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Necking of invar layer in copper-invar laminates during roll-bonding

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Abstract. Sheets of Fe-36%Ni (Invar) and copper alloys are bonded by roll-bonding process to produce metallic composites with a low thermal expansion coefficient and large conductivity. To boost the thermal conductivity of the composite, the Invar layers must be fragmented. For a given volume fraction of Invar, the necking/fragmentation depends on the spatial distribution of the Invar layers, meaning their number and thickness. Hence, different configurations of copper/Invar composites are processed to determine the effect of each parameter on the necking/fragmentation. The materials are then mechanically characterised to use the results as input data to the simulation of the process. Finally, to obtain a realistic simulation, a multi-step roll-bonding simulation using a remeshing solution is carried out for each cycle. The occurrence of necking during the cold-roll bonding of copper and Invar layers is both numerically and experimentally studied. In all cases, the experimental and simulation results are in good agreement. Invar layer thickness is of major importance to facilitate the fragmentation.

Introduction

Power modules are increasingly utilized and in demand for applications in energy management or onboard systems [1,2]. They need constant improvement to enhance efficiency and reliability. The development of metallic composites that could serve as substrates or leadframes for electronic components is therefore of major importance. High transverse thermal conductivity and low thermal expansion in the plane of those components are mandatory to mitigate thermal stresses. The combination of copper and Invar sheets is a promising option to achieve optimal properties as proposed in the literature [1]. This work aims to use roll-bonding of copper and Invar simple sheets for manufacturing Invar-copper composites.

The roll-bonding is a solid-state welding process to assemble sheets of different physical and/or mechanical properties and obtain composites with optimized properties [3–5]. When materials of different hardness are rolled together, the hardest material can exhibit, under certain conditions, areas of necking leading to the fragmentation of the hard layer in the soft matrix. This fragmentation is necessary for the application in this work. Indeed, the fragmentation of Invar layers (hard material) inside the copper matrix (soft material) will induce thermal bridges of copper, thereby enhancing the thermal conductivity of the composite. Nonetheless, as it could affect the thermal expansion along the length: the fragmentation has to be optimized. Therefore, roll-bonding process has to be studied in order to control the structure of the final product.

Necking of hard layers during roll-bonding has been studied in the literature. A link between necking of hard layers and yield strength or hardness mismatch between soft and hard materials

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was demonstrated [5–7]. However, the understanding of necking occurrence during roll-bonding is only partially mastered. Criteria for predicting necking in hard layers are typically based on the maximal load criterion, as a generalization of the Considere criterion [4,8,9]. Nevertheless, these criteria underestimate the required reduction ratio to observe this plastic instability [4,10].

In this work, the influence of stacking geometry on Invar layers necking is studied through an experimental approach completed by simulations with the finite element method. For that purpose, stackings with different Invar volume fractions and spatial distribution, meaning the number and thickness of Invar layers, have been considered aiming to optimize their physical properties. The materials behaviour laws were identified to obtain input data for the simulation. The numerical simulation of multi-cycle roll-bonding was then developed and results were compared to the experimental ones.

Experiment

Rolling process:

The Invar and copper sheets were kindly provided by APERAM Alloys Imphy. The copper plate in a strain-hardened state is composed of 99.99% Cu (traces of Pb and Bi) and exhibits a 1.06 mm initial thickness. The Invar sheets (Fe-36%Ni) are received in an annealed state and have an initial thickness of either 1.0 or 2.2 mm.

In order to produce the stackings, a rolling apparatus equipped with a 33.5 mm roll radius is used to roll the copper and Invar sheets to a specific thickness. The rolling machine exhibits an electrical power of 2.2 kW. The rolling speed is set to 48 mm/s for the whole process. Three stackings were studied. They initially measure 75 by 20 mm² in length/width and are composed of rolled sheets of copper and Invar with thicknesses (before roll-bonding) as follows:

- Configuration A: Cu 700 µm / Invar 200 µm / Cu 700 µm
- Configuration B: Cu 600 µm / Invar 400 µm / Cu 600 µm
- Configuration C: Cu 400 µm / Invar 200 µm / Cu 400 µm / Invar 200 µm / Cu 400 µm

Therefore, the stackings have an initial thickness of 1.6 mm and they are rolled down to 180 µm thickness. The volume fraction of Invar is equal to 12.5% for stacking A and 25% for stackings B and C. For the two last configurations with the same Invar volume fraction, configuration B consisted of one 400 µm thick Invar layer embedded between two copper layers, while configuration C consisted of two 200 µm thick Invar layers sandwiched between three copper layers.

As said above, copper sheets were derived from a 1.06 mm thick sheet, which underwent cold rolling to produce sheets of various thicknesses used in configurations A, B, and C. These sheets were then annealed at 550 °C for 1h30 before the stacking. This heat treatment allows copper softening after cold reduction. Hence, the annealing treatment makes thickness reduction easier and likely promotes necking by increasing the yield strength ratio between hard and soft layers.

Invar sheets for configurations A and C were obtained from cold rolling of a plate 1.0 mm thick, while for configuration B, the 400 µm thick sheet was manufactured by cold rolling of a 2.2 mm thick sheet. As the reduction ratio applied to the initial sheets of Invar is approximately the same and they are in a close initial state, 200 µm sheets (from 1.0 mm) and 400 µm (from 2.2 mm) have identical mechanical properties. This was verified with hardness measurements. Thus, the Invar sheets used in the configurations A, B and C, are considered equivalents.

Before the roll-bonding, to have better welding, the sheets are cleaned with acetone, and then mechanically brushed. The sheets are then stacked and held together using iron wires. The roll-bonding is done at 200 °C. After the roll-bonding, each cycle is composed of a heat treatment at 350 °C for 1h30 followed by rolling.

The full thickness reduction of the composite from 1.6 mm to 180 µm is therefore achieved through multiple annealing-rolling cycles: the composite is extracted from the oven at the end of the treatment and directly rolled. The elapsed time of a few seconds between the output of the oven and the entry under the rolls induces a temperature drop of the composite: indeed, the rolling temperature has been measured at 200 °C by infrared camera and thermocouple.

The roll-bonding is performed at the first cycle up to 45% thickness reduction. Each composite is rolled 4 additional times until a thickness of 180 µm is achieved. The experimental setup and procedure are illustrated in Figure 1. The cumulative roll reduction ratio is defined as follow for each cycle j:

$$r_j = \frac{(h_t - h_j)}{h_t} \quad (1)$$

h_j is the height of the stacking after the cycle j and h_t is the initial thickness of the stacking (1.6 mm). The cycles are detailed later for the configuration C (see Table 3).

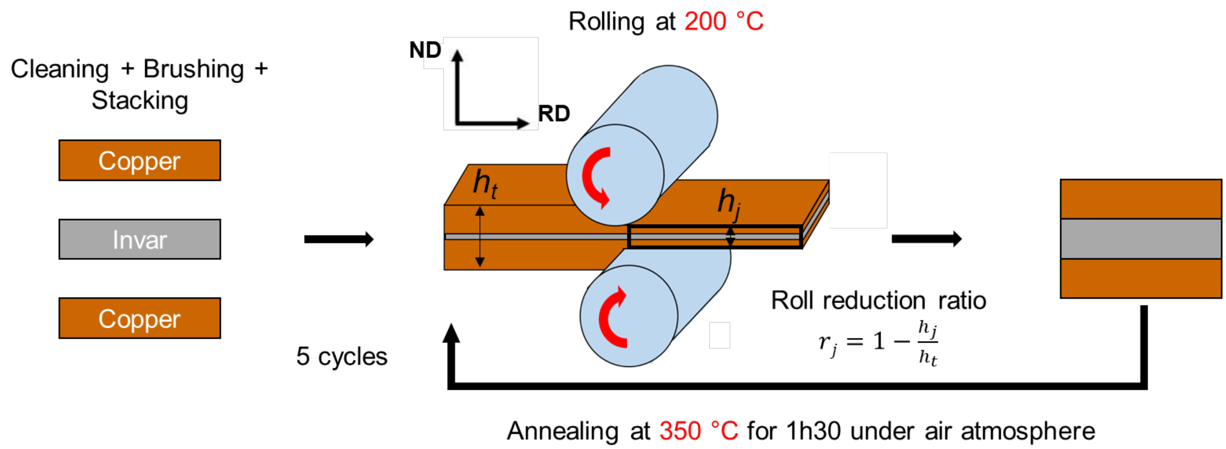

Figure 1: Experimental setup for roll-bonding (3 layers case)

The annealing treatment is used to enable the apparition of necking by softening the Copper, whereas this heat treatment does not modify the Invar mechanical properties. This statement has been verified: the hardness of copper and Invar was measured in a hardened and annealed state. The sheets initial thicknesses of configuration A were chosen (700 µm for copper and 200 µm for Invar) and reduced by 45% (corresponding to the first roll-bonding reduction). The measurements are thus carried out on 110 µm thick sheet of Invar and 385 µm thick sheet of copper sheets in both hardened and annealed state after 350°C for 1h30. As it can be seen in Table 1, the copper hardness is significantly higher in the hardened state than the hardness in annealing state, which means that the annealing permits the recovery and recrystallization of the copper sheets after rolling. For Invar, the hardness is similar in both states, thus Invar is insensitive to the applied annealing.

Table 1: $HV_{0.2}$ hardness measurements of copper and Invar sheets

State	Hardened	Annealed
Copper hardness [$HV_{0.2}$]	135 ± 5	50 ± 5
Invar hardness [$HV_{0.2}$]	257 ± 5	254 ± 3

Structure of composites:
After each cycle, longitudinal cuts (RD/ND plane) of composites were polished and observed with optical microscopy. The structural evolution and in particular, the necking of Invar layers was quantified with the maximal degree of necking calculated as follows:

$$Z_{max} = \frac{t_{max} - t_{min}}{t_{max}} \quad (2)$$

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t_{min} and t_{max} are the maximal and minimal thickness of the Invar layer respectively. If there is no necking, Z_{max} = 0 whereas fragmentation is characterized by Z_{max} = 1

The micrographs obtained after 89 % reduction ratio are presented in Figure 2. The micrographs reveal three different advancements in necking:

- Configuration A: Invar layer has a large degree of necking (Z_{max} = 0.8)
- Configuration B: There is almost no necking (Z_{max} = 0.1)
- Configuration C: Invar layers are fragmented in the copper matrix (Z_{max} = 1)

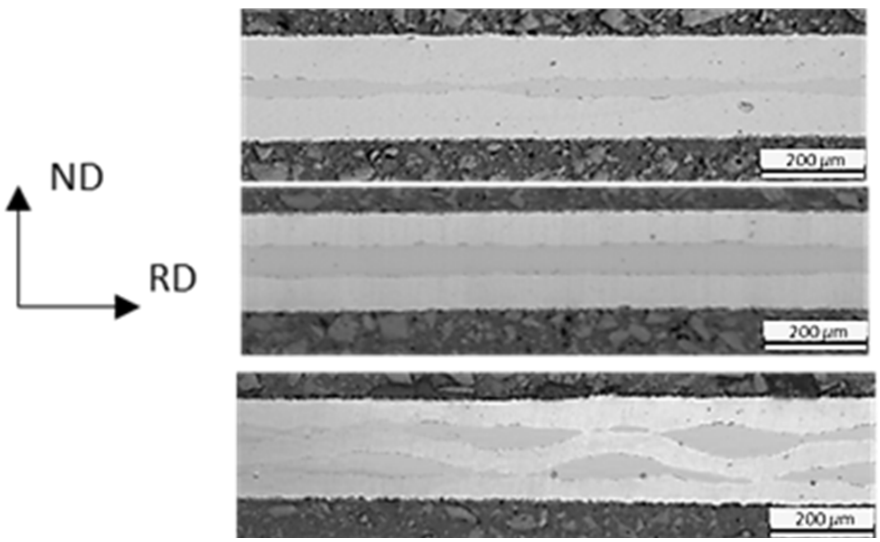


Figure 2: Experimental results of the stackings at a rolling reduction of 89%

Comparing configurations A and B, it is evident that as the volume fraction of Invar increases, necking is delayed (Z_{max} = 0.8 for A and Z_{max} = 0.1 for B). The comparison of A and C highlights the effect of the number of Invar layers on the apparition of necking: configuration C exhibits a fragmentation pattern (Z_{max} = 1), while configuration A is highly necked (Z_{max} = 0.8). Configurations B and C present the same volume fraction of Invar (25%), but different number of layers. Bilayer configuration C shows a higher degree of necking compared to the monolayer configuration B. The effect of Invar layer thickness on necking occurrence is consistent with the literature [4,5,11]. Hard layer volume fraction is widely used in the literature as an indicator to predict necking, as the maximal force-based criterion for necking varies linearly with this fraction [4,5,11]. This parameter is not sufficient to predict the necking of hard layers as necking occurrence depends also on the layer thickness.

Geometrical effects on necking occurrence have been identified, but they are combined with mechanical effects, such as hardness mismatch between soft and hard layers. As there is no reliable criterion to predict the necking of hard layers, finite element simulation of the process is a viable approach to optimize the manufacturing of composites with the expected structure. To model the process accurately, the mechanical behaviour of copper and Invar has to be determined, and this point is studied in the following section.

Characterization of materials mechanical behaviour

Approach:

Copper and Invar sheets used in the composite are obtained from rolling. This can induce crystallographic texture and mechanical anisotropy. Therefore, the mechanical behaviours of copper and Invar are determined as follows:

1) The strain hardening is obtained through tensile tests carried out at 200 °C (rolling temperature) along the rolling direction in quasi-static conditions;

2) Anisotropy is determined numerically with an elastoplastic self-consistent model [12] which takes into account the experimental crystallographic texture. This procedure allows an easy determination of properties out of the sheet plane, whereas complex instrumentation is required for thin sheets to obtain these properties through tensile tests.

Furthermore, composites are manufactured using a multi-cycle process, which includes a heat treatment before each warm rolling. While Invar is not sensitive to this thermal treatment (Table 1), copper is. Therefore, the evolution of the mechanical behaviour of the materials is studied as a function of the reduction applied to the sheets.

Copper sheets:
The mechanical behaviour of copper sheets should be determined in the annealed state for modelling each rolling pass. The thermo-mechanical treatment applied to copper sheets for the first 3 reductions is illustrated in Figure 3. Considering uniform thickness reduction, the copper layer thickness for configuration A is 700 µm at the 1st pass entry, 385 µm at the 2nd pass entry, and 217 µm at the 3rd pass entry. Concerning configuration C, the copper layer thickness is: 400 µm at the 1st pass entry, 220 µm at the 2nd pass entry, and 125 µm at the 3rd pass entry. Amongst those thicknesses, three thicknesses are characterized (Figure 3):

1) Cu700: Copper from an annealed 700 µm thick sheet;
2) Cu400: Copper from an annealed 400 µm thick sheet;
3) Cu200: Copper from an annealed 200 µm thick sheet.

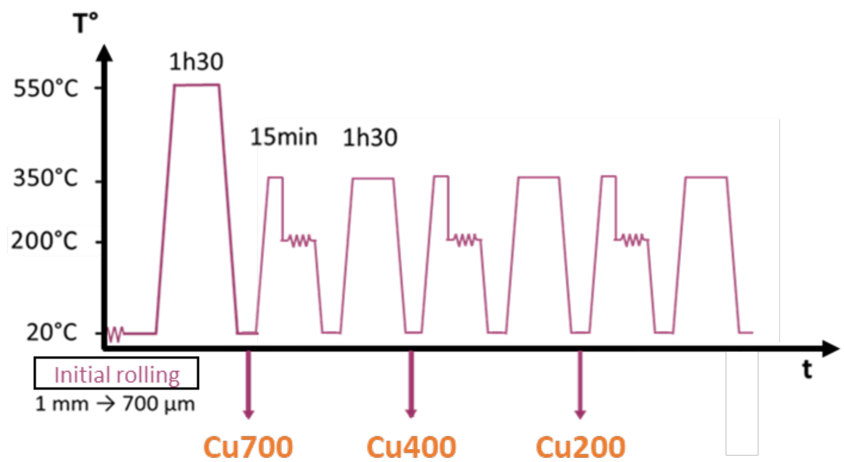


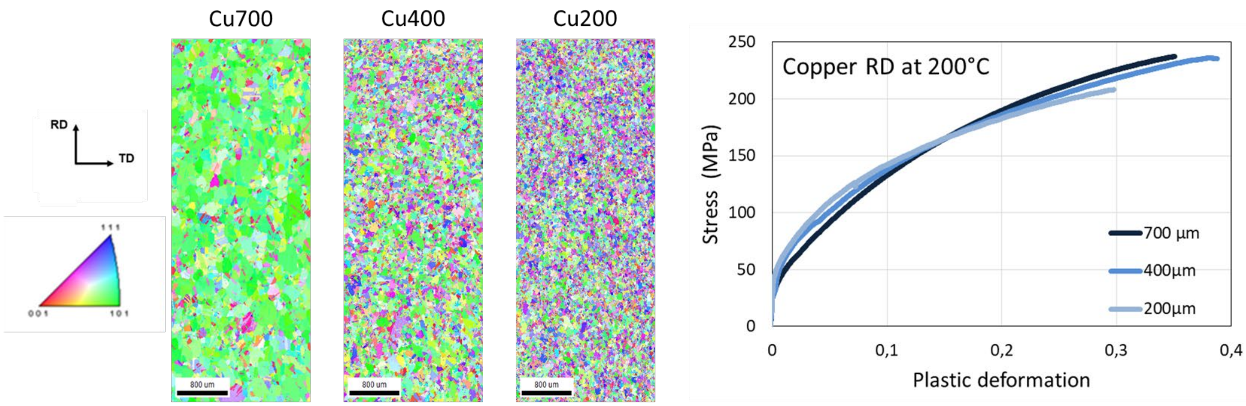
Figure 3: Thermo-mechanical treatment of copper sheets

The microstructure of the plates is characterized by electron backscatter diffraction (EBSD) with a 1 µm step size. The results are treated using the software OIM™. For that purpose, samples are polished and chemically attacked using a phosphoric acid solution before the observation. In order to get statistical results, the investigations are performed in the RD/TD plane.

Microstructures show a grain size drop (from approximately 150 µm to 35 µm) with annealing-rolling cycles (and copper thickness reduction from 700 to 200 µm) (Figure 4). Concerning crystallographic texture, with the annealing and the subsequent thickness reduction, texture becomes weaker, and orientations largely change since crystallographic direction along ND rotates from dominant <110> direction (green) to dominant <112> direction (purple). Grain shape remains isotropic due to recrystallization mechanisms during annealing. Copper keeps equivalent tensile behaviour whatever its thickness, meaning the hardening caused by the grain size diminution is compensated by the texture evolution. These tendencies are consistent with the literature [13-15]. It can be concluded that the copper strain hardening is reset at each cycle thanks to annealing. Strain hardening (in MPa) can be fitted by the following hardening function (in MPa) (Figure 4.b):

$$R^{Cu}(p) = 35 + 39 * (1 - e^{-33.6*p}) + 237 * (1 - e^{-3.2*p}) \quad (3)$$

With p the cumulative equivalent plastic strain equal to plastic strain measured in tensile tests.



(a) (b)

Figure 4: Copper characterisation: (a) ND-IPF maps and (b) stress-strain curves for different thicknesses

Following [12], an elastic-plastic self-consistent (EPSC) model is used to obtain the yield strengths in different directions derived from the experimental crystallographic texture. Each grain is considered as an elastoplastic inclusion embedded in an elastoplastic homogeneous equivalent medium (HEM) whose properties are sought. The elastoplastic behaviour of the inclusion is defined by the glide on the 12 slip systems of the face-centered cubic crystal. The interaction equation between each grain and the HEM is obtained by solving the Eshelby problem of an elastoplastic inclusion in the HEM. If the single crystal behaviour, the orientation distribution, and grain morphology are known, the EPSC model gives the relationship between the stress rate and strain rate of the polycrystal. Using incremental time steps, it is possible to compute the elastoplastic behaviour of the polycrystal deformed by simple traction under different directions. The ratio between yield strengths of the HEM, *i.e.* copper, can be determined in different directions. The yield strengths along the rolling, transverse and normal directions and the yield strength at 45° across the transverse/rolling plane are called respectively σ_{0R}, σ_{0T}, σ_{0N}, σ_{045TR}. The yield strength σ_{0R} is equal to 35 MPa as indicated in eq. (3). Results from EPSC calculations are presented in Table 2.

Table 2: Yield strength ratios for copper in 3 different mechanical states

	σ_{0T}/σ_{0R}	σ_{0N}/σ_{0R}	$\sigma_{045TR}/\sigma_{0L}$
Cu700	1.04	0.92	0.92
Cu400	1.01	1.01	1.02
Cu200	0.99	1.00	1.01

As shown in Table 2, mechanical anisotropy resulting from the crystallographic texture is rather low for the first state of copper, Cu700. For a larger reduction ratio, copper sheets can be considered isotropic. This can be explained by the texture evolution noticed in Figure 4. Initially, copper is textured at 700 µm, but it becomes isotropic at 400 and 200 µm. Based on these results, it can be inferred that copper sheets of lower thicknesses than 400 µm remain isotropic. Thus, for all the cycles, the copper is considered isotropic except when a Cu700 sheet is used.

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Invar sheets:
Therefore, the evolution of the mechanical behaviour of Invar sheets as a function of thickness reduction will be essentially derived from strain hardening and texture development. Tensile tests have been performed at 200 °C on both 200 µm and 400 µm thick plates. Fracture elongation is lower than 1% which is consistent with the fact that Invar is not affected by heat treatment and its behaviour is characteristic of large strained metal. But this brittleness makes difficult hardening strain law determination. Thus, the evolution of hardness with a reduction ratio combined with a relation between hardness and yield strength is used to characterize the hardening law of Invar. A linear law is found and the strain hardening of Invar sheets is then defined by the hardening function defined for each roll cycle j as follows (MPa):

$$R_j^{Invar}(p, p_{0j}) = 680 + 65\,(p + p_{0j}) \tag{4}$$

With p the cumulative equivalent plastic strain and p_{0j} the equivalent plastic strain accumulated from the previous reduction (see Table 3):

$$p_{0j} = \frac{2}{\sqrt{3}}\left|ln(1 - r_{j-1})\right| \quad \text{with } r_0 = 0 \tag{5}$$

For Invar, crystallographic anisotropy (calculated from the EPSC model) can be considered negligible.

Finite element modelling of multi-cycle rolling
Model design:
The finite element software Ansys 2023 R1 is used with the static procedure and updated Lagrangian formulation to solve problems with large strains and large displacements. The models are designed in 2D under the assumption of plane strain considering that experimentally the width enlargement is not significant.

As determined in the previous section, the mechanical behaviour of the copper needs to be reset at the start of each rolling cycle. As a result, simulating the reduction process from a 1.6 mm thick stacking to a 180 µm thick composite cannot be conducted in a single rolling pass, as commonly done in the existing literature [4,5]. To achieve the simulation of the multi-cycle process, a specific procedure is implemented: each rolling cycle is simulated from the deformed shape of the composite computed by the preceding rolling cycle simulation. For that purpose, the deformed sheet is loaded in the design module of the software; the ends of the sheet are removed with numerical tools and the remaining part is meshed in order to use it as the entry in the simulation of the following cycle as schemed in Figure 5. The procedure is repeated for each cycle. Only the simulation of the configuration C is presented in this paper.

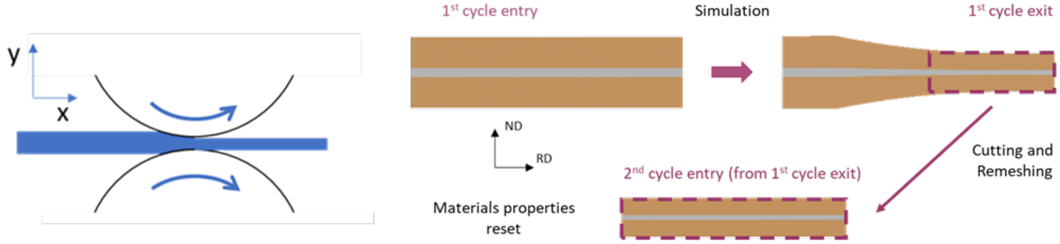


Figure 5: Scheme of the numerical procedure used to simulate the forming cycle by cycle

Stackings are meshed using reduced integration 8 nodes elements for most of the part. Layers are considered as one part, so that same nodes are shared at the interfaces between copper and

Invar layers. The rolls are modelled as rigid bodies. The contact behaviour between rolls and the composite is modelled by a Coulomb model with a 0.2 friction coefficient.

The meshed part is positioned between the rolls and the loading is applied in two steps: 1) The rolls are displaced to simulate thickness reduction of the given cycle as experimentally applied (Table 3), and 2) a rotation is applied around the roll centre so that the composite moves into the roll-gap thanks to the friction between the roll and the plate. The rotation is specified to have at least five lengths of roll-grip (distance between the entry and exit of the rolls).

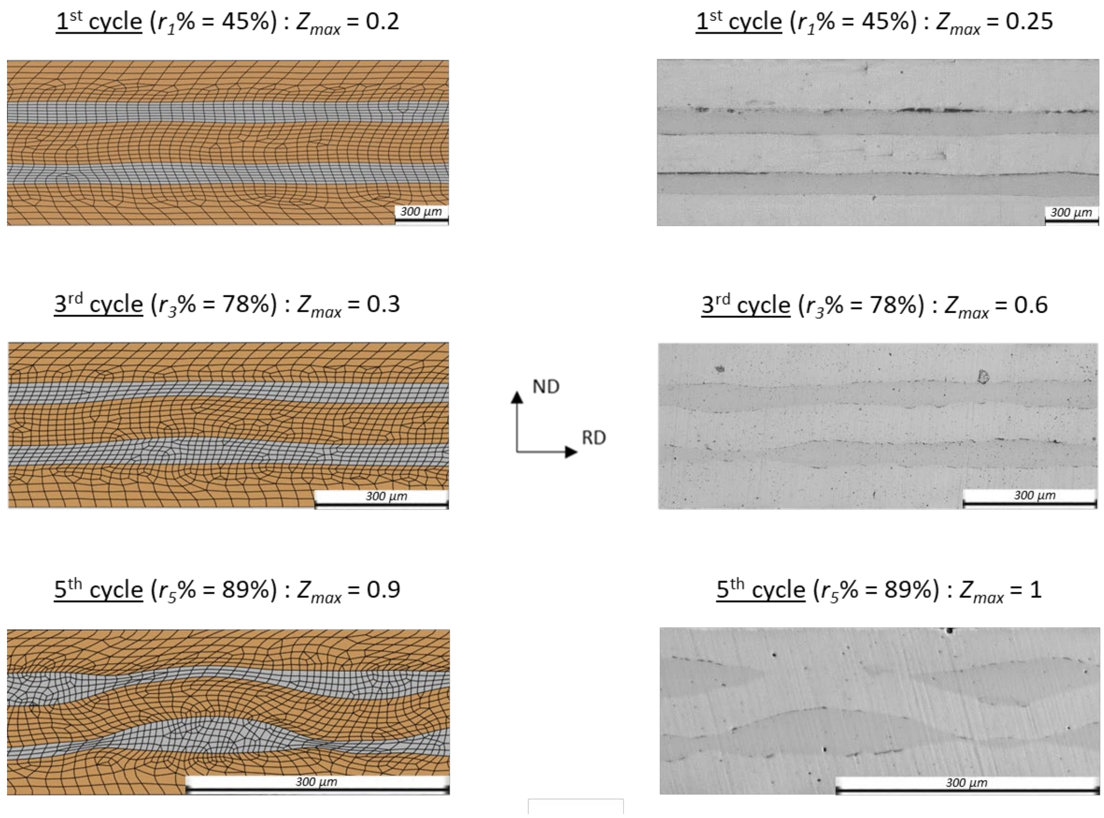
Thanks to the material characterization, the copper and Invar mechanical properties are experimentally defined at the start of each cycle. The effect of the annealing is taken into consideration with the laws previously defined in eq. (3) and (4). For copper, the properties are reset before each cycle and isotropy is considered as the copper layer thickness is initially 400 µm. For Invar, it is considered strain-hardened during the whole procedure since the annealing does not affect its mechanical properties.

Table 3: Roll reduction ratios r_j% and output thickness h_j evolution during roll-bonding for the configuration C

Cycle j	1	2	3	4	5
h_j [mm]	880	500	350	250	180
r_j%	45	69	79	85	89

Comparison to the experimental results:
The simulation and experimental results for configuration C after the 1st cycle, 3rd cycle and at the end of the forming *i.e.* after the 5th cycle, are shown in Figures 6a and 6b, respectively. Concerning the simulated results, for the 1st and 3rd cycle, almost equivalent necking coefficients (Z_{max} = 0.2 for the 1st cycle and Z_{max} = 0.3 for the 3rd cycle) and equal fragment sizes are observed. However, different types of plastic instability are spotted between the 1st and 3rd cycle, with a wavier pattern and more advanced necking in the latter simulation. For the 5th cycle simulation, a clear increase in maximal degree of necking is noted (Z_{max} = 0.9). The same type of wavy pattern as the one in the 3rd cycle is visible, but with a more pronounced necking. Experimentally, the evolution is more progressive, and fragmentation of Invar layers is observed after the 5th cycle. Both experimentally and numerically, an increase of necking with the increase of thickness reduction is noticed.

In the comparison between simulated and experimental results, similar effects are observed, and overall, a good correlation between them is noticed in terms of the maximal degree of necking. Obviously, for the 5th cycle simulation, the fragmentation does not appear since no fracture criterion is defined in the simulation. However, it is important to remark that the fragment general aspect is like the experiment one.



(a) (b)

Figure 6: (a) Simulated and (b) experimental results for configuration C at different r_j%

Conclusion

In this study, the effect of stacking parameters such as the number and thickness of Invar layers, which promote necking during roll-bonding of Invar and copper sheets has been studied. The following conclusions can be highlighted:

- For monolayer configurations, a lower thickness of the Invar layer enhances necking
- For a fixed volume fraction of Invar, a higher number of Invar layers favours necking

Hence, the volume fraction of the hard layer alone is insufficient for predicting the necking trend, contrary to common findings in the literature. The Invar layer thickness is likely to be an important parameter.

The finite element simulations of the multi-cycle process exhibit good agreement with experimental results. While this outcome needs confirmation for remaining configurations, these simulations hold the potential to efficiently model future setups, saving both time and materials.

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