Simulation of pulsed water cooling for continuous casting with Ls-Dyna

Stefan Scheiblhofer[1], Johannes Kronsteiner[1], Stephan Ucsnik[1], Peter Simon[2], Holm Böttcher[3]

[1] LKR Leichtmetallkompetenzzentrum Ranshofen GmbH, Ranshofen, Austria
[2] AMAG Rolling Gmbh, Ranshofen, Austria
[3] AMAG Casting Gmbh, Ranshofen, Austria

1 Introduction

Continuous Casting Processes (CCP) are used for the production of metal billets and the semi-finished material for further processing of metal sheets. The process is generically described in figure 1. Molten aluminium is poured through a casting mold into the starting head. To efficiently control the cooling of the billet water is then sprayed onto the billet. Due to the influence on the quality, stress distribution and success of CCP water cooling is a critical feature (figure 2).
In the casting process, high cooling rates are triggered by the contact of the cast material with the starting head at the beginning of the process. Consequently, only a limited amount of water is necessary to obtain the desired cooling effect. In the later stage of the casting process, the thermal mass of the already cast material is limiting the cooling effect. Therefore, additional and increased water cooling is required to obtain further cooling of the billet. Consequence of the cooling process is a first solid shell at the start of the cast what then leads to shrinkage leading to thermal stresses in the cast material. Pulsed water cooling (PWC) can help to release those stresses for the later stage of the casting process. Furthermore PWC is an efficient possibility to reduce the amount of water for the start of the process.

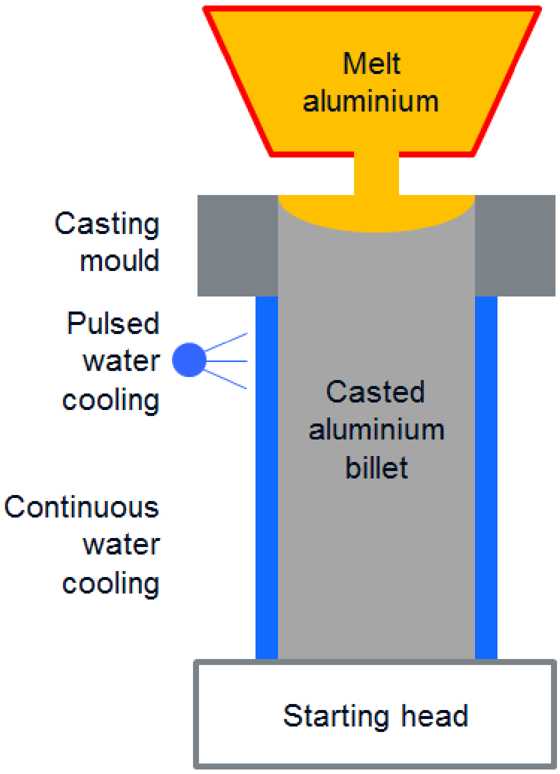


Fig.1: Description of the continuous casting process

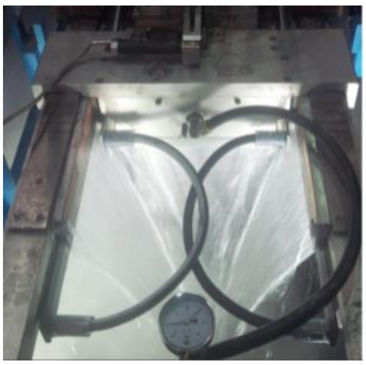


Fig.2: Water flow in a CC mould

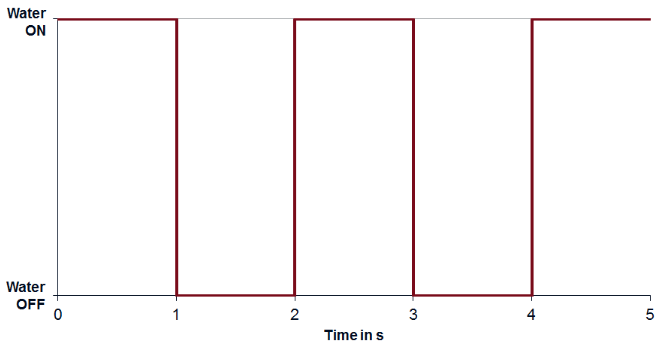


Fig.3: Square wave signal for PWC

The modelling of the Pulsed Water Cooling (PWC) is an important feature for an accurate simulation of the CCP in order to capture the thermal evolution of the billet over time. Although the modelling of such cooling schemes is originally not supported by Ls-Dyna® keywords, it is possible to consider and implement them by extending the solver through user-defined interfaces and sub-routines.

2 Modelling approach

The description of water cooling in finite element simulations is possible through the use of heat transfer coefficients (HTC) in contact definitions. These definitions can be expanded to further model PWC. For this the HTC is described via parameters like water flow rate, the pulse rate, the temperatures of both water and billet and the timeline of the casting process. These parameters are critical for the CCP and depend on time as they vary during the process. In general, PWC is characterised by a square wave signal as illustrated in figure 3.
A mathematical formulation has been developed by means of Fourier series of order N (formula 1) to implement PWC into Ls-Dyna®. A Fourier series has the big advantage of being a continuous function. Nevertheless, for a sufficient order N the Fourier series is capable of accurately approximating the square wave signal (figure 4). The further developed approximation is capable of including the dependencies on the time, the magnitude of the signal and the duty cycle, which can also vary during the casting process.

$$f(x) = \frac{4}{\pi} \cdot \left[\sum_{i=1}^{N} \frac{\sin((2i-1)x)}{2i-1} \right] \qquad (1)$$

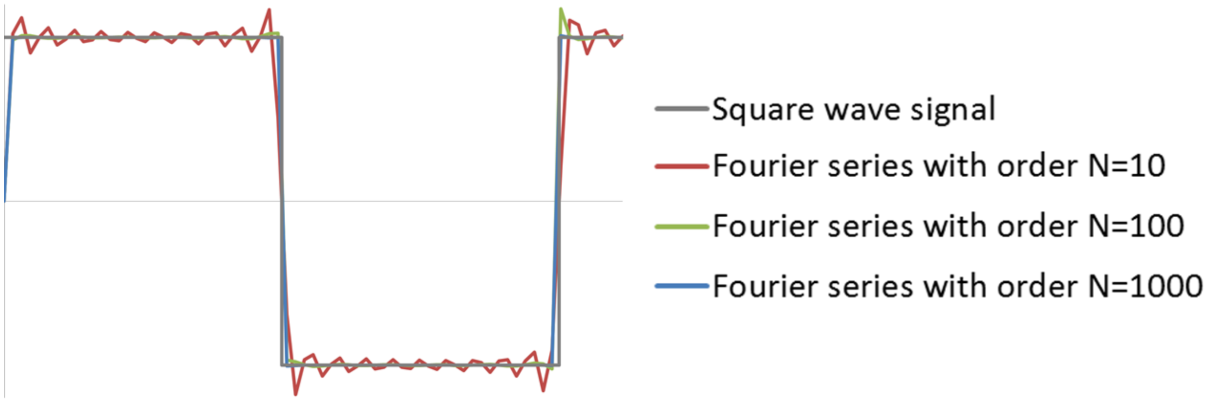


Fig.4: Comparison of a square wave signal with the corresponding fourier series with order N=10, 100 and 1000

The thermal energy exchange between a cast billet and the surrounding environment is modelled by contacts and the implementation of HTC definitions. Ls-Dyna® naturally supports the HTC definition of constant values as well as functions of temperature, pressure and time. This detailed description is already possible with the keyword ***CONTACT_..._THERMAL_FRICTION_...**.
As the most important dependencies are already implemented in the used contact-keyword, PWC can be modelled through ***DEFINE_FUNCTION** or by using a user-defined subroutine for calculating the HTC. ***DEFINE_FUNCTION** is able to include source codes in C, enabling the implementation of the derived Fourier series. It is also possible to integrate additional look-up tables to ***DEFINE_FUNCTION**. However, the more efficient way is to implement the user-defined subroutine, which is able to reduce the calculation due to the more efficient integration into the solver executable. The user-defined subroutine *usrhcon* is directly called within the keyword ***CONTACT_..._THERMAL_FRICTION_...**.

3 FE-Model and results

A simple FE-model was setup to study the functionality of the PWC module and to show the influence of PWC on the thermal . The FE-model is a basic quarter model of the CCP in steady state conditions. For this evaluation case, the geometric features of real casting billets were simplified and reduced. The simplifications resulted in a small and flat ingot, surrounded by shell elements on the outside faces which were needed for the simulation of the water cooling (figure 5). The aluminium ingot has an initial temperature of 400°C and is cooled by water with constant temperature of 20°C. To represent the characteristics of CCP the billet is moved downwards with a speed of 1 mm/s.

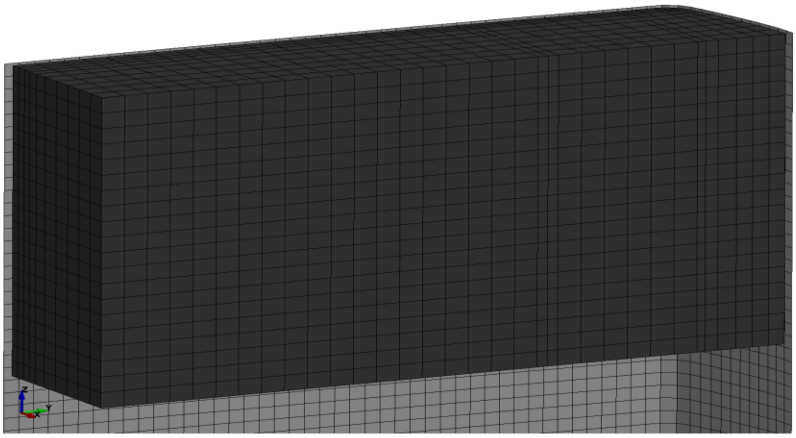


Fig.5: 1/4 -billet-model for the evaluation of PWC, with the simplified ingot (dark grey) surrounded by thermal contact shell elements (light grey)

The results displayed in figure 6 and 7 show the influence of the individual cooling methods for the Constant Water Cooling (CWC) and PWC respectively. The temperature graphs are plotted for the billet surface and for different distances from the ingot surface inside of the billet. On the ingot surface the effects of pulse water can directly be seen at the corresponding cooling curve. The PWC effect is highest at the surface and decreases with increasing distance from the surface. When the distance is more than 27 mm from the surface, almost no effect is visible anymore. Furthermore, the cooling curves show a smaller cooling rate for the PWC as the temperature after 50 seconds of casting is higher than CWC case.

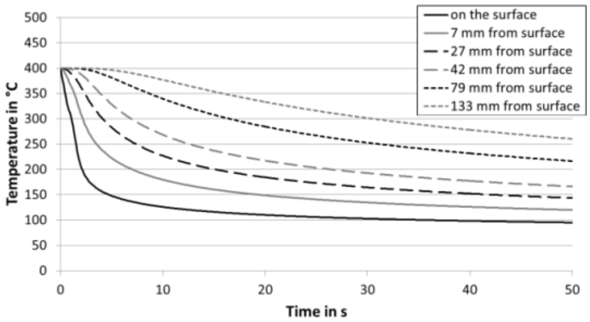


Fig.6: Cooling curves for CWC

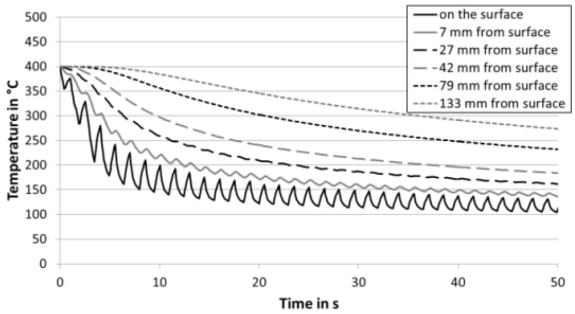
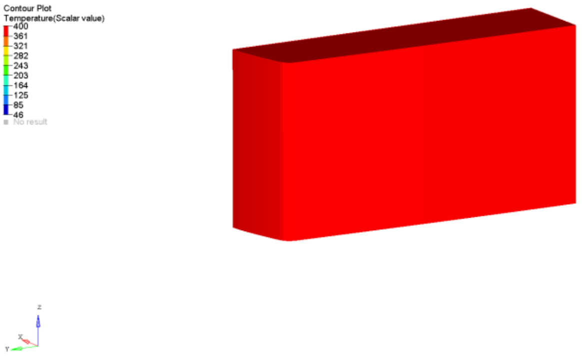
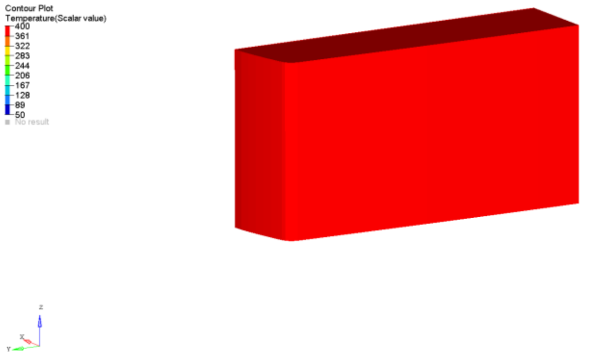


Fig.7: Cooling curves for PWC

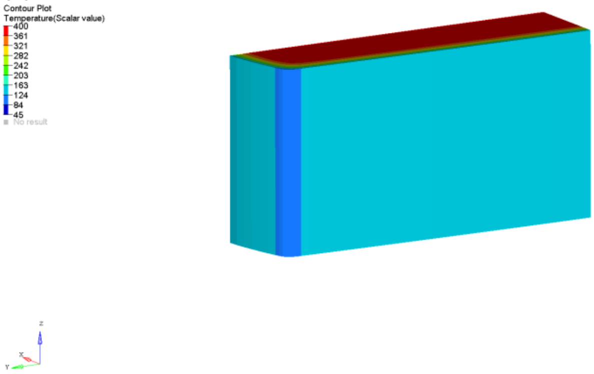
The comparison between continuous and pulsed water cooled billet can be seen in figure 8 at different stages during the simulation of the simplified billet. As it can be seen in the temperature plots (figure 7 and 8) the continuously cooled billet cools down faster. In general the edge of the billet is the coolest part of the billet, followed by the short side with the long side being the hottest surface part. For the PWC the difference between the long and short side can be seen more clearly (e.g. figure 8.d). Figures 6, 7 and 8 also indicate that with PWC the temperature gradient between the surface of the billet and a position inside the billet is smaller than with CWC due to the slower cooling.
The two different presented modelling approaches for PWC also result in slightly different calculation times, as shown in figure 9. Nevertheless the order of the fourier series has a bigger impact on the calculation (figure 10).



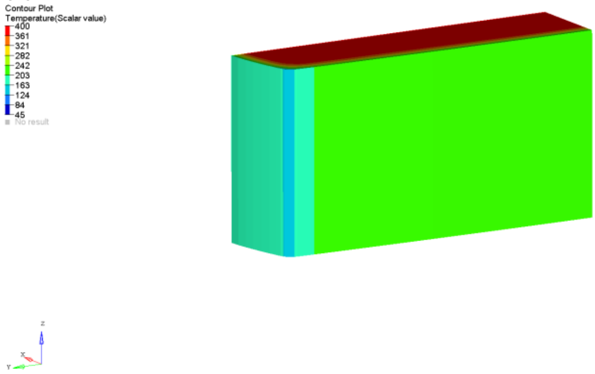
(a) billet with CWC at the start of the simulation



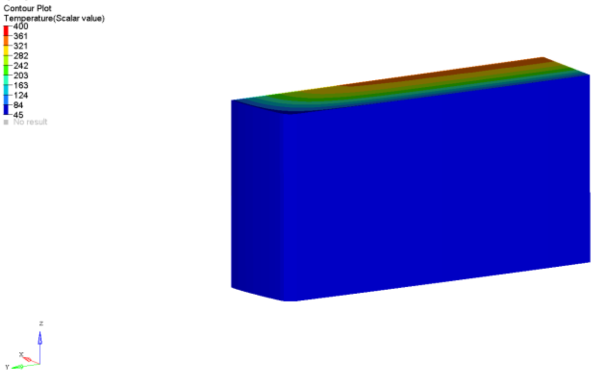
(b) billet with PWC at the start of the simulation



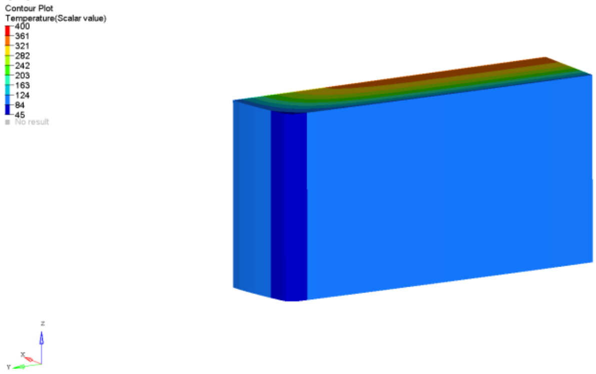
(e) billet with CWC after 10s



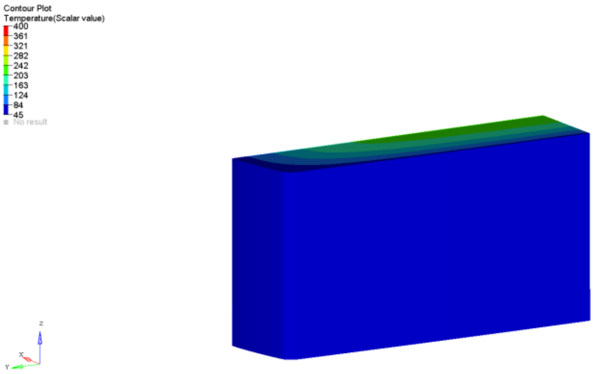
(d) billet with PWC after 10s



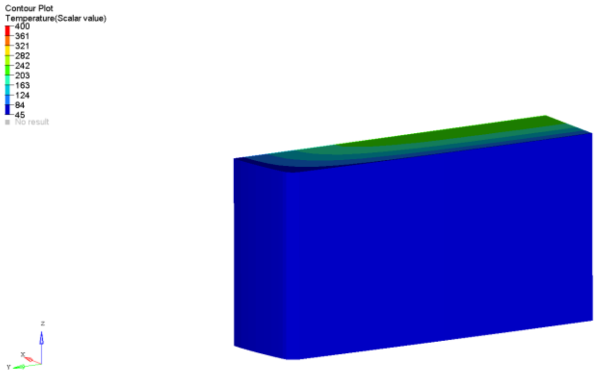
(e) billet with CWC after 90s



(f) billet with PWC after 90s



(g) billet with CWC after 200s



(h) billet with PWC after 200s

Fig.8: Pictures of the cooling simulation of the simplified billet at different stages for CWC (left column) and PWC (right column)

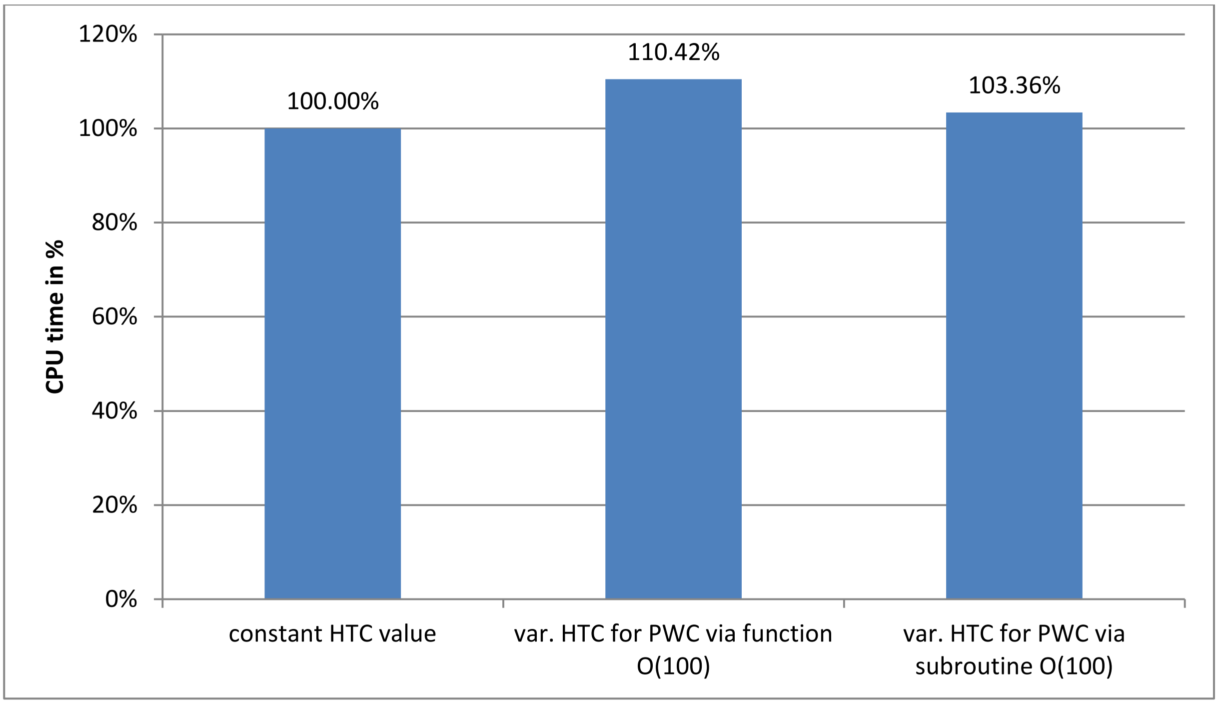


*Fig.9: Comparison of calculation time for the modelling approach with *DEFINE_FUNCTION and the user-defined subroutine respectively for a fourier-series with order N=100*

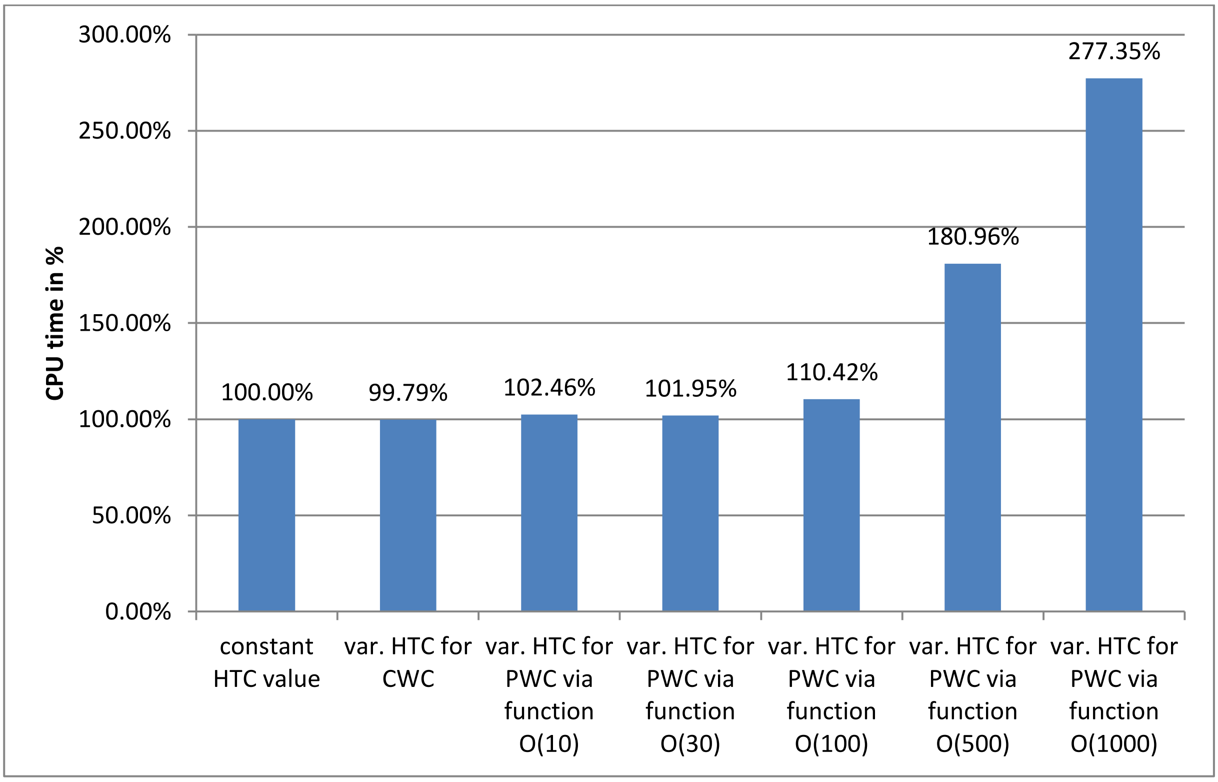


*Fig.10: Comparison of calculation time for the modelling approach with *DEFINE_FUNCTION for different orders of the fourier series*

4 Summary

This paper presents a modelling approach for pulse water cooling within Ls-Dyna®. For the implementation, the conventional square wave signal of the cooling method is approximated by a fourier series of order N, which can be addressed by Ls-Dyna® within the user-defined subroutine for the heat transfer coefficient. The results of the simulation show the impact of pulse water cooling on the cooling curve, as this is an efficient way to control the water flow and therefore the cooling rate of the process without limiting the amount of water towards the end of the process.

5 Acknowledgement

The authors would like to thank the Austrian Research Promotion Agency (FFG), the Federal Ministry for Transport, Innovation and Technology (BMVIT) and the State of Upper Austria for sponsoring this research work in the framework of COMET. This work has been supported by the European Regional Development Fund (EFRE) in the framework of the EU-program "IWB Investition in Wachstum und Beschäftigung Österreich 2014-2020", and the federal state Upper Austria.