Continuous casting of copper compounds

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A horizontal continuous casting process is developed to form a copper compound strip with cohesive bonding character. The process is investigated experimentally and numerically. The casting mould system consists of three stages. The substrate bronze (CuSn6) strip solidifies in the first mould stage. The (semi-)solid substrate passes through the compound casting region where the substrate strip surface is covered with molten pure copper (Cu99.5). The bilayer strip forwards into the third stage where the compound product cools down. Specimens are extracted from the bilayer semi-finished product to study the correlation between process conditions and bonding quality. The copper compound is characterized optically by incident light microscopy and energy-dispersive X-ray spectroscopy (EDX) and mechanically by hardness, shear tensile and 2-point bending tests.

Compound casting is a material- and energy-efficient technology which combines the production operations *casting* and *joining*. Using the melting heat of the casting process, a stable cohesive compound can be established between metallic alloys. Conventionally bimetallic compounds are produced by rolling technologies obtaining a plastic deformation at the interface under high pressure load. These techniques require subsequent steps of heat treatment to relieve residual stresses and strengthen the adhesive bond [1]. By integrating the joining step into the casting operation the compound casting technology has the potential to shorten the production chain and reduce the energy input at the same time.

In the last decades considerable efforts have been made academically and industrially to develop various production techniques for bimetallic compounds based on the continuous casting technology. Due to its high output rate the continuous casting is predestined as a production technology for compound products.

Under the name Novelis Fusion™ a vertical semi-continuous compound casting process for aluminium ingots is patented [2]. Studies published by HAGA ET AL. [3] focus the development of a vertical and horizontal twin roll compound casting method. The molten aluminium join partners are poured into counterrotating rolls. A scriber separates the two molten alloys and regulates the wetting between the (semi-)solidified substrate layer and the liquid upper layer. LIANG ET AL. [4] and SU ET AL. [5] investigated the horizontal core-filling continuous casting of copper clad aluminium rods. Pure copper is supplied into a crystallizer forming a solid metallic conduit. Subsequently the molten aluminium core material fills the inner cavity building a composite rod. Recent studies have been made on the coating of aluminium hollow billets shown in [6]. The 3003 aluminium substrate alloy is poured into a graphite mould. After solidification the billet advances into a tundish getting in contact with the 4045 aluminium coating alloy. Of particular interest are the investigations made by NERL ET AL. [7]. The simulation-aided development of a compound casting process for the production of bilayer aluminium strips is based on the horizontal continuous casting technology. The intermittently drawn bimetal strip consisting of an AlSn6Cu substrate layer and an Al99.5 top layer is formed in a multi-stage casting mould system.

This paper describes an innovative casting method for the production of copper compound strips. The investigation focuses on the achievement of a cohesive compound at the interface of a bilayered tin-bronze/pure copper strip produced by means of horizontal continuous casting. The bronze/copper compound combines the particular advantages corrosion resistance and strength respectively electric and thermal conductivity. Pretests have been made in a

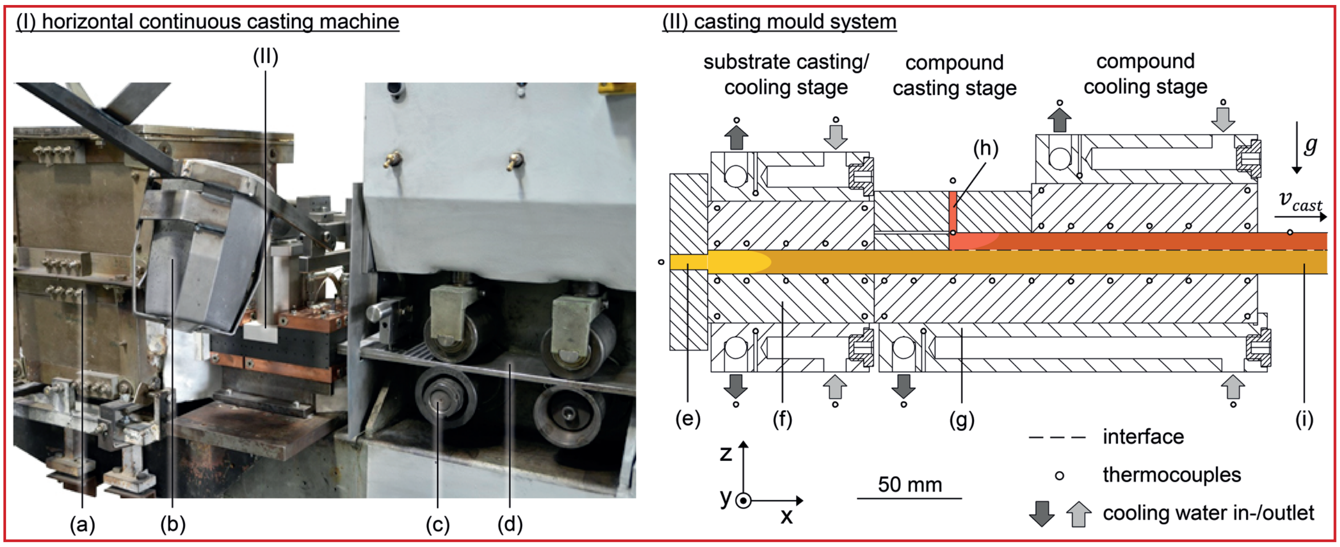

Fig. 1: Continuous casting system for the production of copper bilayer strips: (a) substrate melt induction furnace, (b) top-layer melt crucible, (c) drawing unit, (d) dummy bar, (e) substrate melt (CuSn6), (f) graphite mould, (g) cooling plates, (h) top-layer melt (Cu99.5), (i) compound strip

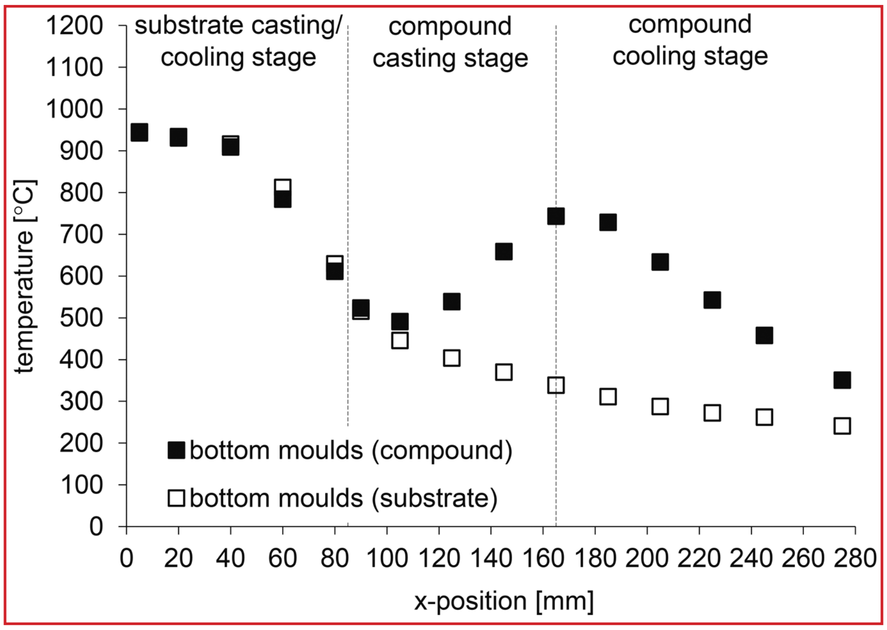

Fig. 2: Temperature profile within the casting mould system during substrate and compound casting

semi-continuous compound casting process published by MITTLER ET AL. [8].

Compound casting process

The compound casting process is implemented on a modified Demag Technica type 30/10 D I MCP N continuous casting machine. Figure 1-I shows the experimental setup consisting of the main components melt supply, drawing unit and casting mould system. The molten copper-tin alloy with 5-7 percent by weight of tin (CuSn6) is supplied by a crucible induction furnace that is mounted on the arm of the casting machine. The pure copper (Cu99.5) is supplied separately by a melting and holding furnace with electric resistance heat and is carried manually to the crucible fixture above the casting system. The drawing unit forwards the strip intermittently in horizontal direction.

The casting mould system (figure 1-II) is divided into three functional stages and consists mainly of graphite plates that are clamped between water-driven cooling plates. In the first stage the CuSn6 melt solidifies and cools down inside a cavity with a cross-section dimension of 150 mm x 12 mm. As the temperatures in the first stage mould reach the steady state the Cu99.5 melt is supplied to the compound casting stage where it gets in direct contact with the (semi-)solid substrate strip. The cavity for the Cu99.5 (cross-section dimension of 140 mm x 9 mm) is fed through a vertical slot from the melt reservoir that is located above a ceramic plate. Considering a single stroke of the substrate strip into this cavity the Cu99.5 melt wets the substrate surface that constitutes an appropriate heat sink for a directional solidification of the top-layer material. In the third stage heat of the compound strip is transferred into the cooling water.

Figure 2 shows the measured temperature profile along the bottom graphite plates for both substrate and compound casting. The cast cycle configuration consists of a 7.5 mm stroke length in combination with a 1.1 s waiting period. As can be seen from the temperature distribution in the first stage the solidification front of the CuSn6 strip is located approximately 50 mm behind entering the cavity and the temperatures in the first mould are not affected significantly by the compound casting process. However, the temperatures in the second and third stage increase distinctly due to pouring of Cu99.5 melt. The maximum temperature inside the second bottom plate is reached downwards (x-direction) from the first material contact position caused by vertical heat transfer through the substrate strip during simultaneous horizontal strip transport. Heat transfer against the casting direction results in a preheating of the substrate surface before entering the contact zone with the top-layer material. Calculating the interface temperature using numerical simulation it can be shown that the interface temperature exceeds the solidus temperature of CuSn6 for several casting cycles. This offers suitable thermal conditions for the formation of a cohesive bonding between the compound partners.

Compound characterization

The quality of the bonding is investigated using different testing methods. Therefore some specimens are taken from the compound strip.

Structural analysis

Figure 3 shows the microstructure of a longitudinal compound cross-section in the strip center. From the macroscopic view the compound exists without undesired mixing or large-scale bonding defects. Some small bonding defects occur frequently in a distance according to the stroke length of 7.5 mm. These bonding defects are formed at the beginning and ending of the stroke during the first casting cycle in which the compound partners are getting in contact. In these particular cycle phases the vertical orientated surfaces defined by the ceramic plate (geometrical boundary at the stroke ending) and the already solidified Cu99.5 edge layer of the preceding cycle (geometrical boundary at stroke beginning) form in combination with the horizontal orientated substrat top surface the geometrical condition for the wetting. These geometrical boundary conditions inhibit along with the surface tension of the liquid Cu99.5 and the fast solidification a full wetting of the

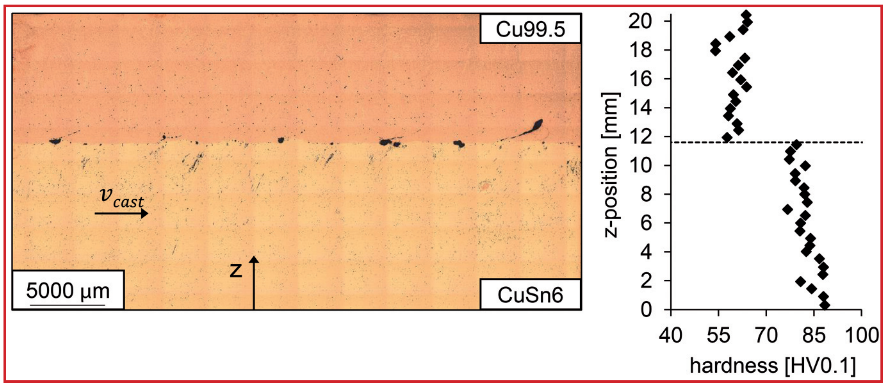

Fig. 3: Structure and hardness analysis of a compound specimen

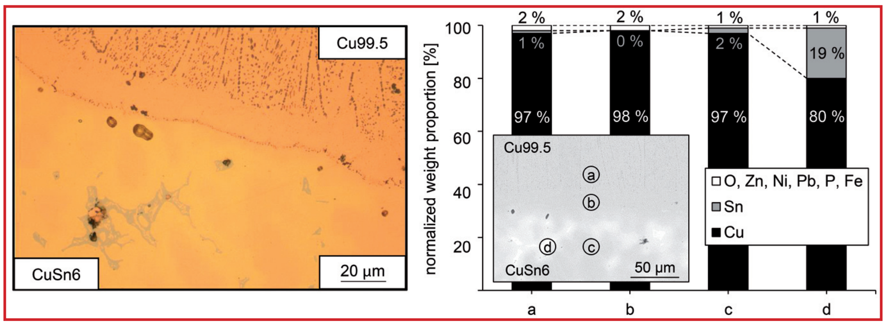

Fig. 4: Microstructure analysis and element determination of a compound specimen

substrate top surface. The hardness profile across the specimen thickness (figure 3) shows a distinct hardness transition at the interface and confirms representatively for each compound partner the conservation of its single material property. Thus the tin-bronze shows an average hardness of 83 HV0.1 and the oxide-containing copper 60 HV0.1.

An adequate cohesive bonding is proven by a microscopic analysis (figure 4). The near interface microstructure of the CuSn6 layer consists of a dendrite structure that is filled up with a tin-rich alloy composition and scattered microporosity. The Cu99.5 layer contains scattered cuprous oxide across its whole layer thickness. The interface between the compound partners is built up as a sharp transition zone with a thickness of approximately 10-50 µm. Some small voids that have been caused by insufficient wetting are filled up with tin-enriched material. According to the calculated temperature profile the near-interface tin-rich alloy composition is remelted and can wet the already solidified bottom copper surface. The result of the hardness measurement appropriately fits with the chemical interface composition measured by EDX (figure 4). Across the thickness direction of the interface there is a significant tin gradient detectable. The CuSn6 structure shows a large distinction of its local tin content parallel to the horizontal interface. This segregation-based distribution is well-known from the single strip casting of tin-bronze.

Mechanical testing

To investigate the load-bearing capacity of the copper compound destructive materials testing methods are applied to compound samples. Tensile stress and shear stress allocate to the critical loading situations for compound material. Due to the special geometry of the bilayer strips shear tensile tests and bending tests are chosen to characterize the interface. Special test setups are designed shown in figure 5.

The shear tensile test provides an appropriate testing method to determine the bonding strength of a semi-finished product formed by continuous compound casting [9]. The specimens are taken orthogonally to the casting direction and milling operations are used to get a test surface of 25 mm (casting direction) x 2.5 mm that is directly located at the interface. Figure 5-I shows the test setup (traverse speed 1 mm/min) at a tensile testing machine after the interface failure. The bonding strength is calculated as the ratio between the measured maximum force and the size of the test surface and is shown in figure 6-I depending on the sampling x-position. The maximum bonding strength that has been achieved so far is 173 N/mm². An analysis of the fracture surface shows that the failure in the interface zone occurs within the Cu99.5 layer.

In the 2-point bending test a pressure load causes the bending of a specimen which is fixed in one clamp (figure 5-II). Thus tension is transmitted orthogonally to the interface. The test setup is designed to characterize specimens of the size 21 mm x 8 mm x 5 mm. The distance between clamp and interface is 1.5 mm and between interface and punch 6.25 mm (level-arm). The sample deformation is recorded by a digital image correlation system (DIC) at the side surface as well as by a strain gauge placed on the upper surface at the central interface position. A mechanical testing machine provides the pressure load at a constant feed of 1 mm/min at room temperature. The bending stress is calculated as function of testing force, level-arm and sample geometry. Figure 6-II shows the result of the bending test on a representative compound specimen extracted from the centre of the bilayer strip. The sample reaches a maximum bending stress of 210 N/mm² when a tear is initiated at the upper interface area (figure 6-II) propagating along the interface. The strain on the side surface is similar to that measured on the upper surface up to the time when the strain gauge fails at a sample deformation of 2 %. The compound specimen shows

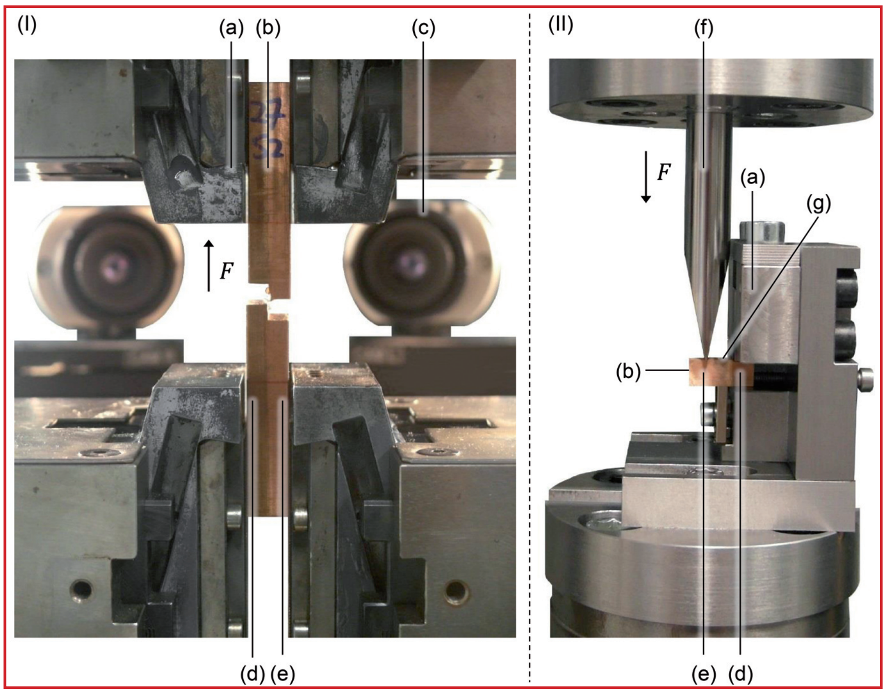

Fig. 5: Test setup for the mechanical characterization of compound specimens by (I) a shear tensile test and (II) a 2-point bending test: (a) clamping jaws, (b) compound specimen, (c) optical sensor system (DIC), (d) substrate layer (CuSn6), (e) top layer (Cu99.5), (f) bending punch, (g) strain gauge

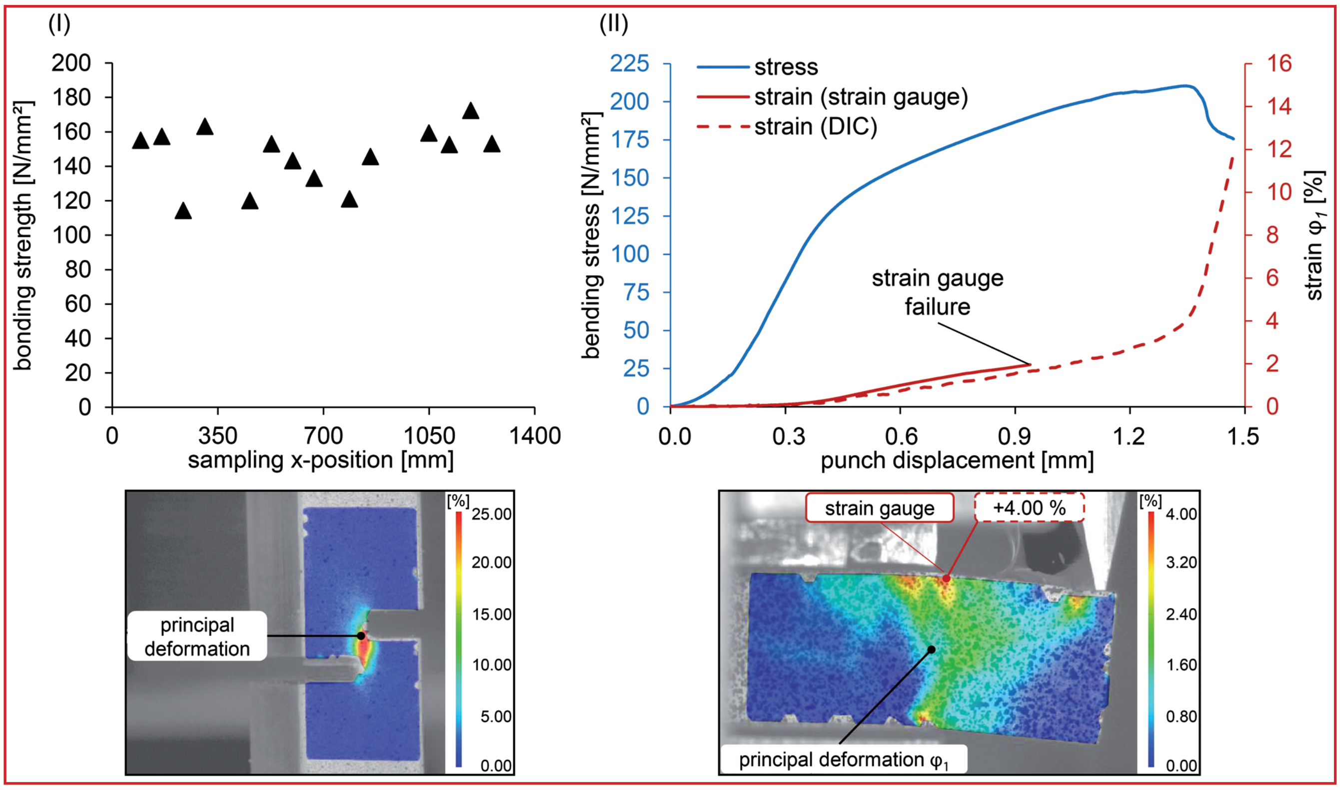

Fig. 6: Mechanical characterization of the bonding strength by (I) a shear tensile test and (II) a 2-point bending test

a ductil deformation behaviour with 4 % elongation at break. To interpret the result of the compound sample monolithic reference bending tests are performed providing a maximum bending stress of 300 N/mm² for a CuSn6 alloy and 190 N/mm² for a Cu99.5 material.

Conclusion

In this project a continuous casting process was developed to form a bilayer CuSn6/Cu99.5 strip. A special casting mould system was designed mainly consisting of graphite plates and copper coolers. The proof of concept was provided experimentally. A cohesive compound at the interface of the two layers was achieved and subsequently characterized by optical and mechanical testing methods. Due to the high process temperatures and miscibility of the alloy elements the conditions to form a solid solution at the interface were given. However, the join partners largely kept their characteristic properties within the respectiv strip layers. By means of destructive mechanical testing the evidence of a sufficient bonding strength was provided matching the level of monolithic reference samples.
The experimental and numerical results suggest that the drawing kinematics particularly affects the formation of copper compound strips. Thus further research has to be done on the continuous compound casting technology under the variation of process parameters.

Acknowledgement

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