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Design of a Mould System for Horizontal Continuous Casting of Bilayer Aluminium Strips

Ch. Nerl, M. Wimmer, P. Hofer, E. Kaschnitz

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Abstract**—**The present article deals with a composite casting process that allows to produce bilayer AlSn6-Al strips based on the technique of horizontal continuous casting. In the first part experimental investigations on the production of a single layer AlSn6 strip are described. Afterwards essential results of basic compound casting trials using simple test specimen are presented to define the thermal conditions required for a metallurgical compound between the alloy AlSn6 and pure aluminium. Subsequently, numerical analyses are described. A finite element model was used to examine a continuous composite casting process. As a result of the simulations the main influencing parameters concerning the thermal conditions within the composite casting region could be pointed out. Finally, basic guidance is given for the design of an appropriate composite mould system.

Keywords**—**Aluminium alloys, composite casting, compound casting, continuous casting, numerical simulation

I. INTRODUCTION

ALUMINIUM clad alloys are commonly used because they allow to combine the individual advantages of different alloys concerning their physical, mechanical or chemical properties. In the combustion engine sector aluminium composite strips are used as basic materials for sliding bearing applications [1]–[3].

Up to now most of the aluminium clad alloys are produced by means of cold or hot roll bonding processes. With this joining technique various alloys can be bonded in the solid state. The bonding is caused by adhesion, which requires especially clean surfaces and a sufficient grade of plastic deformation of the materials to be joined [4]. Therefore, roll bonding processes require additional efforts in order to pre-heat the join partners or to ensure appropriate surface conditions. Furthermore, there are serious problems with the processing of hard, brittle and high strength alloys which leads to a decrease in the interface quality.

Using a composite casting process instead of roll bonding techniques would have the benefit that a cohesive metallurgical compound occurs between the aluminium metals. Furthermore, it is assumed that a larger number of aluminium alloys can be joined. The production of bimetallic strips within a single continuous casting process is thus an attractive alternative to roll bonding processes with a high potential to save manufacturing costs and energy by shortening the process chain. Within this article the examinations are based on the aluminium alloy AlSn6 and pure aluminium.

II. EXPERIMENTAL INVESTIGATIONS

A. Horizontal Continuous Casting of a Single Layer Strip

As a first step within the development of a continuous composite casting process, a single strip has to be cast. In this case the substrate strip consists of the alloy AlSn6. AlSn6 is a hypoeutectic Al-Sn alloy that is commonly used to produce sliding bearings [1]–[3]. The microstructure consists mainly of an equiaxed α-Al matrix in which the tin phase is precipitated as a separate phase at the grain boundaries [5]. This alloy exhibits a wide solidification range which leads to a hot-short material behavior during casting processes [1], [2]. Usually thin strips of the alloy AlSn6 are produced by horizontal continuous casting processes using furnace-dependent moulds and an intermittent withdrawal regime [6].

The experiments were carried out using a horizontal continuous casting machine (Demag Technica type 30/10 D I MCP N) with a furnace-dependent setup. The schematic of the mould system is shown in Fig. 1.

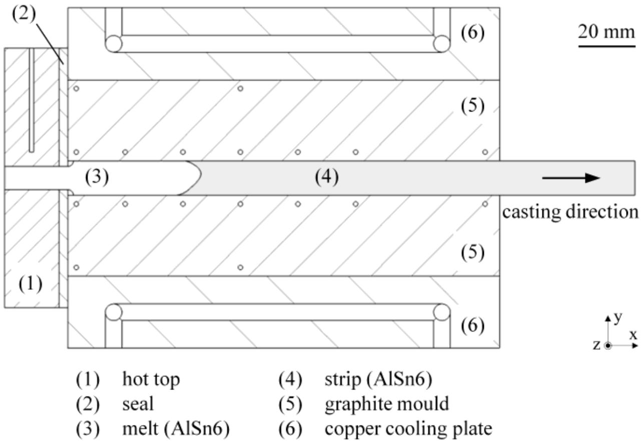

Fig. 1 Schematic of the casting mould to produce a single layer AlSn6 strip

The mould system consists of a graphite mould which is cooled by copper cooling plates at the top and bottom surface. The liquid metal enters the mould where it solidifies after passing through a hot top. The solidified strip (cross-sectional area 150 mm x 12 mm) is withdrawn in the x-direction. Within the graphite mould thermocouples can be positioned close to

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Christoph Nerl is with the Institute of Metal Forming and Casting, Technische Universität München, Garching, Germany (phone: 0049-89-28913769; fax: 0049-89-28913738; e-mail: cn@utg.de).

Martin Wimmer is with the Institute of Metal Forming and Casting, Technische Universität München, Garching, Germany (e-mail: mw@utg.de).

Peter Hofer is with the Austrian Foundry Research Institute (ÖGI), Leoben, Austria (e-mail:peter.hofer@ogi.at).

Erhard Kaschnitz is with the Austrian Foundry Research Institute (ÖGI), Leoben, Austria (e-mail:erhard.kaschnitz@ogi.at).

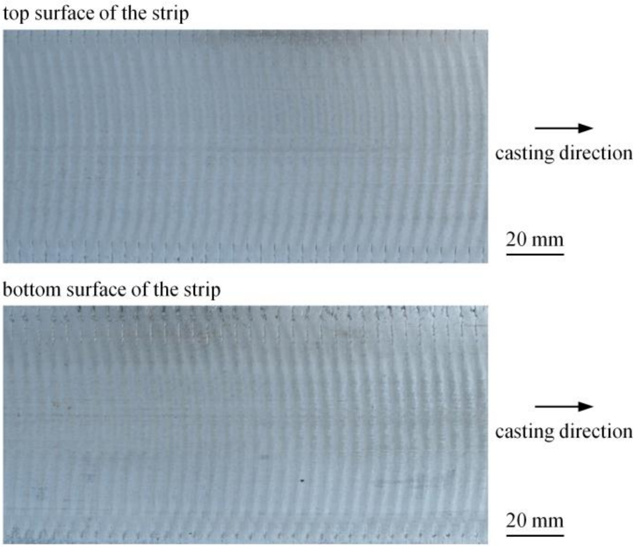
the inner surface. They allow measuring the mould temperatures during the casting process.

In order to determine the required process parameters for producing a single layer strip consisting of the alloy AlSn6 horizontal continuous casting trials were carried out. The main objective of the experiments was to investigate the influence of different process parameters on the quality of the cast product. Therefore, the casting speed, the withdrawal regime, the cooling water flow rate, and the melt temperature were varied. The experimental results revealed that, using the parameters listed in Table I, a good quality of the strip could be achieved. By means of the experimental setup strips with a length of 6 m could be cast under stable process conditions.

TABLE I
PROCESS WINDOW FOR CASTING A SINGLE LAYER ALSN6 STRIP

Symbol	Quantity	Range
$T_{AlSn6\text{-}melt}$	melt temperature	720-770 °C
V_{water}	water flow rate through cooling plates	10-20 l/min
v	casting speed	180-260 mm/min
$T_{strip\text{-}outlet}$	strip outlet temperature	150-300 °C

The corresponding top and bottom surface of a single layer AlSn6 strip and the predominant parameters of the casting process are illustrated in Fig. 2.



casting parameters
- $T_{AlSn6\text{-}melt}$ 750 °C
- V_{water} 20 l/min
- v 200 mm/min
intermittent withdrawal regime (stroke 7,5 mm, pause 2,2 s)
- $T_{strip\text{-}outlet}$ 230 °C

Fig. 2 Casting parameters and corresponding surfaces of an AlSn6 strip

Both the top and bottom surface exhibit an excellent surface quality without any casting defects such as cracks or cold runs.

B. Preliminary Compound Casting Trials

Preliminary compound casting trials were carried out in order to determine the thermal conditions which are necessary to obtain a proper metallurgical compound between the alloy AlSn6 and pure aluminium. During these trials, simple cylindrical composite cast parts with a diameter and height of 40 mm were produced by casting a melt of pure aluminium onto a substrate consisting of AlSn6. In order to measure the temperature, type K thermocouples with a diameter of 0.2 mm were positioned close to the interface. The temperature of the substrate was varied when casting the liquid aluminium upon it. A detailed discussion of the experimental setup and the results has been presented elsewhere [7], [8].

The examinations revealed that a substrate temperature of at least 500-550 °C at the interface is necessary in order to re-melt the surface and thus to ensure a good metallurgical compound. Fig. 3 illustrates the microstructure at the interface between the alloy AlSn6 and pure aluminium. The metals are well bonded, and no defects such as porosity or included oxide skins can be seen.

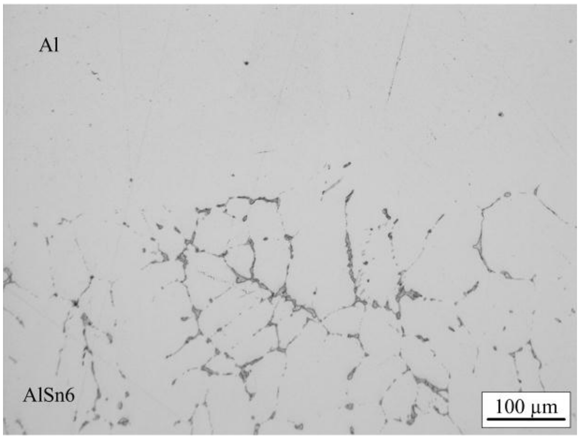


Fig. 3 Microstructure at the interface Al-AlSn6 (substrate temperature 550 °C)

Fig. 4 illustrates that in case of lower substrate temperatures no metallurgical compound could be achieved.

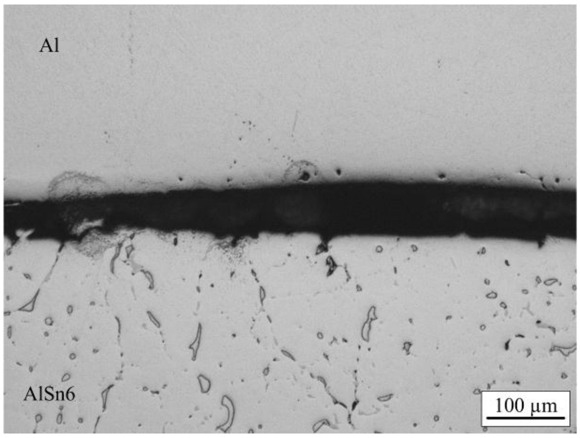


Fig. 4 Microstructure at the interface Al-AlSn6 (substrate temperature 450 °C)

By means of these preliminary tests important basic information could be provided concerning the design of a mould system which allows the continuous casting of a respective bimetallic composite strip.

III. LAYOUT OF THE COMPOSITE CASTING MOULD

The basic idea of continuously casting a bimetallic composite strip is to cast a liquid metal onto a solid or semisolid substrate strip. Providing proper thermal conditions in order to achieve a metallurgical compound is the major goal of the mould system design process. In this case, liquid pure aluminium is supposed to be cast upon a solid AlSn6 strip.

Therefore, the existing mould system for casting a single strip shown in Fig. 1 should be extracted in such a manner that the liquid aluminium melt can be cast upon the substrate strip. Fig. 5 shows a schematic of the corresponding composite casting mould. It is designed modularly and consists of a two-part graphite mould, which is cooled by copper cooling plates at its upper and lower surfaces, and a composite casting unit.

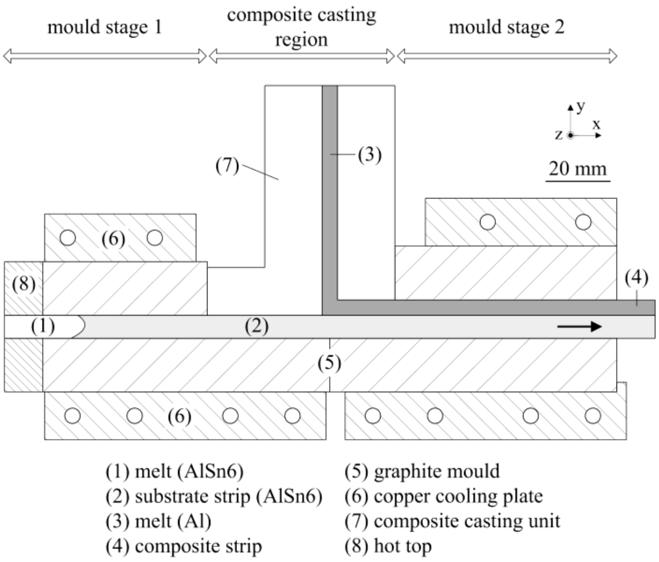


Fig. 5 Schematic of the composite casting mould system

The substrate strip is supposed to be cast in the first stage of the mould system. After its solidification the cast product enters the composite casting unit which can be heated. Within the casting unit, the melt of pure aluminium is delivered by a vertical slot which may be fed by a crucible located above it. After casting the melt onto the base material the composite strip is withdrawn horizontally in x-direction and is cooled while passing through the second stage of the mould system.

IV. NUMERICAL SIMULATIONS

The main objective of the numerical simulations was to find out the main influencing variables concerning the predominant thermal conditions during the composite casting process.

A. Model Setup

Based on the presented mould system, a simulation model was built up using the commercial software package WinCast®. We assumed that the width of the strip is much greater than its height. Therefore, a thin layer having a thickness of 5 mm in z-direction representing the longitudinal section of the composite casting mould shown in Fig. 5 was investigated. The meshing was done by using a single layer of prismatic elements with triangular base areas. The cast material domains were meshed with a maximum edge length of 2 mm within the xy-plane. In order to approximate two-dimensional conditions, adiabatic boundary conditions were set at the top and bottom surface of the meshed geometry.

Heat transfer and fluid flow were calculated by means of a coupled algorithm implemented in WinCast®. Both Fourier's heat conduction equation and the Navier-Stokes equations were solved using the finite element method. According to the casting speed, the macroscopic movement of the strips was taken into account by transporting the temperature field within the completely solidified material in the casting direction at each time step. Two cast material domains could be defined, each with its own thermo physical properties.

In the calculations the following assumptions and simplifications were made:

1) The withdrawal of the strip occurs continuously at a constant casting speed in x-direction.
2) The liquid metal was treated as a Newtonian fluid, and the fluid flow was assumed to be laminar.
3) There is no mixing between the pure aluminium and the alloy AlSn6. Thus, solute transfer was not taken into account.
4) The temperatures of the mould and the casting unit were assumed to be constant.

A schematic of the geometrical details in the composite casting region is shown in Fig. 6.

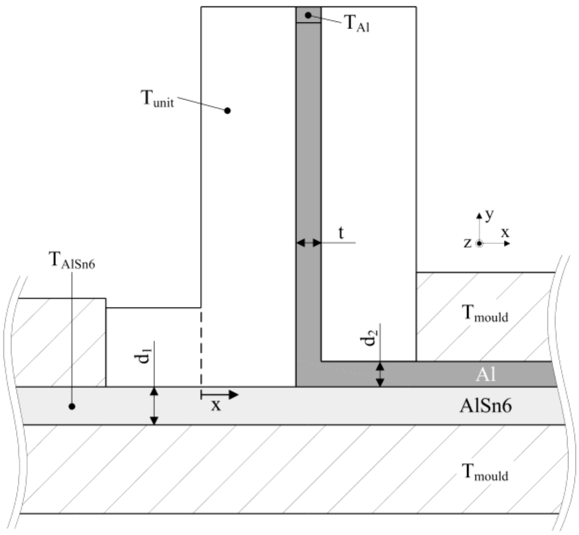


Fig. 6 Geometrical details of the composite casting mould used in the simulations

The geometrical conditions of the composite casting region can be described by the thickness of the substrate strip d_1, the thickness of the up cast strip d_2, and the width of the slot in the casting unit t. The ratio of the strip thicknesses D can then be calculated as

$$D = d_1 / d_2 . \tag{1}$$

We then define the quantity T as the ratio of the width of the slot in the casting unit t and the thickness of the up cast strip d_2, which can be expressed as

$$T = t / d_2 . \tag{2}$$

Furthermore, we define that the total thickness of both strips must not exceed a value of 20 mm. In Table II the geometrical conditions and casting parameters are listed together with the boundary conditions used in the numerical analysis. In order to determine the main influences on the thermal conditions of the composite casting process a sensitivity analysis was accomplished. In doing so we varied the initial temperature of the AlSn6 substrate strip before entering the casting unit, the casting speed, and the geometrical conditions.

TABLE II
GEOMETRICAL CONDITIONS, CASTING PARAMETERS, AND BOUNDARY CONDITIONS USED IN THE SIMULATIONS

Symbol	Quantity	Value
D	thickness ratio of lower and upper strip	1, 1.5
T	ratio of slot width and upper strip thickness	0.5, 1, 2
v	casting speed	200, 250, 300 mm/min
T_{Al}	inlet temperature of the aluminium melt	750 °C
T_{AlSn6}	initial temperature of the AlSn6 substrate strip	200, 250, 300, 350, 400 °C
T_{mould}	temperature of the mould	100 °C
T_{unit}	temperature of the casting unit	750 °C
$\alpha_{Al\text{-}AlSn6}$	heat transfer coefficient Al-AlSn6	ideal thermal contact
$\alpha_{Al\text{-}mould}$	heat transfer coefficient Al-mould	1000 W/(m²K)
$\alpha_{AlSn6\text{-}mould}$	heat transfer coefficient AlSn6-mould	500 W/(m²K)
$\alpha_{Al\text{-}unit}$	heat transfer coefficient Al-casting unit	1000 W/(m²K)
$\alpha_{AlSn6\text{-}unit}$	heat transfer coefficient AlSn6-casting unit	0 W/(m²K)

In the calculations the thermal contact between the AlSn6 substrate strip and the up cast aluminium was assumed to be ideal. This assumption of an ideal contact between these materials could be verified within the preliminary compound casting experiments which were accompanied by a numerical study [8]. The thermo physical properties of the cast materials AlSn6 and pure aluminium used in the simulations are listed in Table III.

TABLE III
THERMO PHYSICAL PROPERTIES

Symbol	Quantity	Value
Al		
T_{liq}	liquidus temperature	661 °C
T_{sol}	solidus temperature	660 °C
L	latent heat of fusion	1073 J/cm³
a	thermal diffusivity	0.3-0.4 cm²/s (liquid state) 0.7-1.0 cm²/s (solid state)
AlSn6		
T_{liq}	liquidus temperature	638 °C
T_{sol}	solidus temperature	227 °C
L	latent heat of fusion	988 J/cm³
a	thermal diffusivity	0.3 cm²/s (liquid state) 0.7-0.8 cm²/s (solid state)

B. Results

The simulations were stopped when steady state conditions were reached. First, the influence of the thickness ratio D was investigated. The steady state temperature field in case of a thickness ratio of D = 1, an initial substrate temperature of T_{AlSn6} = 300 °C, and a casting speed of v = 250 mm/min is shown in Fig. 7 (a), whereas Fig. 7 (b) illustrates the steady state temperature field in case of a thickness ratio of D = 1.5 under the same conditions.

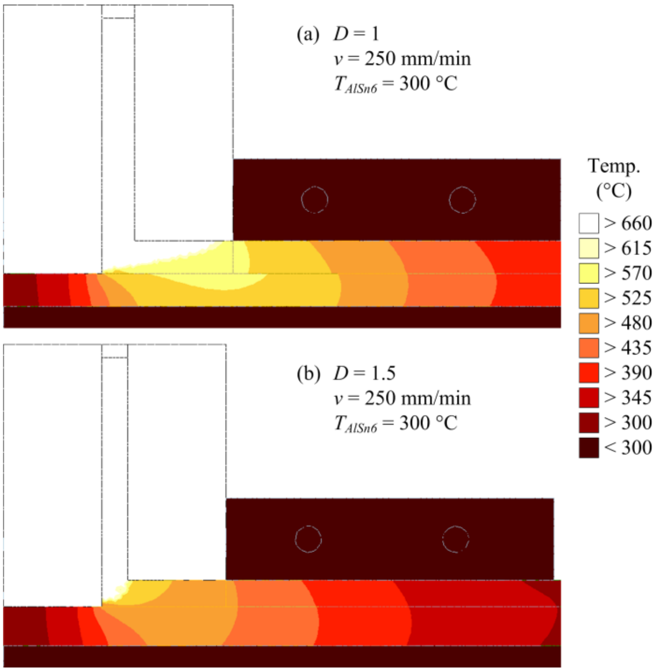


Fig. 7 Calculated steady state temperature fields within the composite casting region

The isothermal curves reveal that the substrate strip is reheated intensely while passing through the composite casting unit due to the ideal thermal contact with the incoming aluminium melt applied in the simulations. It can be seen that the composite casting region reaches higher temperature values at the lower thickness ratio D due to the higher incoming enthalpy flux caused by the liquid metal flowing through the slot within the composite casting unit. It is obvious that in case of a thickness ratio of $D = 1.5$ the solidification front of the pure aluminium may reach the edge of the vertical slot within the casting unit. This premature solidification could make the withdrawing of the composite strip impossible and must therefore be avoided. With regard to the calculated temperature fields, a conflict of objective arises: On the one hand, a premature solidification of the pure aluminium has to be avoided as mentioned above, and the preheating of the substrate must be sufficient in order to ensure a proper formation of the metallurgical compound. On the other hand, the incoming heat flux due to the up cast liquid aluminium must not be too high in order to avoid an excessive remelting of the AlSn6 substrate strip. This may cause the breaking of the strip during the withdrawal movement.

Further information of the thermal conditions can be gained from the steady state temperature profile along the top surface of the substrate strip. According to the preliminary compound casting trials the surface of the AlSn6 substrate has to be reheated up to the semisolid state, so that a metallurgical compound can be formed. Fig. 8 opposes two simulated temperature profiles. It becomes clear that a lower thickness ratio D leads to a higher maximum temperature T_{max} on the surface of the AlSn6 substrate strip. In addition a higher temperature level can be maintained over a longer distance and time respectively. Both simulations were carried out applying a casting speed of $v = 250$ mm/min, a ratio of $T = 1$, and an initial substrate temperature of $T_{AlSn6} = 300$ °C.

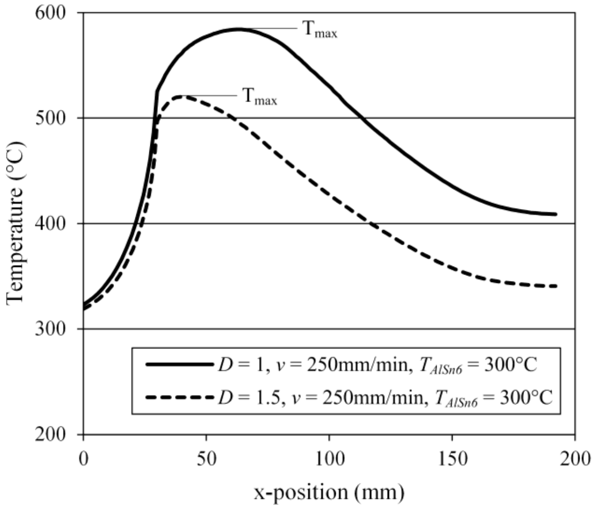


Fig. 8 Calculated temperature profiles along the top surface of the substrate strip

With regard to the preliminary compound casting trials, the maximum temperature T_{max} within the composite interface turned out to be the most determining factor in order to evaluate the predominant thermal conditions and the quality of the metallurgical compound. Thus the calculated values of T_{max} depending on the substrate temperature T_{AlSn6}, the thickness ratio D and the casting speed v are compared in Fig. 9.

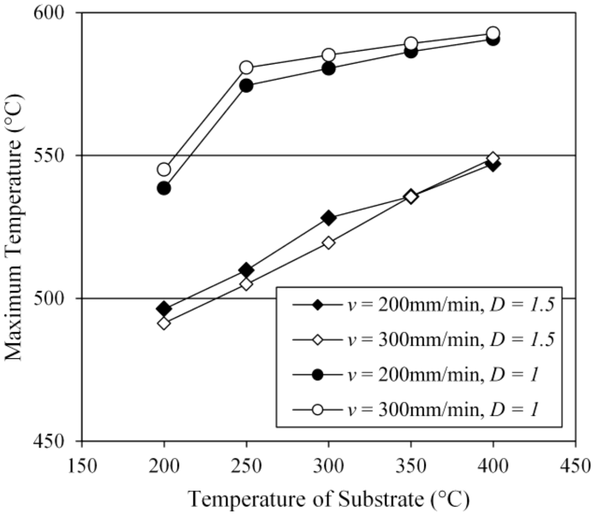


Fig. 9 Calculated maximum temperatures at the top surface of the substrate strip

The simulated maximum temperatures T_{max} lay in the range of about 490-590 °C. It becomes clear that the thermal conditions are mainly influenced by the geometrical conditions and the initial temperature of the substrate strip. Generally increasing substrate temperatures contribute to higher maximum temperatures at the interface. Furthermore, the thickness ratio D strongly influences the thermal conditions. In case of a thickness ratio of $D = 1$ the maximum temperatures are about 50-80 °C higher than in case of a thickness ratio of $D = 1.5$. This can be explained by the fact that a lower thickness ratio causes a higher enthalpy flux into the composite casting region. Therefore a higher amount of heat is available in order to reheat the substrate. In contrast to the thickness ratio D, the applied casting speed v does not influence the maximum temperatures T_{max} significantly.

At last the influence of the ratio T on the thermal conditions was investigated. It is clear that a lower ratio T will narrow the vertical slot in the casting unit and consequently cause a higher average flow velocity of the liquid aluminium. Fig. 10 opposes the steady state temperature fields within the composite casting region for three different widths of the slot. In all cases the substrate temperature T_{AlSn6} was 300 °C, the thickness ratio was set to a value of $D = 1$, and a casting speed of $v = 250$ mm/min was applied.

As can be seen in Fig. 10, the temperature of the liquid aluminium within the vertical slot of the casting unit decreases with increasing values of the ratio T. This indicates that a narrow slot may help to avoid premature solidification of the aluminium melt owing to a higher average flow velocity of the aluminium melt.

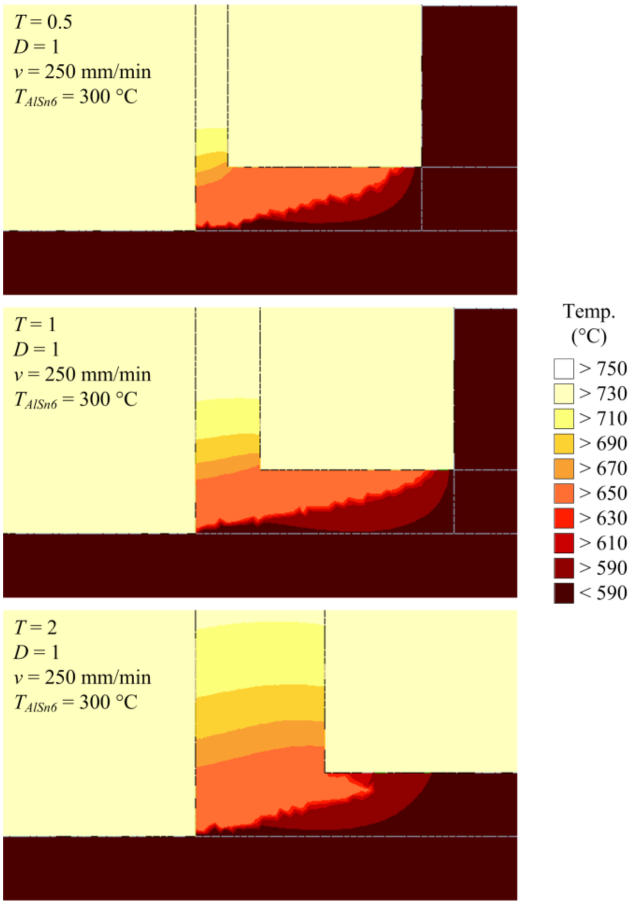


Fig. 10 Detailed view of the calculated temperature fields within the composite casting region

V. CONCLUSION

According to the investigations carried out the following conclusions can be drawn:

1) Based on the horizontal continuous casting technology the process window for producing a single layer AlSn6 strip could be worked out.
2) A modularly designed mould system for a continuous composite casting process to produce bilayer AlSn6-Al strips is presented.
3) The required thermal conditions in order to obtain a proper metallurgical compound between the alloy AlSn6 and pure aluminium could be defined with the help of preliminary composite casting experiments.
4) Numerical analyses were carried out using a finite element simulation model representing a continuous composite casting process. The model approximated two-dimensional conditions, and the numerical results were evaluated at steady state conditions. The results revealed that the thermal conditions within the composite casting region can mainly be influenced by the initial temperature of the AlSn6 substrate strip and the geometrical layout of the composite casting unit.

Taking these conclusions into account, the casting plant equipment for continuously casting a bilayer aluminium strip will be realized. The casting process will then be examined experimentally, and the simulation model will be validated. In addition, the quality of the metallurgical compound within the composite cast strips is supposed to be characterized.

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