Hot-work tool steels are used in casting and hot-forming processes and are subjected to thermal, mechanical and chemical stresses that can cause damage to various parts of the tool. Therefore, knowledge of the interaction between tool steel and molten aluminium alloy is necessary to extend the life of the tool. The present work was carried out to predict the influence of temperature on the interaction kinetics between tool steel and molten aluminium. To investigate the effect of temperature on the dissolution rate of tool steel in molten aluminium and the rate of formation of interaction layers, DSC analysis was performed at two different temperatures, 670 °C and 700 °C, for 12 h. The results were corroborated and supported by a detailed microstructure analysis.

It was found that very small temperature changes, in this case 30 °C, significantly affect the kinetics of the interaction layer’s formation between the tool steel H11 and molten aluminium Al99.7. All test methods show a pronounced influence of the test temperature. A significantly faster dissolution was observed in the DSC curve, with the slope of the curve being larger for the specimen tested at 700 °C, which was also confirmed by measurements of the thicknesses of the interaction layers. The thickness of the composite layer was almost the same in both cases, and the temperature has no effect on this layer. The types of interaction layers do not differ from each other.

Keywords: interaction between tool steel and molten aluminium, reaction kinetics, temperature, differential scanning calorimetry.
ing to the formation of intermetallic phases in certain stoichiometric ratios based on the binary phase diagram for Al-Fe. The most frequently formed phases are \( \text{Al}_5\text{Fe}_2 \) and \( \text{Al}_{13}\text{Fe}_4 \), which form a reaction layer. Optimal wetting and diffusion are required for the formation of these phases, which result from the difference in chemical potentials between the solid tool steel and the molten aluminium. However, to achieve the desired mechanical and physical properties of the tools, the formation of these phases must be limited or prevented.

When tool steels dissolve in molten aluminium, the dissolution is initially intense but slows down after about 250 s due to the difficult diffusion of aluminium and iron atoms through the resulting interaction layer. The interlayer between the tool steel and the aluminium alloy consists of an intermetallic and a composite layer, and the thickness of the interaction layer is influenced by the alloying elements in the molten aluminium and the tool steel. Tool-steel alloying elements such as chromium, manganese, silicon, molybdenum, and vanadium are present in the reaction layer and reduce or prevent the formation of an intermetallic layer. The iron content in the aluminium alloy also affects the lower layer thickness, but should not be too high to avoid deterioration of the mechanical properties. The temperature of the aluminium melt also influences the thickness of the interaction layer, with higher temperatures leading to a thicker layer.

The present work was carried out to predict the influence of temperature on the interaction kinetics between tool steel and molten aluminium. To investigate the effect of temperature on the dissolution rate of tool steel in molten aluminium and the rate of formation of the interaction layers, a DSC analysis was performed at two different temperatures, 670 °C and 700 °C, for 12 h. The results were substantiated and supported by a detailed SEM analysis.

2 MATERIALS AND METHODS

The reaction kinetics between molten aluminium and tool steel were analysed using differential scanning calorimetry (STA Jupiter 449c, NETZSCH Holding, Selb, Germany), which provides information on the dissolution rate of tool steel in molten aluminium and the rate of formation of the interaction layers. A DSC analysis was performed at two different temperatures, 670 °C and 700 °C, for 12 h. The results were substantiated and supported by a detailed SEM analysis.

After completion of the DSC testing, the specimens were examined metallographically, and the thicknesses and types of interaction layers were analysed by light and scanning electron microscopy. For the microstructural characterization of the interaction layer, the specimens were carefully removed from the crucibles after the DSC analysis and placed in a horizontal position in the specimen-preparation models for the microstructural analysis to obtain an overview of the cross-section of the interaction layer between aluminium and tool steel. This was followed by metallographic specimen preparation. The specimens were then examined using an Olympus BX61 light microscope. Micrographs were produced and the thicknesses of the interaction layers were measured.

A detailed analysis of the interaction layers and the phases occurring in the interaction layer was performed using a Thermo Fisher Scientific Quattro S FEG SEM (ThermoFisher Scientific, Waltham, MA, USA) microscope with an Oxford Ultim® Max 65 mm² EDS SDD EDS analyzer (Ultim®Max, Oxford Instruments, Abingdon, UK). For imaging and EDS analyses the accelerating voltage was 15 kV. For secondary electron imaging (SEI) an Everhart–Thornley detector was used, while for the backscatter electron imaging an angular backscatter (ABS) detector was used.

3 RESULTS AND DISCUSSION

Figure 1 shows the DSC curves for both samples tested at 670 °C and 700 °C. The slopes of the curves are different, with the DSC curve of the specimen tested at 700 °C rising faster and the slope being larger, indicating the faster dissolution of the tool steel in the aluminium alloy and greater diffusion of the atoms of some ele-
ments through the protective layer. Based on these results, a thicker interaction layer is expected in the sample tested at 700 °C. The temperature difference of 30 °C plays an important role.

The microstructure analysis presented in Figure 2 confirmed that an interaction layer was formed at the contact between the tool steel H11 and the molten aluminium Al99.7, which was divided into two parts: a layer consisting of an intermetallic phase based on Al5Fe2 closer to the tool steel and composite layers based on the intermetallic phase Al3Fe formed closer to the aluminium alloy. As a result of the reaction between the tool steel and the liquid aluminium alloy, an Al3Fe intermetallic phase is formed, which slows down the interphase reaction because it acts as a diffusion barrier. This is reflected in a drop in the slope of the DSC curve. The thicknesses of the layers are different. The layer closer to the tool steel has an average thickness of about 420 μm for the sample tested at 670 °C and 540 μm for the sample tested at 700 °C. The reason for the change in the thickness of the interaction layer is the faster diffusion of atoms at a higher temperature. The layer closer to the aluminium alloy is much thinner, about 130 μm in both cases.

SEM and EDS analyses confirmed that the layer closer to the tool steel consists of an intermetallic phase...
based on Al$_5$Fe$_2$ (Figure 3a, site 3 and 4). This also contains a greater proportion of certain alloying elements such as cobalt, molybdenum and vanadium (Figure 4), which are present in the microstructure due to the steel. These elements form carbides, e.g., based on Mo of the $M_6C$ type, based on Cr of the $M_23C_6$ type, and based on V of the MC type. These carbides can further inhibit the formation of a reaction layer and the diffusion of elements through this layer. The silicon content in this layer increases from the aluminium alloy towards the tool steel, while the iron content increases and the aluminium content decreases (Figures 3a and 5a). This is followed by the so-called composite layer, which is formed by an intermetallic phase based on Al$_3$Fe (site 5) and is much thicker. The analysis sites 1 and 2 in Figure 3a confirm the composition of the tool steel H11.

![Figure 4: SEM (SEI) micrographs of the transitions between the intermetallic layer and the tool steel of samples tested at: a) 670 °C and b) 700 °C. The corresponding EDS results are given in at. %.

![Figure 5: EDS line-scan analyses across the interface between tool-steel H11 and Al99.7 aluminium alloy tested at: a) 670 °C and b) 700 °C.](image-url)
Sites marked 6 and 8 represent the region of primary α-Al in the presence of iron phases (Al:Fe), which dissolve in the molten aluminium. A similar phenomenon is observed in the sample tested at 700 °C (Figure 3b): tool steel (sites 1 and 2), intermetallic layer Al:Fe (sites 3-5), composite layer Al:Fe (sometimes written as Al:Fe) (site 6), and aluminium alloy in which iron dissolves in the form of the Al:Fe phase (sites 8 and 9).

4 CONCLUSIONS

Even very small temperature changes, in this case 30 °C, significantly affect the kinetics of the formation of interaction layers between the tool-steel H11 and molten aluminium Al99.7. All the test methods show a pronounced influence of the test temperature. From the DSC curve, a significantly faster dissolution can be seen, with the slope of the curve being larger for the sample tested at 700 °C, which was also confirmed by measurements of the thicknesses of the interaction layers. The thickness of the intermetallic layer is 520 μm for the sample tested at 700 °C and 420 μm for the sample tested at 670 °C. The thickness of the composite layer is about 130 μm in both cases, which is not affected by the temperature. The types of interaction layers do not differ from each other. An intermetallic layer based on the Al:Fe phase, which is thicker, always forms next to the tool steel H11, and a composite layer based on the Al:Fe phase always forms next to the aluminium alloy.

5 REFERENCES