Numerical Simulation Approach for Immersion Quenching of Aluminum and Steel Components

David Greif¹⁾ Rok Kopun²⁾ Nejc Kosir²⁾ Dongsheng Zhang³⁾

1) AVL-Advance Simulation Technologies d.o.o., Ul. Kneza Koclja 22,
2000 Maribor, Slovenia (E-mail:david.greif@avl.com)

2) AVL-AST d.o.o., Maribor Slovenia

3) AVL List GmbH, Graz, Austria

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ABSTRACT: The paper describes the simulation approach for quenching of aluminum and steel parts. The two materials require different treatment due to the release of latent heat during the cooling of steel. The boiling process within the liquid domain is treated with the CFD tool AVL FIRETM regardless of the solid material being quenched. For aluminum parts the solid is simulated using the same software, whereas for steel the latent effect requires usage of DANTE[®] running within a commercial Finite Element tool. Liquid and solid domains are online coupled in both configurations.

KEY WORDS: Materials, immersion quenching, latent heat, different quenching media and material [D3]

1. Introduction

Efficient heat treatment techniques, such as immersion quenching, are introduced in order to replace heavier metals with lower weight alloys, which results in vehicle weight reduction and consequently improved fuel economy and lower emission values. Immersion quenching cooling process, among all other heat treatment techniques, has been long identified as one of the most useful techniques to prevent component failure and provide even temperature distributions during the cooling process. An accurate prediction and optimization of the thermal treatment process is important in order to achieve low residual stress levels resulting from even temperature distribution during cooling process. In order to achieve the desirable microstructure and mechanical properties of the metal piece, solid is heated to a high temperature and then immediately submerged into a sub-cooled liquid^(1,2).

For quenching the aluminum parts in pre-heated water, the boiling phase change process, occurring between the heated part and the sub-cooled liquid phase, is handled by using the Euler-Eulerian multi-fluid modelling approach applied in CFD code AVL FIRETM. Within the fluid domain mass, momentum and energy equations are solved in the framework of the multi-fluid modelling approach, and only the energy equation is solved to predict the thermal field in the solid part of the domain. Aforementioned model, is presented by Kopun et al.^(3,4). The second case present in this paper is a steel gear, which is treated with a finite element tool in combination with DANTE Solutions[®] to account for the latent heat release, which leads to slower cooling. The coupled modeling is capable of considering the solid phase transformation kinetics, which affects the microstructure, thermal and mechanical properties. Phase transformation during quench hardening involves the latent heat release. During the coupled analyses utilizing the newly established SIMULIA bridge between AVL FIRETM and DANTE Solutions[®], the heat flux between the steel gear and the surrounding oil is calculated in the CFD model of AVL FIRETM and transferred to the solid heat treatment model (DANTE), where the gear surface temperature predicted by the heat treatment model is passed back to the transient AVL FIRETM simulation. The relations between carbon content, temperature field, phase transformation, internal stress,

and shape change during quenching are explained from the heat treatment modelling results, which include the entire history of the part response during the hardening process including heating and quenching are described by Li et al.⁽⁵⁾. The temperature gradients predicted by the presented model reproduce the latent heat release during the phase transformation. It is clear that neglecting the additional heat source would result in very different thermal gradients and consequently very different thermal stresses and surface properties of the treated component. It turns out that aforementioned approach is considered as unique, taking into account much more than just the sole cooling history.

Simulation results of a simplified cylinder head structure and steel gear component in a real-time quenching process are compared and discussed. The temperature gradients predicted by the presented model correlate very well with the available measurement data and represent a reliable spatially resolved temperature input for the subsequent Finite Element Analysis (FEA) of thermal stresses.

2. Mathematical Model

2.1. Governing equations

Eulerian multi-fluid model considers each phase as interpenetrating continua coexisting in the flow domain, with inter-phase transfer terms accounting for phase interactions where conservation laws apply. The averaged continuity and momentum equations are presented by Kopun et al.^(3,4).

2.1.1. Continuity

$$\frac{\partial \alpha_k \rho_k}{\partial t} + \nabla \cdot (\alpha_k \rho_k \mathbf{v}_k) = \sum_{l=1, l \neq k}^N \Gamma_{kl} \quad (1)$$

where α , ρ and $\mathbf{v}$ stand for volume fraction, density and velocity. The phase change rate (in this particular case boiling) is Γ_k and the subscript k is a phase indicator ($k = l$ or $k = v$), with a range

of $k = 1, \dots, N$. The sum of volume fractions over all phases equals 1.

2.1.2. Momentum

$$\frac{\partial \alpha_k \rho_k \mathbf{v}_k}{\partial t} + \nabla \cdot (\alpha_k \rho_k \mathbf{v}_k \mathbf{v}_k) = -\alpha_k \nabla p + \nabla \cdot \alpha_k \boldsymbol{\tau}_k + \alpha_k \rho_k \mathbf{g} + \mathbf{M}_k + \mathbf{v}_{\text{int}} \Gamma_k \quad (2)$$

where p , $\boldsymbol{\tau}$ and $\mathbf{v}_{\text{int}}$ are pressure, stress and interfacial velocity, respectively

2.1.3. Energy

With the assumption that the heat transfer rate between vapor and liquid phase is relatively rapid, the vapor and liquid phase are in thermal equilibrium. In this case, the mixture enthalpy equation is given as

$$\frac{\partial \rho_m h}{\partial t} + \nabla \cdot (\rho_m \mathbf{v} \cdot h) = \nabla \cdot \mathbf{q} + \rho_m \mathbf{q}''' + \rho_m \mathbf{g} \cdot \mathbf{v} + \nabla \cdot \boldsymbol{\tau} \cdot \mathbf{v} + \alpha_m \frac{\partial p}{\partial t} + \sum_{l=1, l \neq k, l \neq N}^N H_{kl} + h \sum_{l=1, l \neq k, l \neq N}^N \Gamma_{kl} \quad (3)$$

where enthalpy volumetric flow is denoted as $\mathbf{q}'''$, interfacial energy exchange between phases k and l is denoted as H_{kl} . Dynamic viscosity and thermal conductivity are presented as μ and κ , respectively. Heat flux $\mathbf{q}$ is given as

$$\mathbf{q} = -\frac{\kappa_m}{C_{p,m}} \nabla h \quad (4)$$

2.1.4. Boiling model

Based on the assumption that the heat transfer rate is proportional to the phase change rate, the mass transfer predominantly controls the heat transfer and the phase change rate due to the boiling process can be written as:

$$\Gamma_c = \frac{C_m \cdot C_b \cdot \tilde{h}_b \cdot A_{\text{int}} \cdot \Delta T'}{H_{fg}} \quad (5)$$

where C_m , C_b , $\tilde{h}_b$, A_{int} , $\Delta T'$ and H_{fg} are the closure coefficient, the boiling correction coefficient, the boiling heat transfer coefficient, interfacial area density, wall superheated temperature and the latent heat of vaporization, respectively.

2.1.5. Film boiling

The Bromley's model, originally applied for a horizontal tube, is employed to predict the film boiling heat transfer coefficient $\tilde{h}_{FB}$

$$h_{FB} = 0.62 \left[\frac{k_v^3 \rho_v (\rho_l - \rho_v) g (H_{fg} + 0.4 C_{pv} \Delta T'')}{D_0 \mu_v \Delta T''} \right]^{1/4} \quad (6)$$

where H_{fg} is the latent heat of evaporation, D_0 is the length scale (vapor bubble diameter), k_v is the vapor thermal conductivity and C_v stands for the specific heat of vapor.

2.1.6. Transition boiling

The heat transfer coefficient, $\tilde{h}_{TB}$, for transition boiling stage is given by

$$h_{TB} = \frac{Q_{TB}}{T'_w - T'_{\text{sat}}} \quad (7)$$

where the heat flux in the transition boiling regime Q_{TB} is computed as follows

$$Q_{TB} = Q_{CHF} \cdot \phi + Q_{MHF} \cdot (1.0 - \phi) \quad (8)$$

Variable Leidenfrost temperature has been modeled according to Kopun et al. ⁽⁴⁾. Detailed information about the applied quenching model can be obtained from the AVL FIRETM theory guide and from the references ^(3, 4).

3. Simulation Setup

3.1. Water Quenching – Simplified Cylinder Head

The simplified aluminum cylinder head structure was used in order to investigate the heat treatment characteristic during the water quenching. A computational domain with applied boundary conditions is depicted in Fig. 1. The test piece utilizes the temperature measurements at nine different monitoring locations. The computational domain applied in the CFD simulation and also the physical model with detailed positions of monitoring points are described by Kopun et al. ⁽⁴⁾.

Fig. 1 Computational domain – simplified cylinder head ⁽⁴⁾.

3.2. Oil Quenching - Gear

The simulation of oil quench hardening process was performed using two different computational codes, namely AVL FIRETM and DANTE solutions[®], the later running within the ABAQUS environment. The volume element mesh which was applied to simulate the physical phenomena in the fluid domain was coupled with the finite element mesh, which was used for the heat treatment analysis. Fig. 2 shows the computational grid used in the coupled simulation. The description of the geometry and the computational model are discussed in detail by Li et al. ⁽⁵⁾. Further details about the treatment of material phase transformation through the latent heat effect are available in the same reference ⁽⁵⁾.

Fig. 2 Computational model – gear ⁽⁵⁾.

4. Results and Discussion

4.1. Water quenching

The comparison between measured data and the results obtained by simulation was performed for different monitoring points. Temperature measurements are described by Kopun et al.⁽⁴⁾ and were performed at nine different locations along the test piece (Fig. 3). Temperature measurements were described by Kopun et al.⁽⁴⁾ and were performed at nine different locations along the test piece (Fig. 3).

Fig. 3 Detailed positions of the monitoring points ⁽⁴⁾.

Figures 4 and 5 show the comparison (measured vs. computed temperature) at two different monitoring points. Fig. 4 shows the comparison of cooling curves at the first location (T1). Transition between different boiling regimes is well predicted by simulation and also the whole cooling curve is in excellent agreement with the measurement data.

Results predicted by simulation at the second measurement location (Ts) are shown in Fig. 5. Although the simulated cooling curve does not entirely fit the measured profile, the transition between the boiling regimes is still well predicted. It can be clearly seen that the model is able to predict the temperatures at different locations along the test piece with good accuracy when comparing to experimental data.

Fig. 4 Comparison of measured and numerically predicted solid temperature at monitoring point T1 ⁽⁴⁾.

Fig. 5 Comparison of measured and numerically predicted solid temperature at monitoring point T5 ⁽⁴⁾.

Detailed analysis of 3D results can be performed, as the results exist for the entire liquid and solid domains for the entire cooling period. Typically special attention is given to the eventual stress distribution in the solid as well as to the deformations at different times. In order to investigate transition of boiling regimes during the quenching process the liquid volume fraction distribution was plotted on the planar cut through the fluid domain at different time instants (Fig. 6).

It can be seen that after 1 second the quenched part is not completely submerged into water. Soon after the whole part is completely submerged, rapid boiling appears, which can be also observed from monitoring points. It can be clearly seen that after 10 seconds some regions are still in no contact with liquid water. The vapor pocket generation hinders the liquid water flow within the quenched part. After 50 seconds the uniform temperature distribution has been reached.

Fig. 6 Liquid volume fraction distribution at different time steps (4).

Development of temperature field and deformations within the solid part (predicted by FEA using CFD results as input) during the immersion quenching are presented in Fig. 7.

Fig. 7 Temperature and deformation distribution at different times steps (4).

The principal mechanism of deformation development is contraction at the bottom which is immersed first, accompanied by a mostly tensile stress state at warm conditions and ductile response of the material. It has been found that after 20 seconds, tensile reaction begins to turn, because the initially cooled material has to follow the contraction of the still warmer side.

Details about transferring the CFD result to FEA as accurate, time and space resolved input are described by Kopun et al. (4).

Exactly the same methodology can be applied for components of high complexity such as cylinder heads and engine blocks as described by Jan et al. (6) and Mulayim Kaynar et al. (7). The most favorable quenching orientation can be determined, the best water temperature can be chosen, and the agitation effects within the quenchant pool can be investigated. One can look into the clustering effects as well. The above aspects allow for optimization of the thermal treatment process of thermally treated cast (or otherwise produced) components.

4.2. Oil quenching

Thermal properties during quenching are affected by local temperatures, as well as material phase transformations because different phases (e.g. austenite, martensite) have different thermal properties.

Fig. 8 shows the volumetric fraction of oil at three time instants where strong boiling process is notable at all times.

Fig. 8 Oil phase volume fractions distributions at different time steps: (a) 1.0 s, (b) 5.0 s, (c) 15 s (5).

The temperature distribution of the solid gear during quenching is shown in Fig. 9 for the same time instants as above. The initial gear temperature prior to quenching is 915 °C.

Fig. 9 Temperature distributions at different time steps (5).

Additionally the latent heat released due to phase transformation within the gear plays an important role when plotting the cooling history. Phase transformation involves latent heat due to the enthalpy difference between parent and product phases. For example, heat generation occurs when austenite decomposes to other phases during cooling, leading to temperature change.

The effect of latent heat is shown in Fig. 10. Brown and blue curves show the cases without latent heat consideration at two different monitoring points (surface and core). When considering the latent heat release, the bump in the time-temperature profile after 15-20 s is clearly visible. At both monitoring points slower cooling is detected (yellow and gray profile).

Fig. 10 Temperature profiles at monitoring points ⁽⁵⁾.

Prior to quench hardening, the gear tooth is gas carburized and then reheated to 915°C. The heating process is modeled by applying a uniform heat transfer coefficient on the gear surface with the constant furnace temperature. At the end of heating process the uniform distribution of temperature is reached with full austenite structure. Fig. 11 depicts the temperature (left), austenite volume fraction (middle) and radial displacement (right) at the end of the heating process (after 3600s) ⁽⁵⁾.

Fig. 11 Temperature, austenite and radial displacement at the end of heating ⁽⁵⁾.

Finite Element Analysis of stresses and deformations was performed through online coupling of AVL FIRE™ and the model in ABAQUS / DANTE®.

Fig. 12 depicts the temperature distribution on the gear surface at the end of the quenching process. Additionally, volume fraction of martensite and the residual stress level in the circumferential direction are also presented.

Fig. 12 Temperature, martensite, and circumferential stress at the end of quenching ⁽⁵⁾.

5. Conclusion

The applied CFD code AVL FIRE™ is capable of accurately predicting real-time quenching effects, local temperature gradients and the overall cooling history of complex quenched components. The method features a single-shot approach avoiding time consuming iterative steps.

Capturing the effects during different boiling regimes is the key. The influence of film and transition boiling can be captured, where the variable Leidenfrost temperature approximation has a significant impact. It has been found that the water sub-cooling temperature affects the cooling history. Higher rate of cooling improves the eventual surface properties, but also results in higher residual stresses after the quenching process. In all presented cases, very good agreement between the numerical and measured data has been achieved.

The code is capable of predicting quenching of aluminum in water and/or steel components in oil. When steel components are quenched, the solid needs to be handled with a Finite Element Analysis tool in combination with DANTE®, which can predict the latent heat effect during the phase transformation in steel during the cooling process as heat generation occurs when austenite decomposes to other phases during cooling.

It can be concluded that the introduction of the Multi-Material model, which enables exchange of simulation data during the iterative solution process, leads to a further improvement of computational capability. This, together with the variable Leidenfrost temperature, provides a solid basis for future research in the field of real-time cylinder head immersion quenching application.

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