decisive first rolling pass. Larger initial thicknesses require higher threshold deformations or yield lower bond strengths [7].

To ensure effective bonding, it is essential to remove the contaminant layers by thorough surface preparation. This is typically achieved through chemical cleaning processes such as washing and degreasing [8]. In addition, scratch brushing is employed to eliminate oxide layers and induce work hardening, which promotes surface cracking and thus enhances the coalescence of the base materials [9]. An increased surface roughness has also been shown to improve bond quality [7].

While roll bonding itself is a pressure welding process, the introduction of heat triggers diffusion processes, which can improve the bonding by forming IMC at the Cu/Al interface [6]. Therefore, cold roll bonding followed by an additional annealing is common to improve the interface strength [8,10,11,5]. Other studies use elevated temperatures during rolling itself [12,6]. Regardless of method, the IMC formation at the Cu/Al interface is inevitable [6]. As the IMC evolution depends on diffusion mechanisms, the temperature and time during heat treatment and rolling is decisively affecting the bonding [13]. Post-rolling annealing can initially enhance interfacial diffusion and bond strength but may lead to deterioration if unfavorable IMCs form thereafter [5]. In general, lower temperatures and short heat treatment times favor stronger bonds between Cu and Al layers [10]. Above 250 °C, the growth of IMC accelerates distinctly [8]. Several scientific studies identify 300 °C as an optimal temperature for achieving an uniform distribution of deformation with minimal formation of brittle IMC [5,11]. Conversely, processing at temperatures between 400–500 °C leads to severe development of detrimental IMC [5,11].

Another challenge arises from significantly higher flow stresses of Cu compared to Al during deformation, resulting in unequal thickness reductions for each layer [14]. This can be mitigated either by adjusting initial layer heights or employing asynchronous rolling where roller speeds differ. In [9] the Cu layer was in contact with the faster roller, while in [13], the Cu touched the slower roller. Surprisingly, both found, that a ratio of 1.3 was improving the interface bonding. Furthermore, a higher rolling speed tends to reduce the bond strength [5,7].

Despite its efficiency compared to other methods, roll bonding still necessitates multiple processing steps before achieving a final composite product. This includes separate casting and rolling processes and the extensive surface preparation. To streamline this process chain while reducing energy consumption, direct composite casting approaches such as hybrid casting have been explored. One option is twin-roll casting, where a solid Cu strip passes through an Al melt pool so that Al solidifies onto its surface. This technique produces thin and uniform diffusion layers due to brief exposure at high temperature together with large interface deformation during subsequent rolling [15]. Additional rolling passes combined with annealing further influence the bond strength [16], with promising results reported at 300 °C and 40% height reduction [17].

Advancing this concept further involves continuous compound casting, in which both components are joined directly during casting (Figure 1 a)). First, the Cu melt solidifies in an open graphite mold with a copper cooler using a horizontal continuous casting process. The solidified rod is pulled through the mold by rollers. Then, Al melt is poured onto the solid Cu rod and solidifies in the second part of the mold. During the solidification, an initial metallurgical bonding between Al and Cu can be achieved for the subsequent rolling process. Since no contaminant or oxide formation can get onto the surfaces, common cleaning steps like degreasing or brushing become unnecessary [18]. Plates from a horizontal continuous compound casting process showed best shear strength when rolled at 300 °C with a first-pass height reduction of 55% [18]. Insufficient height reduction led to delamination during rolling. It is assumed that during rolling, the shear stresses can exceed the initial joint strength created by compound casting. When there are not enough freshly coalesced and bonded surfaces formed to compensate, the part may delaminate.

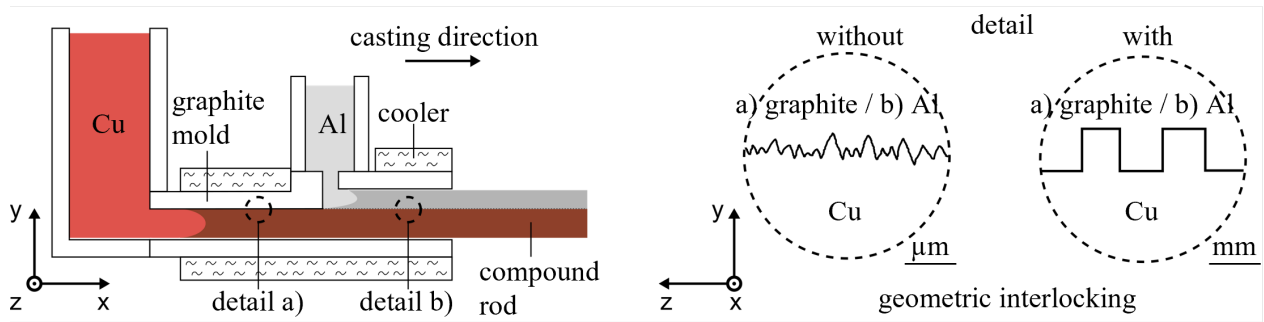


Fig. 1. Continuous compound casting a) without and b) with geometrically designed interface.

The occurring shear stresses can be influenced by factors including the flow stress difference, and thus the temperature and strain rate, the height reduction, the speed ratio between the rollers, the friction coefficient, and the layer thickness. A previous study has explored a geometric design of the interface to counteract the adverse shear stresses [19]. The interface structure is introduced during compound casting by a structured graphite mold (Figure 1 b)). This allows to use both, a metallurgical bond together with a mechanical interlock.

Given that optimum roll bonding conditions for metallurgical bonding between Al and Cu are well established, this study aims to investigate how varying process parameters affect mechanical interlocking between layers. The hypothesis is, that the combination of metallurgical and mechanical bonding would either enhance the overall bond strength or reduce required threshold deformation.

Material and Methods

Materials.

In this study, the Cu (Cu-ETP) and Al (Al99.7) material was cast at utg, TUM, Munich. The flow curves for the materials were measured by compression tests at IBF (Figure 2). The range of the resulting flow stresses of Al is significantly smaller than that for Cu. Thus, no flow stress levelling by choosing a certain temperature seems possible. Therefore, different height reduction and thus elongation of the layers and an inhomogeneous strain distribution between the compound materials is expected.

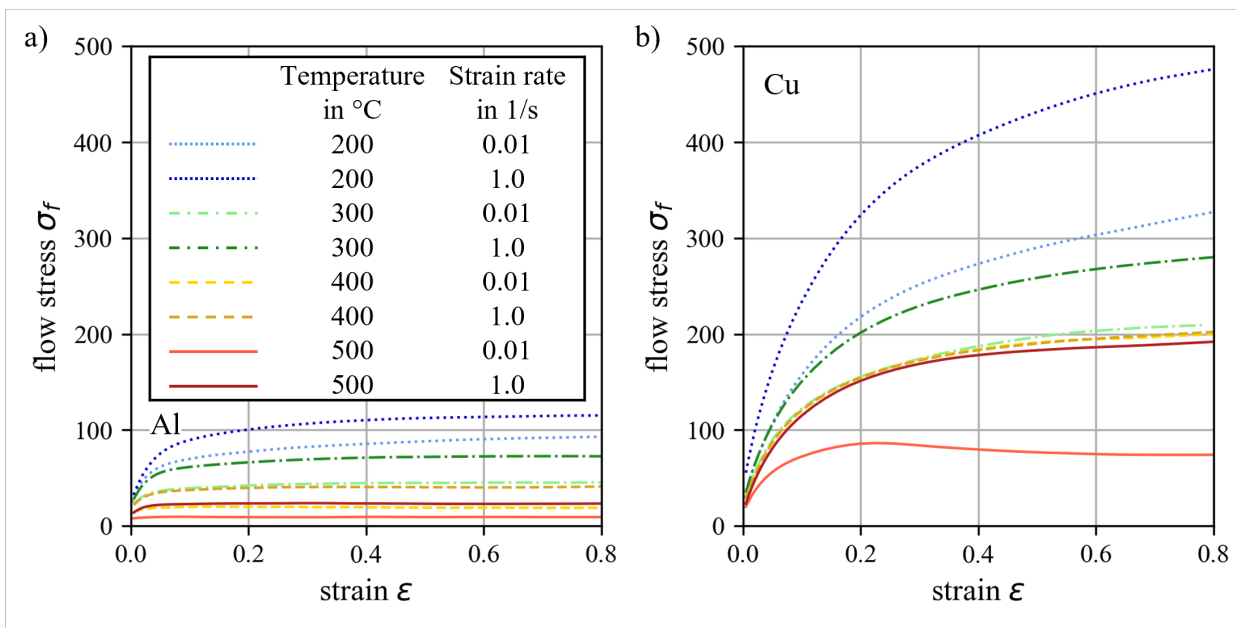


Fig. 2. Flow curves measured in compression test at IBF for a) Al and b) Cu at different temperatures and strain rates.

FE-Rolling Simulation.

The rolling process was simulated using Abaqus 2017 with a dynamic explicit solver, incorporating displacement-temperature coupling to represent the thermo-mechanical interactions during deformation. A two-dimensional plane strain assumption was used, as width spread effects were considered negligible for the investigated geometry. The assembly utilized in the simulation is depicted in Figure 3.

The rolling material consisted of Al and Cu plates, with overall dimensions of 120 mm in length and 24 mm in thickness. At the interface, a quadratic surface structure was designed featuring ribs and channels. Each square segment had a side length of 4 mm, resulting in a height of 10 mm in the channels and 14 mm at the ribs for each material. A fillet radius of 0.5 mm was applied to all corners to reflect realistic manufacturing conditions. To ensure that the rolls bite the part, particularly at large height reductions, the front edge of the slab was machined with a chamfer measuring 20 mm in length and tapering from nominal thickness to 8 mm at its thin end. The material properties for Al and Cu layers were assigned based on the flow stress data obtained from compression tests (Figure 2). The Poisson's ratios were set to 0.33 for Al and 0.343 for Cu. An inelastic heat fraction of 0.9 was used for both materials to account for the conversion from plastic work into heat during deformation. Additional temperature-dependent material parameters, i.e., thermal conductivity, density, elastic modulus, coefficient of thermal expansion, and specific heat capacity, were sourced from Springer Materials for Al, Cu, and the work roll material X40CrMoV5 [20-22]. The work rolls themselves featured an outer diameter of 410 mm and were modeled as rigid bodies that remained thermally active throughout the simulation. Guidance along the rolling direction was provided by a roller table positioned with an offset of 15 mm from the highest point of the lower roller surface.

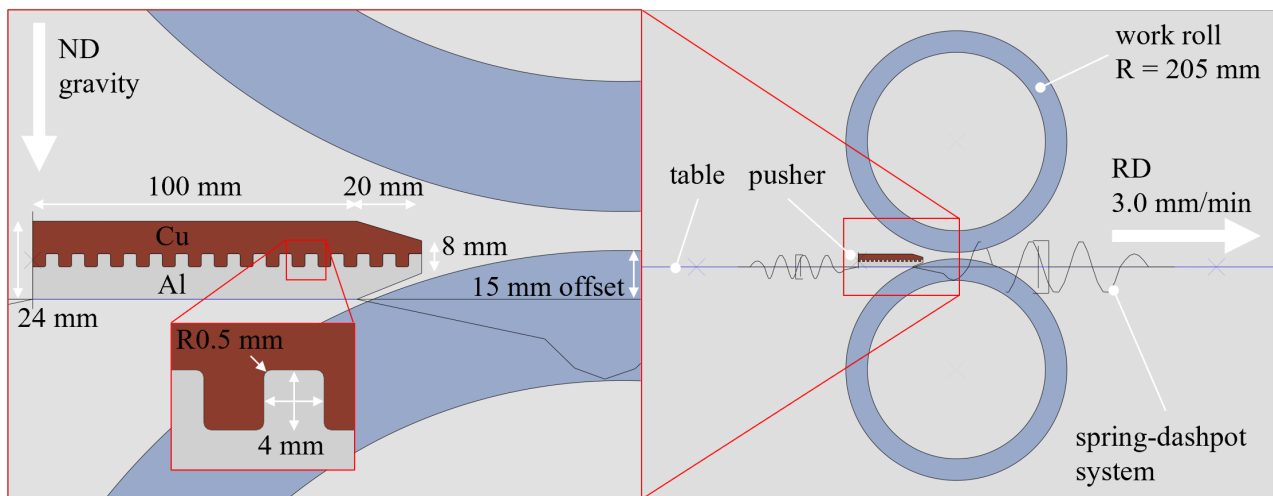


Fig. 3. Setup of the rolling simulation.

The movement along the rolling direction was achieved via a pusher in combination with a spring-dashpot system. The pusher was needed to overcome the bite condition in simulations with large height reductions despite the chamfer on the edge. The spring dash-pot system was used to handle the rolling material in pass schedules with several passes by reverse rolling (spring stiffness: 1E-005); dashpot coefficient: 0.01). The process started with a 5 s waiting time representing the transfer time from the furnace to the rolling mill. By this, the initial temperature gradients could develop realistically before rolling with a rolling speed of 3.0 m/min. If several rolling passes were needed, the rolling direction was reversed with an interpass time of 5 s. After the rolling, a 5 s time for air cooling was assumed.

Displacement-temperature interactions between all components were fully modeled. Free surfaces exchanged heat with ambient air by convection using a film coefficient of 10 W/(m²K) (equivalent to 0.01 t/(s³K)) at a sink temperature of 20 °C. Radiative heat loss was included via emissivity values set at 0.11 for Al and 0.6 for Cu. Thermal contact conductance between the rolling material and both rollers or table surfaces was modeled using tabular data: The maximum conductance values reached

4,000 W/(m²K) at zero clearance but decreased linearly to zero at clearances beyond 0.05 mm. Initial temperatures for both table and rollers were set uniformly at 20 °C. A frictionless contact was assumed between the rolling material and the roller table. For all other friction-based contacts, the Coulomb friction model was employed. Between the rolling material and rollers, a friction coefficient of $\mu = 0.25$ was applied. No metallurgical bond strength was assumed between the Cu and Al layers. However, to account for the initial bonding from the compound casting process, relatively high friction values were selected: An interfacial friction coefficient of $\mu = 0.5$ between Cu and Al, and a value of $\mu = 1.0$ for self-contact within either metal. The thermal interaction across the Cu-Al interface was modelled with a maximum conductance value of 4,500 W/(m²K) and the same clearance values as described above.

To assess the influence of the friction coefficient between the rollers and the rolling material, it was varied between 0.2 to 0.4, which is the typical range for hot or warm rolling. For $\mu = 0.2$, unrealistically high pushing forces were needed to overcome the bite condition. With up to $\mu = 0.4$, the average strain did increase only up to 4.5% for Al and 7.5% for Cu. The fluctuation of the shear stresses in the interface between Al and Cu increased by only 2.65%. Therefore, $\mu = 0.25$ seems to be a valid assumption. Furthermore, the interfacial friction coefficient between Al and Cu was reduced down to $\mu = 0.25$. While the average strain did only decrease by 0.4% for Al and 1.7% for Cu, a significant decrease of the interfacial shear stress of 31.5% was calculated. Thus, the interfacial shear stress is strongly depending on the interfacial friction.

The finite element discretization employed coupled temperature-displacement plane strain elements (CPE4RT) for the compound material and the rollers. For the rollers an approx. element size of 3.75 mm was chosen, resulting in 3410 elements per roll. A sensitivity analysis was performed to select an element size for the compound material that balanced adequate accuracy against computational cost. At the edge in contact with the roller, a mesh size of 1.0 mm was selected. At the interface, an element size of 0.25 mm was chosen. A biasing scheme was used over the height. This resulted in 10429 elements for Al and in 10662 elements for Cu. To optimize computational efficiency, semi-automatic mass scaling was applied throughout all simulations with a target increment time of 1E-006 s. Additional tests using increment times of 1E-005 s and 1E-007 s revealed that while a 1E-007 s produced comparable results at the expense of increased computation time, 1E-005 s resulted in excessive deformation artifacts.

Results and Discussion

Influence of the Surface Structure.

The effect of the geometric interface is shown in comparison to a simulation with a flat interface in Figure 4 for 50% height reduction and 300 °C initial temperature. As there is no metallurgical bond strength modelled, the compound material with the flat interface separated (Figure 4 a)). Furthermore, the Al layer is approx. 3 mm thinner and therefore elongated significantly more. With the geometric interface, the layers stuck together during and after rolling and therefore elongated similarly. The average difference in thickness is only approx. 1.2 mm. Due to the different final length of the layers, an upward curvature of the rolling material is observed.

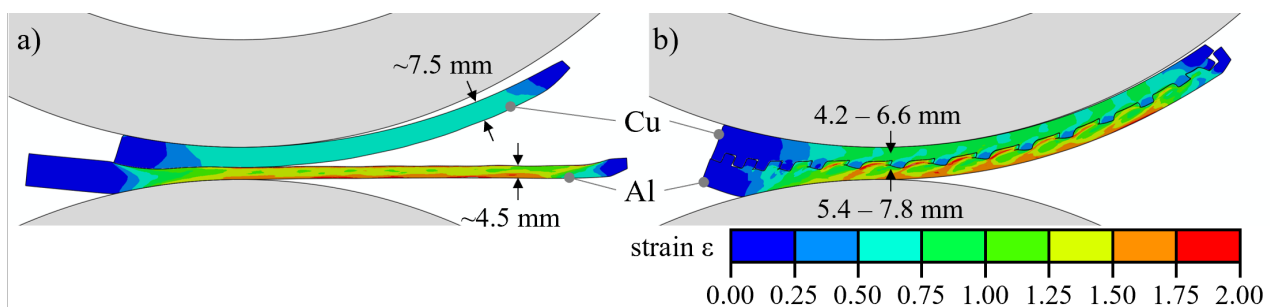


Fig. 4. Compound rolling with a) flat and b) geometric interface at 50% height reduction and 300 °C initial temperature.

To assess the influence of the geometry on the stresses at the interface, the frictional shear stresses (CSHEAR) along with the contact pressure (CPRESS) were evaluated for every node of the interface and every 0.2 s of the rolling process. The data was then matched with the position along the rolling direction and plotted along the roll gap as in Figure 5. A filtering by averaging the values within a 1 mm distance was performed to receive the darker trend lines in the diagrams. Figure 5 a) shows the results for the case without the geometric interface. As expected, the stresses start from the roll gap entry and stop at the roll gap exit. As rolling is a compressive deformation process the contact pressure is positive. The shear stresses of the averaged trend line values increase in the beginning until a maximum of 23.1 MPa and drop to zero at the neutral point. The negative section with a minimum of -20.4 MPa appears, before the shear stresses get back to zero after the roll gap exit. This clear trend is not observable for the geometric interface. Here, the shear stresses strongly fluctuate throughout the roll gap and extend even beyond the contact length. The averaged values of the trend line show a maximum of 3.8 MPa and a minimum of -12.0 MPa.

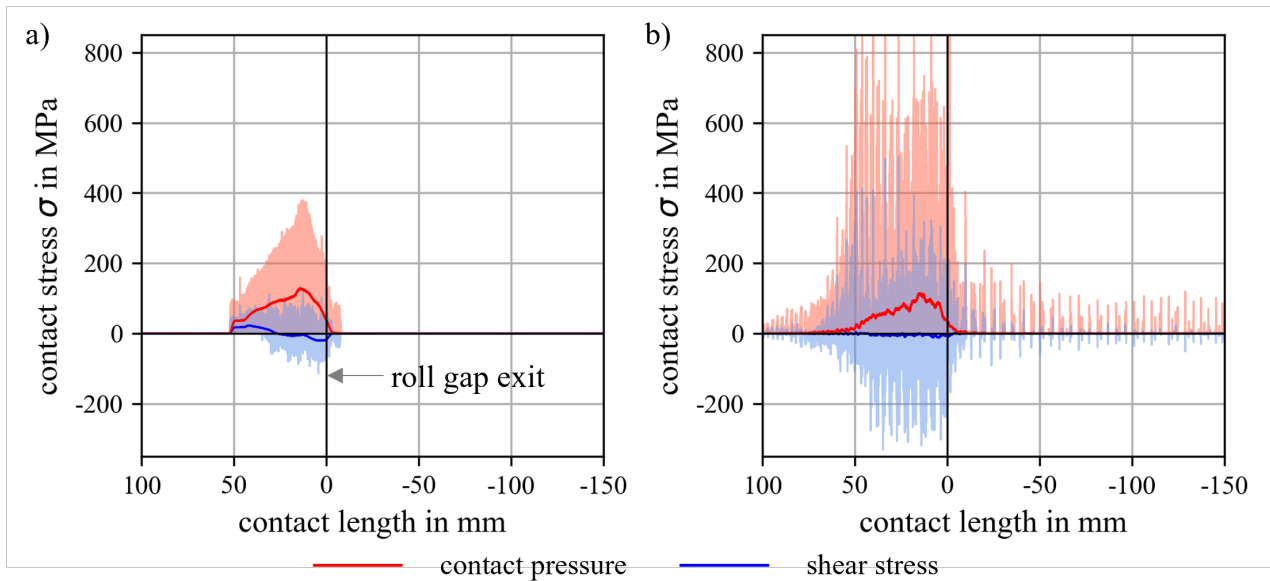


Fig. 5. Comparison of contact pressure and frictional shear stress for a) flat interface b) geometric interface along the rolling direction.

To assess the fluctuation of the original shear stress data, f_{shear} was calculated based on all n data points of the shear stress σ_{shear} in the interface as in Eq. 1.

$$f_{shear} = \sqrt{\frac{1}{n} \sum (\sigma_{shear,n})^2}. \quad (1)$$

Thus f_{shear} considers the shear stress of all interface nodes of both layers within an approx. distance of 0.25 mm (corresponding to mesh size) and over all time frames sampled in 0.2 s intervals. In simulations, the fluctuation of shear stresses was 11.1 MPa for the flat interface, whereas it increased to 17.24 MPa with the structured interface. This indicates that higher peaks of shear stress occur due to the geometric interface structure. However, despite these elevated stresses, no separation of the layers was observed. The interface structure successfully endured the shear stresses and maintained effective mechanical interlocking.

These results suggest that the geometric interface compels both layers to undergo more similar thickness reduction and elongation during rolling. At the same time, it increases shear stresses at the interface because slippage between layers is prevented. If a metallurgical bond would be added to the geometric interface, lower shear stresses may be advantageous for bond strength. Therefore, further investigation into optimized process parameters is necessary to reduce interfacial shear stress.

Influence of Height Reduction and Temperature.

A parameter study with varying height reduction $\epsilon_h = \{20, 30, 40, 50, 60\}\%$ and initial temperature $T_i = \{250, 300, 350, 400, 450\}^\circ\text{C}$ was performed. Figure 6 shows five example final geometries for the different initial temperatures at 50% height reduction. Here, the strains seem to increase with rising temperature, especially for Al.

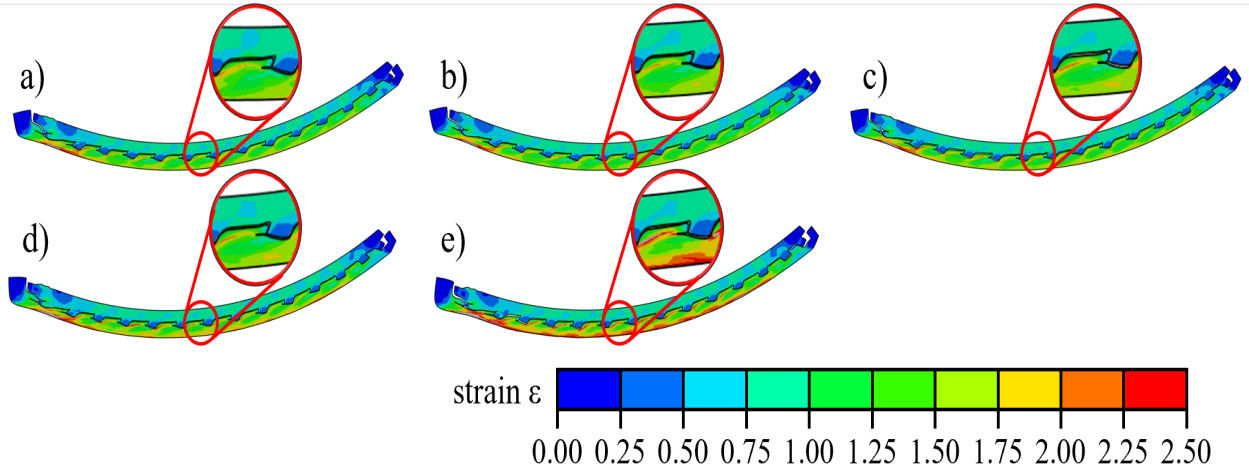


Fig. 6. Final shape with strain distribution after compound rolling at a height reduction of 50% for a) 250 °C, b) 300 °C, c) 350 °C, d) 400 °C and e) 450 °C initial temperature.

The strain data of each element was extracted from the final shape of the compound material for all simulations. The average strain is displayed in Figure 7 a). For the Al part, the average strain shows a minimum at 300 °C. For the Cu part, a maximum average strain can be observed at 300 °C, even though the change is significantly smaller compared to Al. Thus, the strain difference between Cu and Al is smallest at 300 °C, which corresponds to a more homogeneous deformation of the two layers.

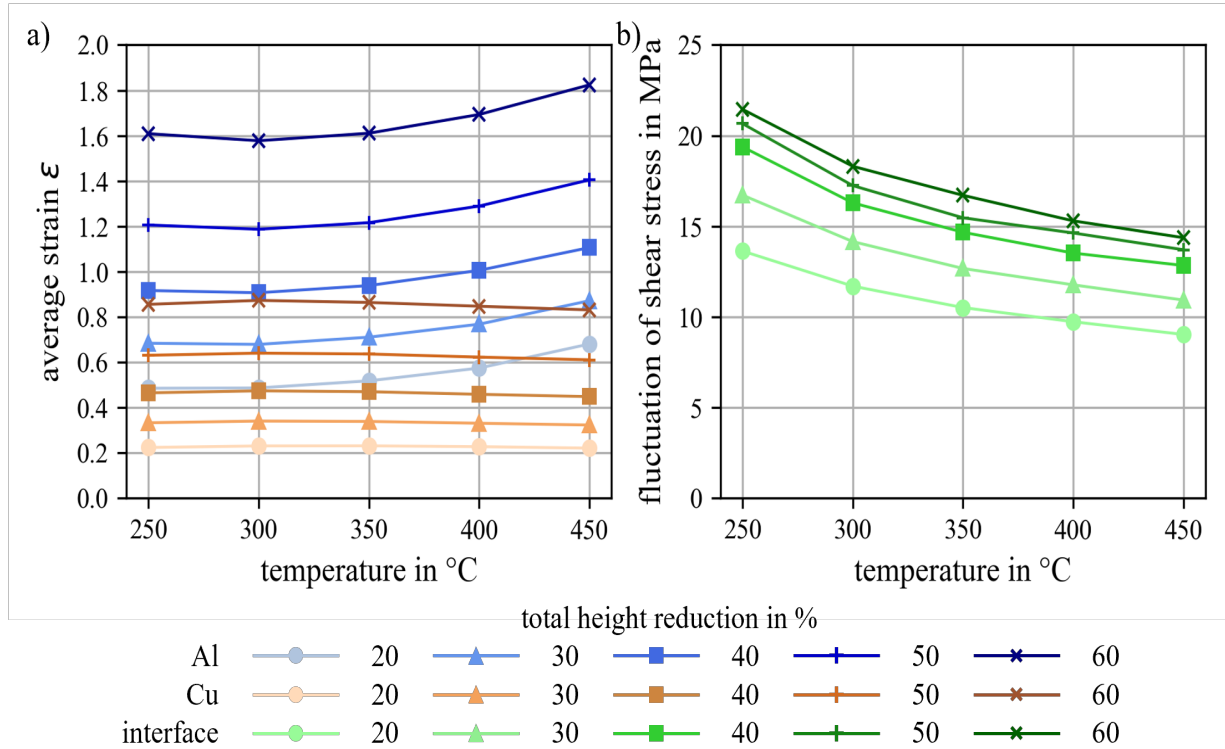


Fig. 7. Influence of the temperature and height reduction on a) average strain and b) fluctuation of shear stress of all elements of the rolled compound material.

In contrast to that, higher temperatures and smaller height reductions reduce the fluctuation of the shear stresses in the interface between Al and Cu and would therefore be beneficial to reduce stresses on a metallurgical bond (Figure 7 b)). However, the geometric interface is effectively avoiding any significant delamination despite the comparably high shear stresses at a rolling temperature of 300 °C. This gets evident by the resulting geometry of the compound material after rolling with different height reduction at 300 °C as it can be seen in Figure 8.

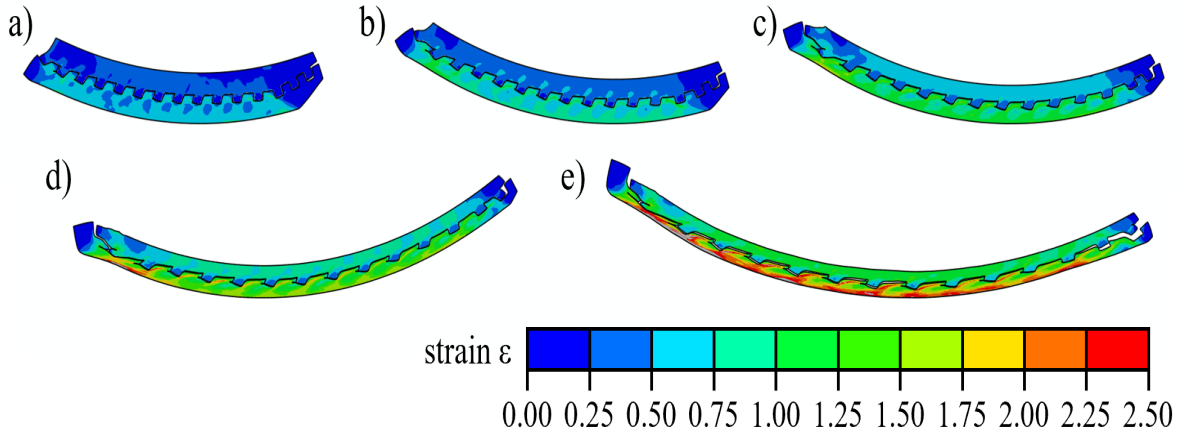


Fig. 8. Final shape with strain distribution after compound rolling at an initial temperature of 300 °C and a) 20%, b) 30%, c) 40%, d) 50% and e) 60% height reduction.

Influence of Asynchronous Rolling.

The effect of asynchronous rolling on the compound material was analyzed by scaling the angular velocity $\dot{\alpha}$ of the upper roller by the factor of the speed ratio given in Eq. 2.

$$r_{\dot{\alpha}} = \frac{\dot{\alpha}_{upper}}{\dot{\alpha}_{lower}}. \quad (2)$$

For the upper roller being 1.3 times faster than the lower roller, $r_{\dot{\alpha}} = 1.3$, while for the lower roller being 1.3 times faster than the upper roller, $r_{\dot{\alpha}} = 0.77$. The resulting geometry of the simulations with the strain distribution is shown in Figure 9.

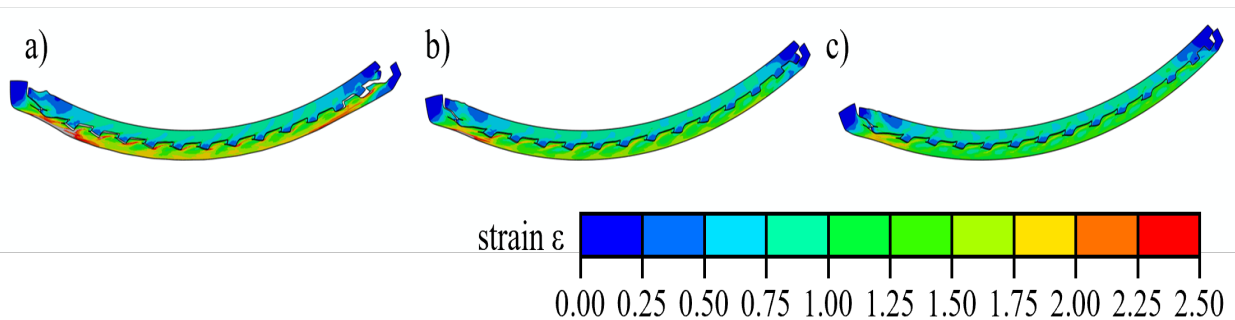


Fig. 9. Influence of the rolling speed ratio of a) 0.77, b) 1.0, and c) 1.3 on the strain distribution of the rolled compound material.

From the simulations, the strains and shear stresses were extracted. Figure 10 a) shows the resulting average strain with the standard deviation given as error bars for Al and Cu.

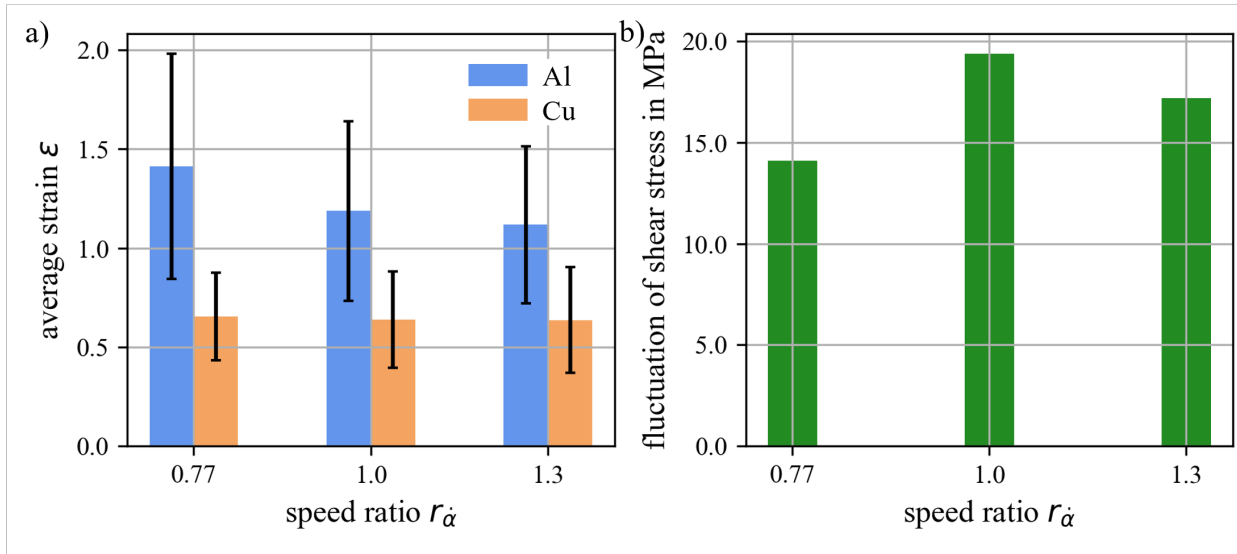


Fig. 10. Influence of the asynchronous rolling speed ratio on the a) strain distribution and b) on the fluctuation of shear stress of all elements of the rolled compound material.

A higher speed ratio reduces the average elongation of Al, so that the stages between Al and Cu increasingly level out. At a ratio of 1.3, the difference between strains of Al and Cu is smallest. In contrast to that, the fluctuation of shear stress at the interface seems to be smallest for the ratio of 0.77 (Figure 10 b)). However, no clear trend is observable, as a maximum was found for a ratio of 1.0.

Additionally, it was investigated, whether the rolling speed ratio was a tool to influence the resulting curvature of the compound material. Therefore, the geometry of the Al and Cu surfaces were interpolated and the curvature calculated. No significant effect of the speed ratio on the curvature was overserved as shown in Figure 11. The curvature remained nearly constant, with values of 0.0044 1/mm for Al and 0.0046 1/mm for Cu.

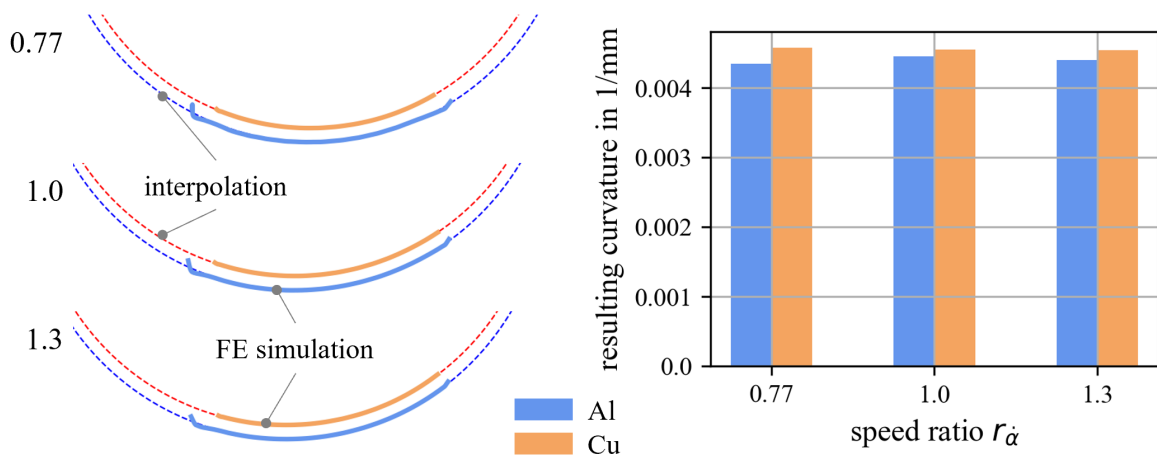


Fig. 11. Influence of the rolling speed ratio on the curvature of the rolled compound material.

Influence of Pass Schedule.

To assess the influence of the pass schedule, the total height reduction of 50% was separated into two and three passes as shown in Table 1.

Table 1. Heights and height reductions for used pass schedules.

Pass schedule	Passes	h_1 [mm]	$\epsilon_{h,1}$ [%]	h_2 [mm]	$\epsilon_{h,2}$ [%]	h_3 [mm]	$\epsilon_{h,3}$ [%]
A	1	12.0	50.0				
B	2	16.8	30.0	12.0	28.6		
C	3	19.2	20.0	15.3	20.3	12.0	21.06

In the simulations, the passes were modelled as reversing rolling without reheating and an interpass time of 5 s. The resulting geometry with the occurring strains is displayed in Figure 12 a) – c). With increasing number of passes, the elongation of the lower Al layer is increasing, so that a free Al end is showing (red circle).

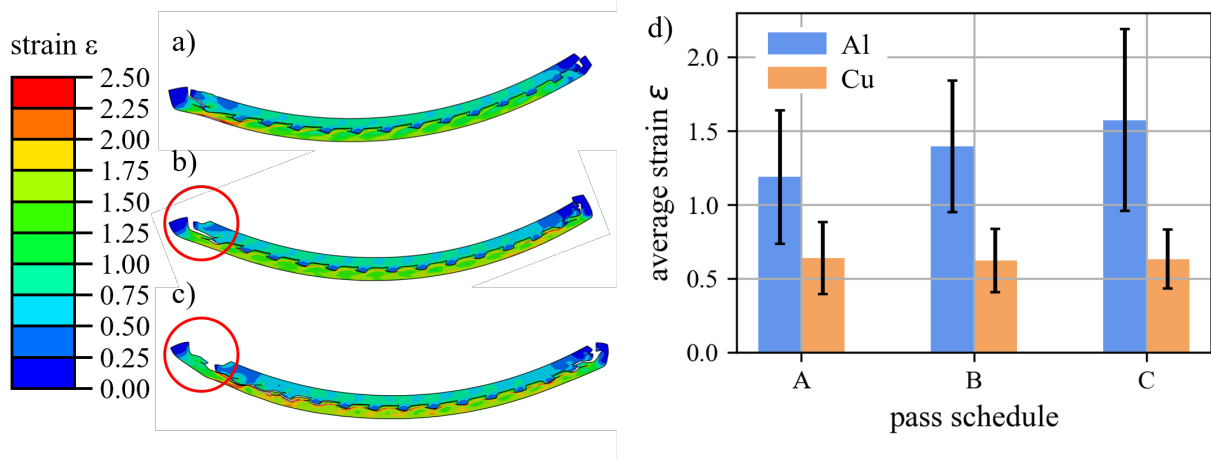


Fig. 12. Influence of pass number for a) 1, b) 2, and c) 3 passes on the geometry and strain distribution of the rolled compound material; d) average strain for schedules A to C.

This is also evident from the average strain (Figure 12 d)). With increasing number of passes, the average strain for Al is increasing, while it stays constant for Cu. This might be due to the fact, that the part cools more with more passes, as the process time increased, which leads to a higher difference in flow stress and thus more dissimilar elongation of the materials (Figure 13 a)). While for pass schedule A, the final temperature after rolling is 270 °C, it is only 223 °C for pass schedule C. The fluctuation of the shear stress is slightly higher, when using only one pass (Figure 13 b)). The pass schedule with three passes (C) appear to show higher shear stresses in the third pass compared to the schedule with two passes.

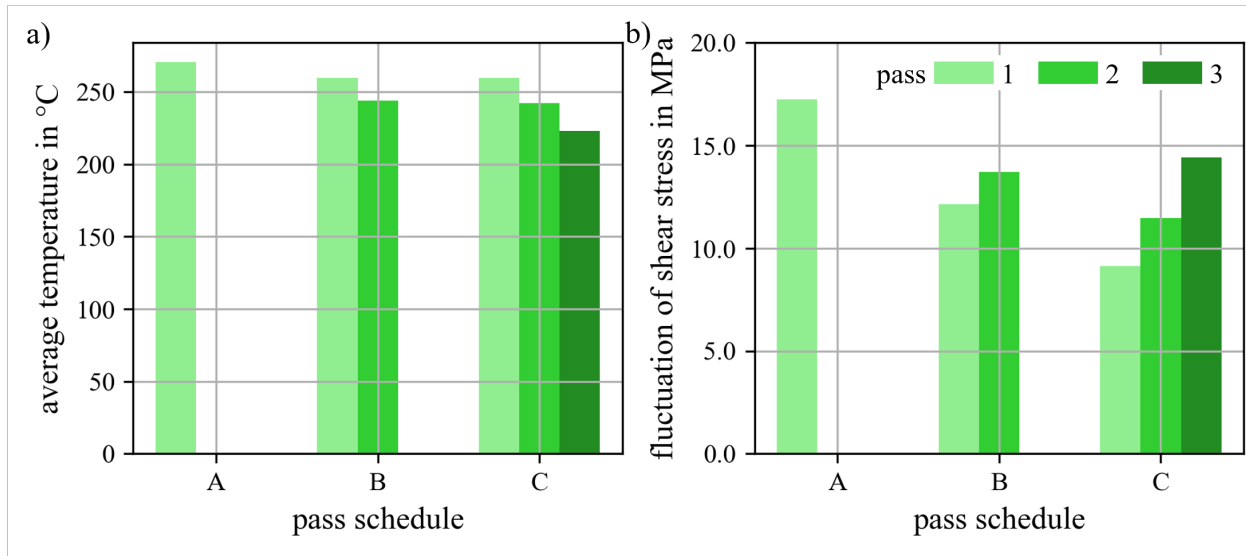


Fig. 13. Influence of number of passes on the a) average temperature and b) fluctuation of shear stress of all elements of the rolled compound material.

Preliminary Experiments for Future Validation

Continuous compound casting experiments were carried out at utg using a Demag Technica continuous casting machine, type 30/10 D I MCP N. The experimental setup comprised three main components: a melting furnace, the casting tool, and a drawing unit. System controls for water flow,

temperature regulation, and kinematic control of the drawing process were developed by utg as previously described [23]. The temperature inside the mold is monitored by integrated thermocouples. The mold is cooled on both sides by copper coolers using water as the cooling medium. In the first stage of the casting tool, the Cu rod solidifies. Subsequently, Al melt is poured onto an additional ceramic and introduced atop the Cu in the second stage of the casting tool. Both Cu and Al rods are solidified and further cooled by the same cooling system. The resulting composite rod is extracted from the mold using rolling drawers that employ a go-stop withdrawal technique to avoid tearing the rod due to friction [24]. Each withdrawal cycle consisted of a 7.5 mm stroke followed by a waiting period of 1.3 s, resulting in a nominal casting speed of 263 mm/min in accordance with previous studies.

The upper side of the graphite mold at the Cu casting stage featured a rectangular structure designed to form the interface geometry within the Cu, resulting in grooves on its surface. However, the interface structure produced in the casting experiments was less pronounced than assumed in the rolling simulation. Due to this discrepancy, the comparability of the simulation results with the experiments is only possible to a limited extent.

Nevertheless, warm rolling of the compound rods was conducted at IBF using a universal rolling mill (Bühler VRW-400), configured in accordance with the setup assumed in the simulations. Three exemplary parameter sets of the simulations were selected for testing during the rolling trials:

- a) Rolling at 300 °C with a speed ratio of 1.3 and a single pass achieving 50% height reduction.
- b) Rolling at 300 °C with a speed ratio of 1.0 and achieving 50% height reduction in three passes according to schedule C (Table 1).
- c) Rolling at 400 °C with a speed ratio of 1.0 and a single pass achieving 50% height reduction.

The rolled plates obtained from these experiments are shown in Figure 14. Consistent with the simulation results, none of the plates exhibited delamination at the Al/Cu layers. Setup a) produced a very homogeneous deformation between the Al and Cu layers, as reflected in both the visual inspection (Figure 14 a)) and the measurements of sample thickness and length (Table 2). In this setup, the thickness proportions of Al and Cu were nearly equal, and the elongation of Al was only 11% greater than that of Cu. In contrast, setup b) resulted in a plate where the Al layer exhibited 36% greater elongation compared to Cu and a 10% difference in thickness proportions. Both findings are in good agreement with simulation predictions, as in Figure 9 c) for setup a) and Figure 12 c) for setup b).



Fig. 14. Experimental results of continuous compound casting and warm rolling with the setup a) – c).

Increasing the rolling temperature to 400 °C, as in setup c), did not lead to any directly observable changes in deformation behavior compared to setup a). However, based on the measured dimensions, the deformation appeared slightly less homogeneous than in setup a). Unlike the simulation results, the speed ratio appeared to influence the final curvature of the rolled plates. While setups b) and c) with speed ratio of 1.0 exhibited curvature values similar to those predicted by simulations (compare Figure 11), setup a) showed a significantly reduced curvature with a speed ratio of 1.3.

Table 2. Dimensions of compound cast and warm rolled slabs for setup a) – c).

Parameter set	Proportion of Al layer thickness	Proportion of Cu layer thickness	Elongation of Al compared to Cu	Curvature of Cu in 1/mm
a)	49%	51%	11%	0.0039
b)	45%	55%	36%	0.0048
c)	48%	52%	14%	0.0047

Despite the discrepancies between the simulated and experimentally realized interface structures, several effects predicted by the simulations were already evident in the experimental outcomes. However, the experiments presented here should be regarded as preliminary findings. Further casting experiments employing controlled solidification fronts will be required in the future to achieve more distinct geometric structuring on the Cu surface and thereby improve mechanical interlocking with Al. Furthermore, to more conclusively evaluate the influence of parameters such as temperature on joint quality, a subsequent quantitative assessment of bond strength will be necessary.

Conclusion and Outlook

The obtained results of this study demonstrate that the introduction of a geometric interface can effectively compensate for shear stresses occurring during rolling and lead to a more homogeneous deformation of the layers. Compared to a flat interface, the mechanically interlocked layers endured higher shear stresses than expected with a flat interface. As the temperature is influencing the flow stress it was found to affect the strain distribution and the fluctuation of the shear stresses in the material compound significantly. The smallest difference in average strain between Al and Cu was observed at an initial temperature of 300 °C. Notably, this temperature also aligns with values reported in the literature as optimal for promoting strong metallurgical bonding while minimizing detrimental intermetallic compound formation [5,11]. However, comparably high fluctuations of shear stresses are expected which can be covered by the geometric interface. The influence on a possible metallurgical bond needs to be investigated. Adjusting the rolling speed ratio provided further control over deformation homogeneity. Increasing the speed ratio led to a reduction in average strain within the Al layer, bringing it closer to that of Cu and thus improving overall uniformity of deformation across the composite. However, no significant effect of rolling speed ratio on the compound material curvature was detected, suggesting that alternative strategies are required to achieve straightening during processing. When splitting the height reduction into several passes, the average strain of Al increased, resulting in less uniform elongation. All in all, a temperature of 300 °C, an increased speed ratio and large height reductions are suggested for good results.

Preliminary warm rolling experiments conducted at IBF using compound cast material produced at utg supported these findings. Although the interface structure formed on the copper surface were less pronounced than assumed in the simulations, several modeled effects were observed experimentally under selected conditions: Rolling at 300 °C with an increased speed ratio resulted in a homogeneous deformation between Al and Cu layers, while multiple passes led to larger elongation of the Al layer. Increasing the rolling temperature to 400 °C did not produce any directly observable changes in deformation behavior.

To fully evaluate joint quality, particularly bond strength, systematic mechanical testing will be required in future work. Further improvements to geometric structuring on copper surfaces will also be explored to enhance mechanical interlocking with aluminum. Finally, it is proposed to couple the current mechanical interlocking model with a model describing metallurgical bonding. To enable this approach, a bond strength model must be calibrated using experimental data obtained from laboratory-scale tensile and shear strength tests at different surface enlargements and temperatures as previously performed [25]. This combined modeling strategy will support more comprehensive optimization of process parameters.

Conflict of Interest

The authors declare that they have no conflict of interest.

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