NUMERICAL MODELLING AND VALIDATION OF A COUPLED INDUCTION HEATING AND FORGING PROCESS FOR THE PRODUCTION OF JOINT CROSSES

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Abstract

Hot forging of complex geometrical components such as joint crosses is highly sensitive to process parameter variations, leading to geometric deviations and increased scrap rates under industrial conditions. A reliable modelling of the forming process, taking varying process parameters into account, is therefore essential for improving process stability and enabling model-based quality assurance. This study presents a comprehensive numerical investigation of a hot forging process of joint crosses made of 1.7225 steel. A numerical model is built using the finite element (FE) software Simufact.Forming 25, consisting of inhomogeneous induction heating, billet transfer and single-stage forging. The predicted temperature field obtained from induction heating is validated by experimental temperature measurements at discrete thermocouple positions, showing deviations of less than 4%. The billet, along with its temperature distribution is subsequently transferred to a thermo-mechanically coupled forming simulation. A reduced 90° symmetry approach is employed to ensure computational efficiency while accurately capturing material flow, contact interactions and geometric feature formation under industrially relevant forging conditions. The numerical results are validated by comparing simulated and experimental force–displacement curves, showing accurate prediction of the maximum forming force with a deviation of <1% and good agreement in the overall curve shape. The validated model provides a robust foundation for future process optimisation and systematic sensitivity-based parameter identification.

Keywords: Finite element method, induction heating, hot forging, joint cross forging

1. INTRODUCTION

Hot bulk metal forming processes as well as the resulting quality and dimensional accuracy of forged parts are influenced by various parameters such as die wear, process conditions, and variability in material properties [1]. To improve process stability and reduce resource consumption, a deeper understanding of the dependencies between process parameters and the resulting component geometry is required. In this context, finite element (FE) simulations have become an established tool for analysing and designing hot forging processes, enabling the prediction of material flow, temperature evolution and forming forces [2]. However, their reliability depends on accurately representing the process conditions that are difficult to measure during forming. Moreover, changes in process conditions require repeated model adjustments and recalculations, which are computationally expensive. The numerical model developed in this study therefore provides a foundation for future investigations on process sensitivity and to generate data for surrogate models supporting inline process monitoring and quality assurance in hot forging.

Despite the extensive use of numerical simulations in hot forging research, several aspects of process modelling remain insufficiently investigated. In particular, thermal phenomena such as billet preheating, inter-stage annealing or cooling, and the post-forming thermal behaviour of forged components are often simplified or neglected. This is primarily due to the difficulty of obtaining accurate thermal data under industrial conditions [2]. Therefore, the reliability of numerical simulations strongly depends on the accurate representation of the thermal state of the billet prior to forming. Induction heating, a widely used method in hot forging, offers advantages such as contactless energy transfer, short heating times, and controlled temperature distribution [3]. However, due to the characteristics of the process, temperature gradients may develop within the billet, leading to inhomogeneous temperature fields prior to forming [4]. Additionally, heat losses during the transfer of the billet from the heating system to the forging press further influence the temperature field and consequently affect the forming behaviour and final component geometry. Therefore, a comprehensive consideration of the entire process chain is required to accurately capture the thermal state prior to forming.

2. METHODOLOGY

In this study, the investigated process chain consists of induction heating, billet transfer and subsequent closed-die forging of a cylindrical billet made of 1.7225 (42CrMo4) steel, as illustrated in **Figure 1**. These steps are considered to capture realistic temperature distributions and their influence on the forming process. The process is analysed using both experimental and numerical approaches.

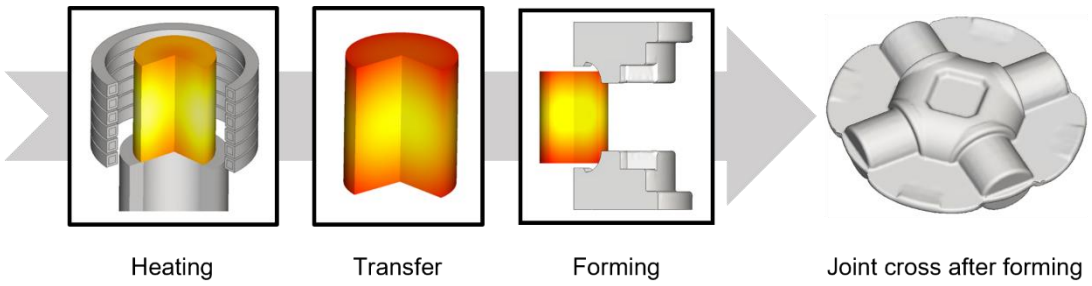

Figure 1 Process chain consisting of induction heating, billet transfer and single-stage closed-die forging

2.1 Experimental investigation of induction heating and forging

The billet with a height of 40 mm and a diameter of 30 mm was positioned inside a water-cooled induction coil, as shown in the experimental setup in **Figure 2 (a)**. The billets were heated to a target temperature of 1,250 °C prior to forging. The temperature was measured using two type-K thermocouples (TCs) with a diameter of 1.5 mm inserted in the billet, as illustrated in **Figure 2 (b)**. Due to the thermal inertia of the thermocouples, the measured temperatures exhibit a delayed response during rapid heating and cooling, which was corrected using an inverse first-order response model by a time constant τ, as shown in equation (1) [5, 6].

$$T_{Real}(t+\Delta t) = T_{TC}(t) + \frac{T_{TC}(t+\Delta t) - T_{TC}(t)}{1-e^{-\Delta t/\tau}} \quad (1)$$

Where $T_{TC}(t)$ and $T_{TC}(t+\Delta t)$ represent the measured thermocouple temperatures at the current and subsequent time steps, respectively. $T_{Real}(t+\Delta t)$ denotes the estimated true material temperature after correcting for the thermocouple response delay. The parameter τ is the thermocouple time constant, and Δt is the time interval between measurements. In addition, the current in the induction coil during the heating process was measured using a Rogowski coil (FLUKE i3000s FLEX), which was placed around one supply cable of the induction coil. The applied current intensity profile during the heating process is shown in **Figure 2 (c),** with an initial base current of approximately 46 A. The process was conducted at an operating

frequency of 15 kHz with a heating duration of 34 s. A stepwise current profile was applied to control the heating rate and to ensure a controlled temperature distribution within the billet.

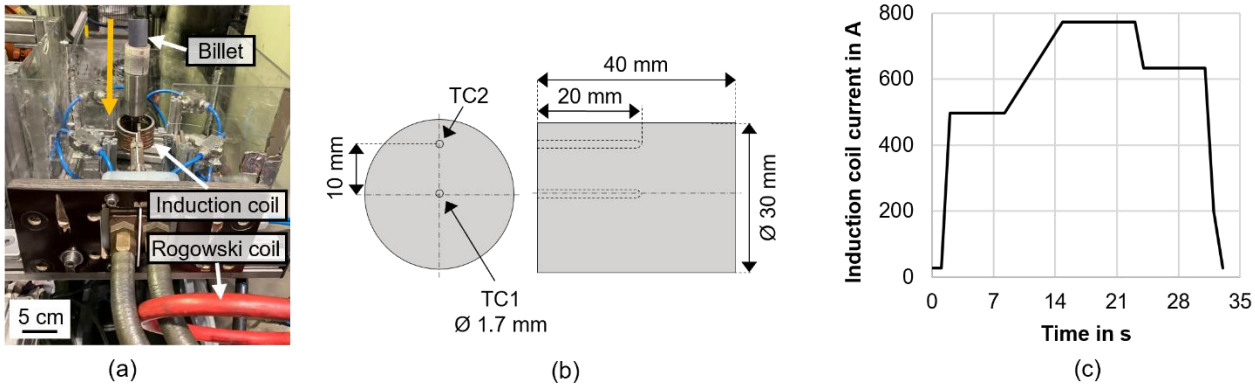

Figure 2 (a) Experimental setup of induction heating, with billet movement indicated by the yellow arrow, (b) TC positions in the billet, and (c) measured current in the induction coil using a Rogowski coil

Following the heating stage, the billets were manually transferred to the forging press (Spindle press – Weingarten Type PSR 160) using a forging tong, with an estimated transfer time of approximately 5 s and then formed into the joint cross geometry. The forging dies were preheated to 250 °C, representing industrial forging conditions and lubricated using a graphite-based lubricant (Fuchs CON TRAER G 300 spray). The forming operation was carried out using a single-stage closed die forging process. The forming force and the displacement were measured and used for validation of the numerical model. The displacement was recorded using a draw wire sensor as the relative displacement between the upper moving and lower stationary die.

2.2 Numerical modelling of induction heating, billet transfer, and closed die forging

A 2D axisymmetric model of the induction heating process was developed based on the experimental setup using Simufact.Forming 25. The model includes the billet, the induction coil, and the surrounding air domain in order to account for the electromagnetic and thermal interactions occurring during the heating process, as shown in **Figure 3 (a)**, with further model details given in [4].

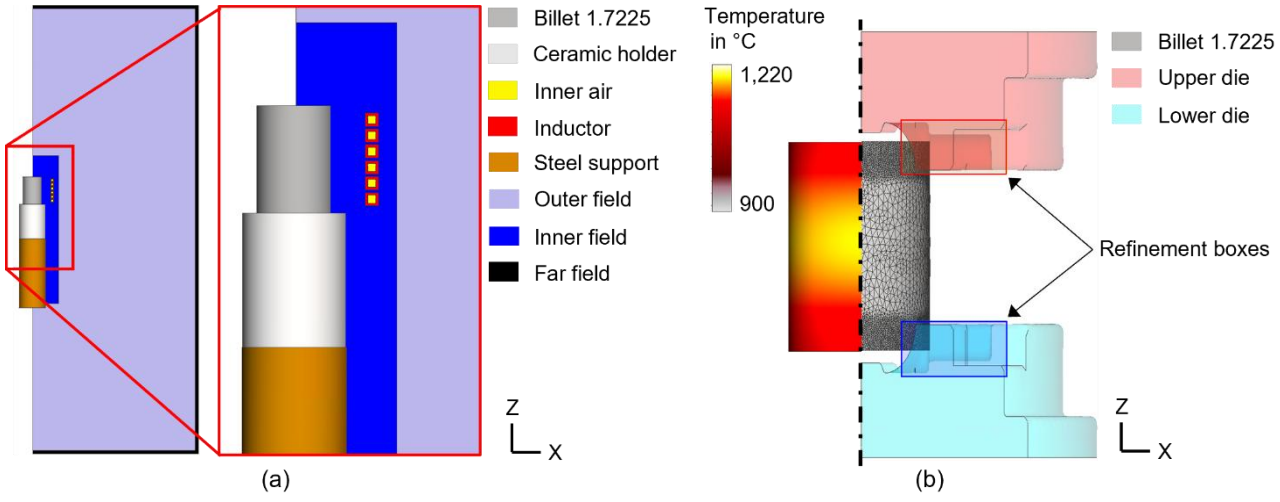

Figure 3 Simulation model of (a) induction heating [4], and (b) closed-die forging

The billet material was defined as 1.7225 steel, with thermal and electromagnetic properties taken from the Simufact database. The induction coil was modelled by representing each winding as an inductance object, to which the experimentally measured time-current curve (**Figure 2(c)**), operating frequency of 15 kHz and the coil geometry were assigned. The water cooling of the induction coil was not explicitly modelled. The internal channels were represented as air domains to facilitate meshing, in accordance with the Simufact manual. The initial billet temperature was set to 29 °C in accordance with the experimental conditions, while heat transfer to the surrounding air was defined as temperature dependent, with the corresponding values taken from [7]. Additionally, the ceramic holder was included as a heat conducting body with material properties taken from Salmang *et al.* [8]. Following the induction heating simulation, the billet transfer to the forging press was modelled in a separate thermal simulation. The temperature field obtained from the heating simulation was transferred as the initial condition, and the cooling behaviour during the 5 s transfer time was simulated considering heat losses due to natural convection and radiation. The resulting 2D axisymmetric billet, including its temperature field, was revolved in to a 3D 90° sector geometry. This was used as the initial condition of the forging process, thereby ensuring a realistic thermal state during forging.

Based on the experimental setup, a FE model of the closed-die forging process was built. The contact conditions between the billet and the dies were set to a combined friction model with a friction coefficient of 0.15 and a friction factor of 0.35, representing conditions close to graphite lubrication [9]. In the numerical model, the dies were modelled as rigid bodies and a 90° symmetry condition was applied to reduce computational effort while preserving the geometric accuracy of the component, as shown in **Figure 3(b)**. The press kinematics were defined based on the experimentally measured slide displacement, which was adapted as a displacement-controlled boundary condition to accurately reproduce the forming process. In addition, a mesh sensitivity study was conducted to ensure that the selected mesh size provided accurate results without unnecessary computational cost. The numerical results, including the forming force, were compared with the experimental data to validate the simulation model.

3. RESULTS

The numerical models of the induction heating and forging processes were validated by comparison with experimental temperature measurements and force-displacement data, respectively. **Figure 4 (a)** shows the simulated and measured temperature evolution at the thermocouple positions TC1 and TC2 during the induction heating and billet transfer stages.

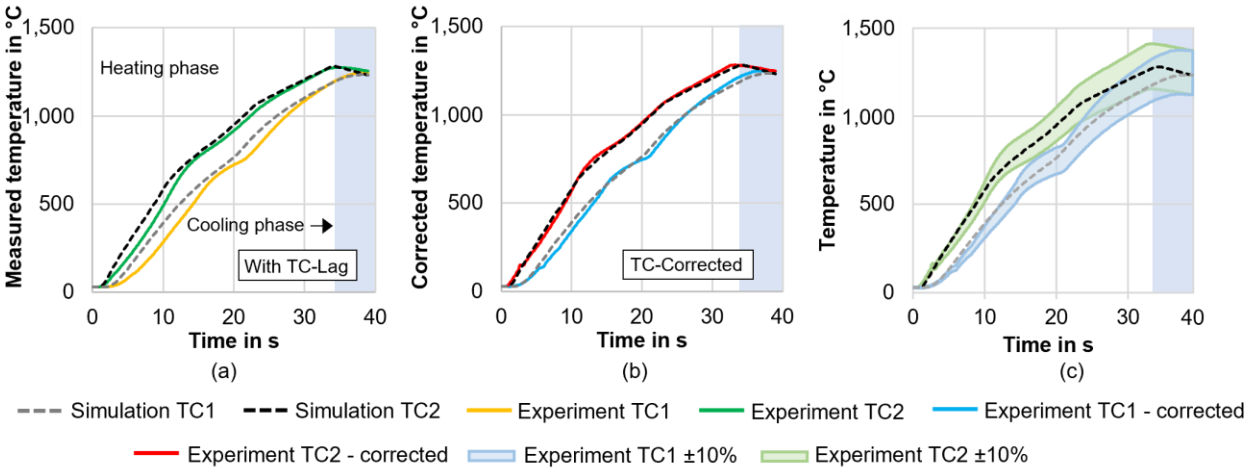

Figure 4 Comparison of simulated and experimental temperature–time curves during induction heating and billet transfer (grey region): (a) without TC-lag correction, (b) with TC-lag correction and (c) comparison with a ±10% experimental variation band

The measured temperature curves exhibit a delayed response compared to the simulation, particularly during the initial heating phase due to thermal inertia of the thermocouples. As shown in **Figure 4 (b)**, the experimental temperatures were corrected for the thermocouple response lag (TC-Lag) using the inverse first-order response model by a time constant of 1.2 s, as defined in equation (1). The corrected temperature curves show a significantly improved agreement with the simulation, and are subsequently used for the quantitative validation of the heating model. A quantitative evaluation using the mean absolute percentage error (MAPE) results in values of approximately 4% for TC1 and 3% for TC2, confirming the high accuracy of the numerical model. Furthermore, the simulation captures both the heating rate and the temperature gradients within the billet, indicating that the electromagnetic-thermal simulation approach provides a reliable representation of the induction heating process. To assess the agreement between simulation and experiment, a ±10% variation band was derived from the experimental temperature measurements, to represent the observed measurement uncertainty and process variability. The simulated temperature evolution was compared with this range, as shown in **Figure 4 (c)**. The simulation curve lies within the experimental variation band during both the heating and transfer stages, demonstrating that the numerical model accurately reproduces the experimental behaviour within the observed variability.

A mesh sensitivity study was performed prior to the forming simulations to determine an appropriate mesh resolution. The influence of mesh size on the predicted forming force, volume loss and computational time was evaluated, as illustrated in **Figure 5 (a).** With decreasing global element size, both the forming force and volume loss decrease and converge due to improved contact representation and reduced numerical artefacts. In contrast, the computational time increases significantly due to the higher number of elements, with all simulations carried out using a single CPU core. Since further mesh refinement had only a minor influence on the results, a global mesh size of 1.3 mm was selected for the mesh sensitivity study. In critical regions, a local refinement with an absolute element size of 0.4 mm was applied, which are indicated in **Figure 3 (b)**. This ensured a reliable compromise between computational efficiency and solution accuracy.

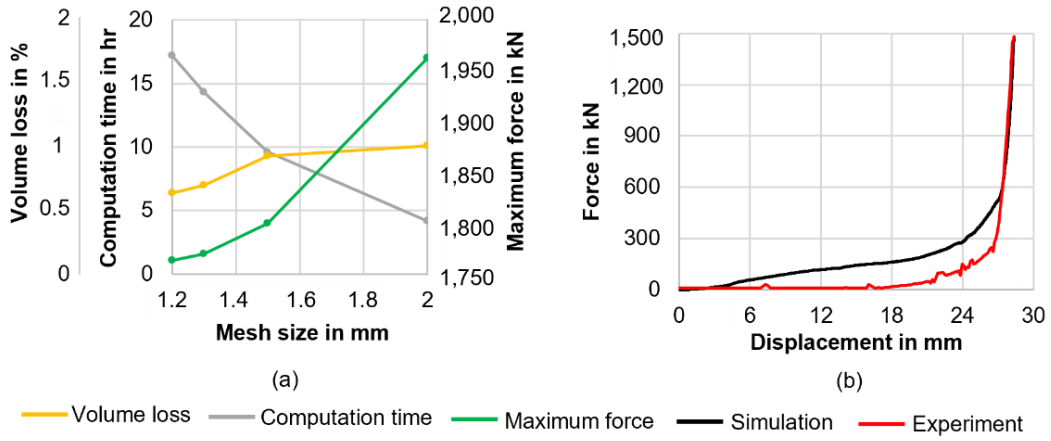

Figure 5 (a) Mesh sensitivity study and (b) comparison of simulated and experimental force-displacement curves

The forging simulation was validated by comparing the simulated and experimentally measured force-displacement behaviour. As shown in **Figure 5 (b)**, the force–displacement curve predicted by the forging simulation shows good agreement with the experimental one throughout the forming stroke. The maximum forming force is predicted with a deviation of less than 1%, although the steep force increase near the end of the stroke is highly sensitive to small displacement variations and the press-based force data may introduce additional uncertainty. However, an overestimation of the experimental force-displacement curve is observed, particularly in the intermediate stage. This deviation can be mainly attributed to the elastic deformation of the forging tools in the experiment, which is neglected in the numerical model. Here, the tools are assumed to be

rigid bodies in order to reduce computational effort and model complexity. Overall, the simulation accurately reproduces the force evolution, confirming the capability of the thermo-mechanically coupled FE model to describe the forging process.

4. CONCLUSION AND OUTLOOK

In this study, the hot forging process of a joint cross made of 1.7225 steel was investigated using an experimental and numerical approach. A thermo-mechanically coupled FE model was set up to simulate the process chain consisting of induction heating, billet transfer, and closed die forging. The heating simulation was validated using experimentally measured temperatures at two thermocouple positions. To account for the delayed response of the thermocouples during rapid heating, the experimental temperature signals were corrected using an inverse first-order response model. The induction heating simulation was validated with low MAPEs between 3% and 4% and the simulated temperatures remaining within a ±10% experimental variation band, confirming the high accuracy and the reliability of the developed heating model. The forging simulation was verified by comparing the simulated and experimentally measured force-displacement curves. The forging simulation accurately reproduced the force-displacement behaviour, with the maximum forming force predicted with a deviation of less than 1%, while minor discrepancies are attributed to the rigid tool assumption. Overall, the developed numerical model provides a reliable representation of the investigated forging process and can serve as a basis for parameter studies and data generation. These enable the development of surrogate models and thereby form the foundation for inline process monitoring and quality assurance in industrial hot forging.

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