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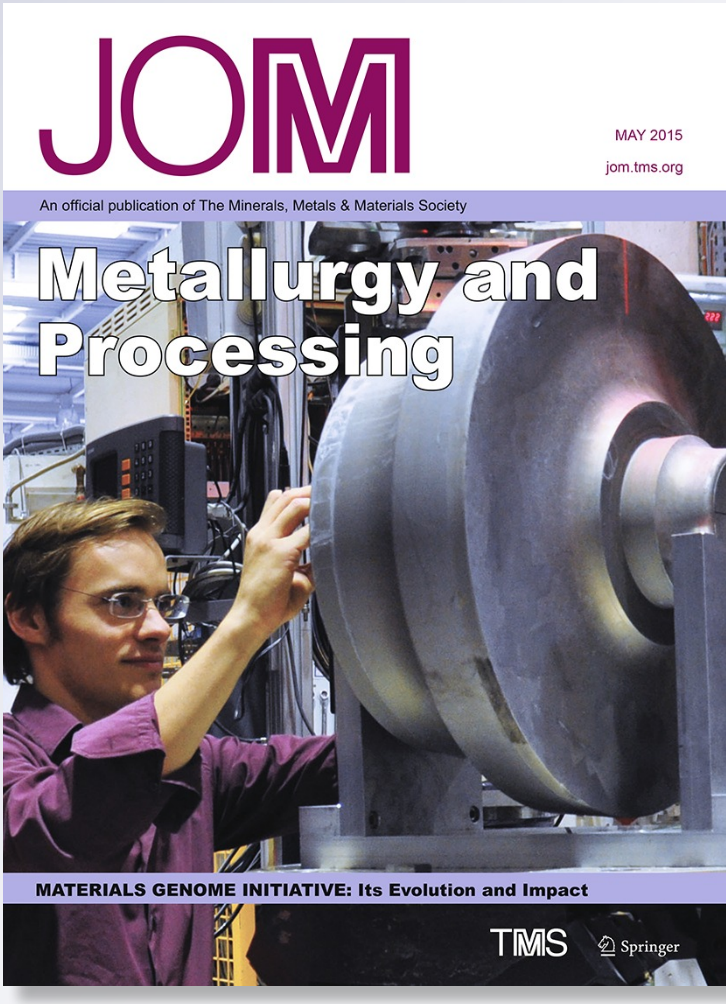

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Quench-Induced Stresses in AA2618 Forgings for Impellers: A Multiphysics and Multiscale Problem

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In the fabrication of heat-treatable aluminum parts such as AA2618 compressor impellers for turbochargers, solutionizing and quenching are key steps to obtain the required mechanical characteristics. Fast quenching is necessary to avoid coarse precipitation as it reduces the mechanical properties obtained after heat treatment. However, fast quenching induces residual stresses that can cause unacceptable distortions during machining. Furthermore, the remaining residual stresses after final machining can lead to unfavorable stresses in service. Predicting and controlling internal stresses during the whole processing from heat treatment to final machining is therefore of particular interest to prevent negative impacts of residual stresses. This problem is multiphysics because processes such as heat transfer during quenching, precipitation phenomena, thermally induced deformations, and stress generation are interacting and need to be taken into account. The problem is also multiscale as precipitates of nanosize form during quenching at locations where the cooling rate is too low. This precipitation affects the local yield strength of the material and thus impacts the level of macroscale residual stresses. A thermomechanical model accounting for precipitation in a simple but realistic way is presented. Instead of modelling precipitation that occurs during quenching, the model parameters are identified using a limited number of tensile tests achieved after representative interrupted cooling paths in a Gleeble machine. The simulation results are compared with as-quenched residual stresses in a forging measured by neutron diffraction.

INTRODUCTION

In the processing route of heat-treatable aluminum alloys (AAs), a determining step to obtain the final properties is quenching from the solution heat-treatment (SHT) temperature. From a metallurgical point of view, the ideal quench must be fast enough to avoid the formation of precipitates during quenching, i.e., to obtain a supersaturated solid solution. However, fast quenching cannot be achieved in the center of large components, where the quenching rate can be more than one order of magnitude lower than at the surface. This results in the following:

- Possible coarse precipitation, which is detrimental to the final yield strength because it decreases the hardening potential by pumping solute elements during quenching
- Usually unwanted residual stresses (RS) that depend on the magnitude of the cooling rate, as well as on the component size and shape.

ABB Turbo Systems Ltd produces turbochargers for large combustion engines with power outputs of 400 kW and above. Their main purpose is to increase the specific power output of engines while reducing their fuel consumption. The Al-Cu-Mg-based AA2618 alloy is used for the compressor impellers owing to its high creep resistance.[1] The impeller is machined out of a forging, which undergoes a heat treatment involving solutionizing, quenching, and artificial aging steps. To reduce internal stresses, quenching is performed in boiling

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water rather than in cold water. To assure sufficient high cooling rates during quenching, the effective cross section must not exceed a certain size. For this reason, the forgings for large impellers are premachined before heat treatment, whereas those for small impellers are usually machined directly from the forging after its heat treatment (Fig. 1). The differences in the size of the heat-treated part, the order of the manufacturing steps, and the amount of material removed by machining determine in the end the resulting material properties and the remaining RS in the final geometry. The control of internal stresses in large impellers is therefore a key issue to optimize its heat-treatment geometry. The knowledge of the internal stress buildup through the different processing steps requires the following:

- The determination of the heat transfer during quenching
- The development of a material model for finite-element calculations, which describes adequately the material properties during quenching
- The calculation of stresses and strains during quenching, aging and machining

The principal steps are illustrated on an experimental AA2618 forging of about 0.5 m in diameter. This forging, heat treated without premachining, was chosen on the one hand because of the rather high thermal gradients during quenching due to the large cross section and on the other hand because it was still possible to measure RS on the entire cross section.[2] Based on the herewith-validated procedure, RS calculation has been performed on a larger premachined forging of about 1 m in diameter.

To determine the heat transfer during quenching, thermocouples (TCs) have been inserted inside the forging and temperature measurements were used in an inverse modeling to calculate the position and temperature-dependent heat-transfer coefficients (HTCs).

The development of the material model is based on measurements with interrupted quench tests performed in a Gleeble machine. The impact of precipitation during quenching is considered in the stress–strain simulations through temperature-dependent yield strength. This approach allows avoiding a complex and fastidious characterization of precipitation during quenching.

Internal stresses have been measured along different scan lines using neutron diffraction measurements because aluminum is rather transparent to neutrons [2,3].

EXPERIMENTAL PROCEDURE

Temperature Measurements During Quenching

Temperature measurements during quenching have been executed with both forgings. The forgings were quenched individually by immersion in an industrial boiling water bath. A water jet is used to increase the cooling rate between approximately 300°C and 400°C to decrease the amount of large precipitates forming in this temperature range. In the following, the temperature measurements with the smaller, not premachined forging are described.

The forging was equipped by ABB Turbo Systems Ltd with 20 type K TCs:

- Fifteen TCs are positioned in six rows (groups) at the external surfaces (Fig. 2). Only these TCs are used for the inverse method.
- TCs 16 through 18 are positioned deep inside the forging to check the identified HTCs.
- TCs 19 and 20 are positioned at ϕ = 180° from two TCs to check the cooling axisymmetric hypothesis (not shown here).

From the SHT temperature, the temperature begins to decrease almost linearly with time but is not uniform within the forging. The side facing the water jet (group 6) cools faster than the other faces. From approximately 300°C to 400°C depending on

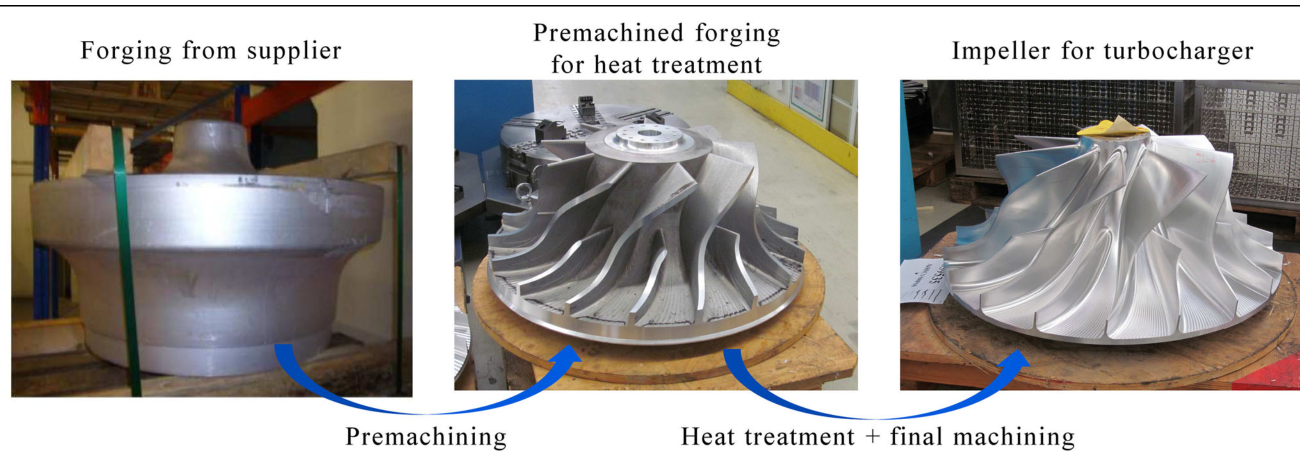

Fig. 1. Manufacturing steps for a large compressor impeller in turbochargers. Small impellers are machined directly from the heat treated forging, i.e., without premachining (courtesy of ABB Turbo Systems Ltd).

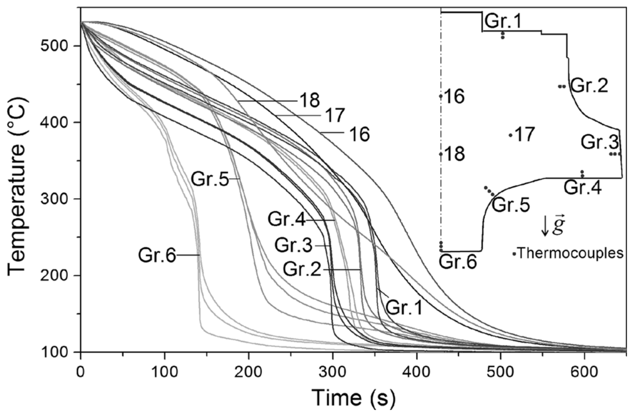

Fig. 2. Position of the thermocouples in the axisymmetric forging (inset) and measured cooling curves.

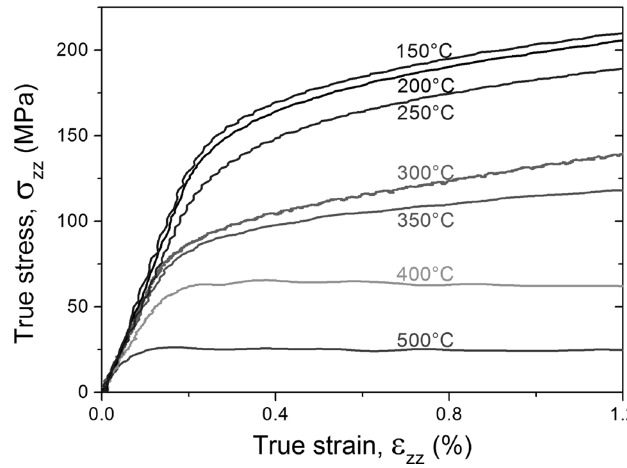

Fig. 3. Measured stress–strain curves for AA2618 Gleeble specimens subjected to interrupted quench tests achieved at 20 K/s. Strain rates are within 0.8–1.7 10^{-2} s^{-1}.

the position, the temperature decreases dramatically but not at the same time within the forging, resulting in huge temperature gradients. As the temperature approaches 100°C, which is the quenchant temperature, natural convection takes place with all cooling curves tending toward the same value. Temperature is almost uniform after approximately 650 s, so that internal stresses will no longer evolve due to thermal gradients.

Characterization of Material Properties During Quenching

Thermomechanical Gleeble tests have been used to determine the impact of precipitation on the yield strength. The Gleeble 3500 machine was chosen for its precise temperature control in order to perform interrupted quench tests.[3] Tensile specimens were cut at different positions (surface and center) and orientations (axial, radial, and hoop) to check that mechanical properties are uniform and isotropic in a forging. Pre-solutionized specimens were heated from room temperature to the SHT temperature at 30 K/s, solutionized for 3 min, and cooled down at 20 K/s, which corresponds to the highest cooling rates between 250°C and 150°C measured in the forging. This cooling rate is higher than the critical cooling rate of S phase ($Al_2\,Cu\,Mg$) in AA2618 of ca. 17 K/s according to Ref. 3. Coarse precipitation is thereby avoided in these tests, which is not the case in forgings where the cooling rates above 300°C are always lower than 5 K/s. The coolings were interrupted at 500°C, 450°C, 400°C, 350°C, 300°C, 250°C, 200°C, and 150°C to perform tensile loads at constant displacement rates while the temperature was maintained constant. The measurement method is fully detailed in Ref. 3. The determined stress–strain curves are shown in Fig. 3.

Flow stress increases during cooling due to the combined effect of temperature decrease and precipitation hardening as shown in Ref. 3.

To fit the experimental results, an elasto-viscoplastic constitutive model with additive hardening is chosen. Assuming negligible kinematic hardening, an uniaxial monotonic load at constant temperature is defined by:

$$\sigma_{zz} = \sigma_y + H.(p_{\mathrm{cum}})^n + K.(\dot{p})^m$$
$$\text{with}\,\dot{p} = \left|\dot{\varepsilon}_{zz}^{in}\right| \;\text{and}\, p_{\mathrm{cum}} = \int_{T<T\mathrm{cum}} \dot{p}\,dt \qquad (1)$$

where σ_{zz} is the axial flow stress, $\dot{p}$ is the inelastic strain rate, and (σ_y, H, n, K, m) are five temperature-dependent parameters. To define the accumulated inelastic deformation, p_{cum}, the parameter T_{cum} is used as the temperature above which inelastic deformation has no effect on subsequent low-temperature behavior. This is a simple way to consider plastic strain recovery at a high temperature. T_{cum} was evaluated from experiment to be approximately 325°C. The yield strength at 0% strain offset, σ_y, is assumed to be the only parameter which depends on precipitation. These parameters were identified by an inverse method using a dedicated optimization software (SiDoLo) developed by Pilvin and Cailletaud.[4] They were tabulated in a UHARD subroutine of Abaqus software (Dassault Systemes, Waltham, MA) and interpolated linearly as a function of temperature.

Residual Stress Measurements

RS measurements executed on the smaller forging have been done in the as-quenched state, i.e., after quenching and before aging. The measurements have been performed using the SALSA diffractometer located at the Institut Laue-Langevin (ILL) in Grenoble, France. RS were measured along three scan lines. The (311) aluminum reflection was used, resulting in a scattering angle of approximately 84.8°. The forging was placed horizontally on the sample table (i.e., forging axis parallel to the scattering plane) to minimize the beam path in the material as shown in Fig. 4 (left).

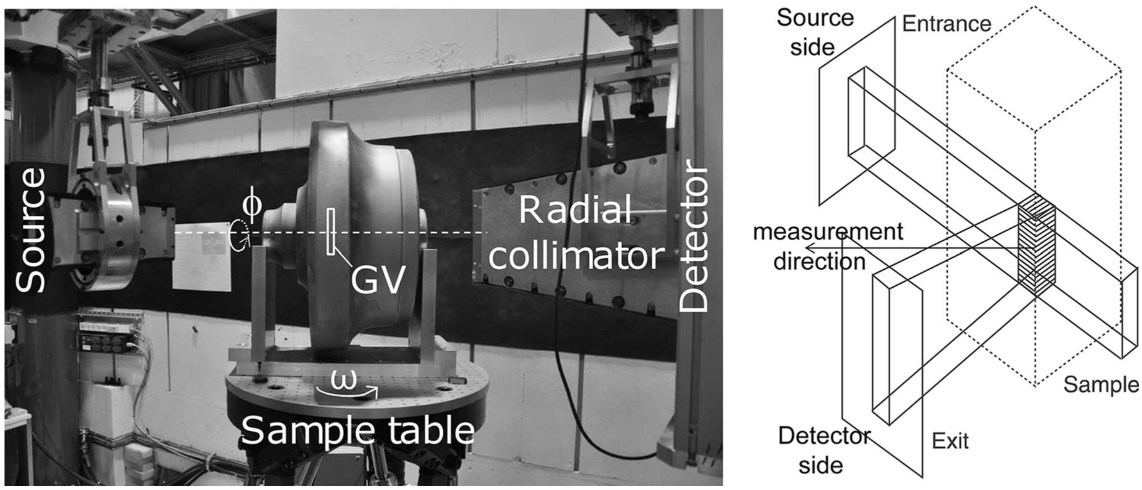

Fig. 4. Setup in the radial configuration (left) and schematic of the nominal gauge volume elongated vertically (right) adapted from Ref.5 Angles ω and ϕ are presented.

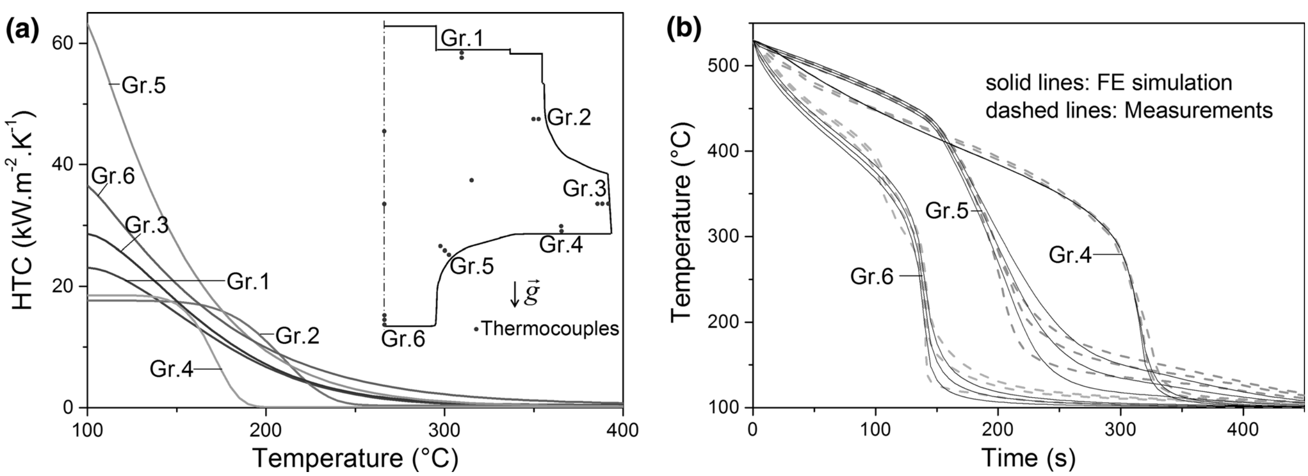

Fig. 5. HTCs versus surface temperature obtained by inverse method using an axisymmetric model of quenching in boiling water (a) and comparison with temperature measurements (b).

Compared with the radial configuration (ω = 0°), the configuration for the axial component measurement is achieved by a table rotation of an angle, ω, of 90°. The configuration for the hoop component is achieved by a forging rotation of an angle, ϕ, of 90° about its axis with ω = 0°. A nominal gauge volume of 2 mm × 2 mm × 15 mm is chosen as shown in Fig. 4 (right) where the elongated dimension guarantees higher intensity. The zero normal stress condition on free surfaces is chosen to determine the stress-free reference value. The measurement method is fully detailed in Refs. 3 and 6.

RESULTS AND DISCUSSION

Heat Flow During Quenching

The forging geometry is meshed in Abaqus using quadratic quadrilateral elements (DCAX8) of about 3 mm × 3 mm in size. To simulate the strongly position-dependent quenching, one HTC per group of TCs was defined in the finite-element model. A parameterization of the six HTCs was used to decrease the number of design variables to be optimized by the inverse method. The identification procedure illustrated in principle for a 3-D model in Ref. 7 was adapted for the current axisymmetric model.[8] The optimized HTCs are given in Fig. 5 together with the measured and simulated temperature evolutions.

As-Quenched Residual Strains and Stresses in the Axisymmetric Forging

An uncoupled heat transfer and subsequent thermal-stress analysis is performed using the HTCs given in Fig. 5a. The temperature field is recorded in the Abaqus results file during the heat-transfer analysis. This file is then used as input to the thermal-stress analysis. In this model, the stress tensor in cylindrical coordinates writes:

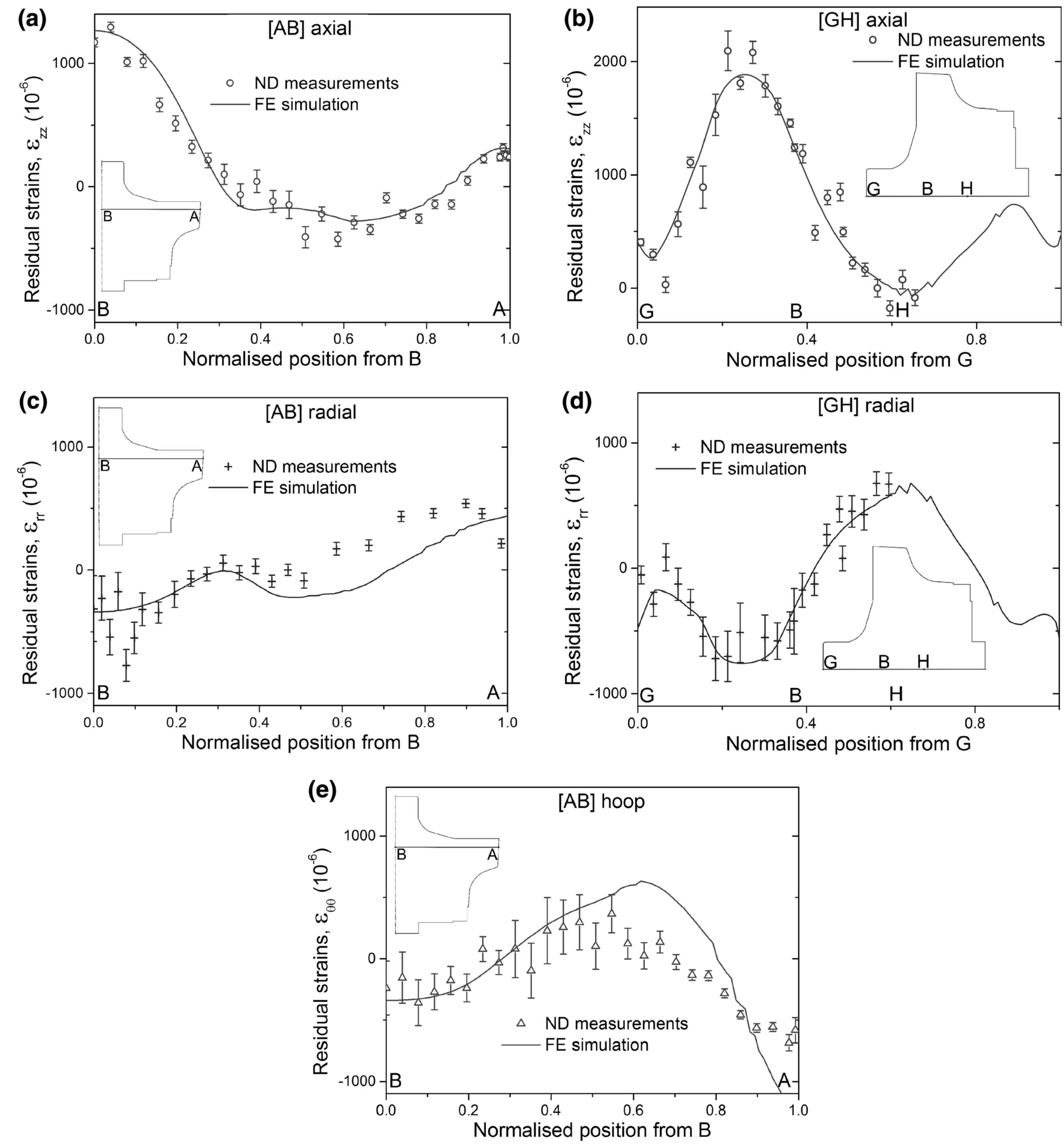

Fig. 6. Comparison between measured residual elastic strain components and simulated ones in as-quenched axisymmetric forging. **a** axial strain along [AB], **b** axial strain along [GH], **c** radial strain along [AB], **d** radial strain along [GH] and **e** hoop strain along [AB]. Please note that on scan line segment [GH], radial and hoop strains are equal owing to symmetry.

$$\underset{\sim}{\sigma} = \begin{pmatrix} \sigma_{rr} & \sigma_{rz} & 0 \\ \sigma_{rz} & \sigma_{zz} & 0 \\ 0 & 0 & \sigma_{\theta\theta} \end{pmatrix} \qquad (2)$$

where r, θ, and z are the radial, hoop and axial directions, respectively. Along the forging axis, the radial σ_{rr} and hoop $\sigma_{\theta\theta}$ components are equal. Shear components σ_{rz} are small but different from zero due to the forging shape. The simulated residual strain profiles are given in Fig. 6 together with the measured residual strains.

Qualitatively, the shape of the measured residual strain profiles is well reproduced by the simulations. This indicates the quality of the calculated thermal

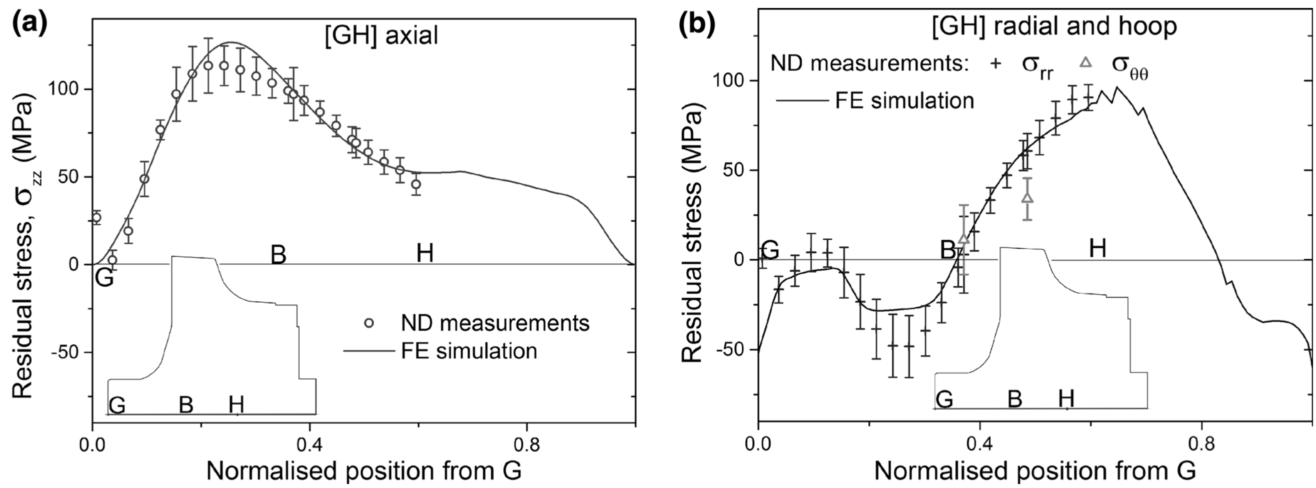

Fig. 7. Comparison between measured residual stress components and simulated ones along [GH] line segment in as-quenched forging.

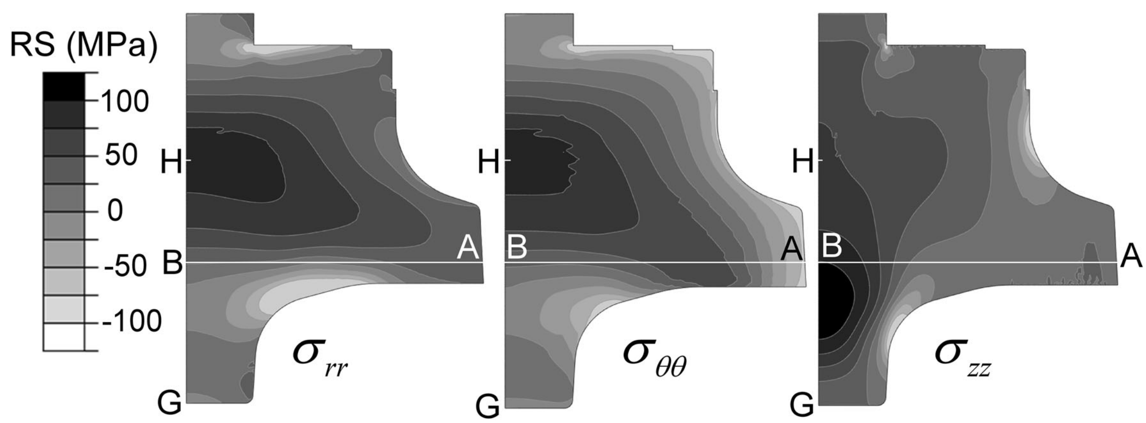

Fig. 8. Residual radial (left), hoop (middle), and axial (right) stress components in axisymmetric forging.

field evolution in the smaller forging to simulate the industrial quench. Quantitatively, the overall agreement between measurements and simulations is good. Consequently, the computed stresses will also match the measured stresses as shown exemplarily along the [GH] segment in Fig. 7.

Figure 7 shows that the finite-element quenching simulation using the thermomechanical model based on a few interrupted quench tests in a Gleeble machine presented above predicts relatively well the measured RS. The simulated as-quenched RS distributions are shown in Fig. 8.

As expected by the measurements, the forging is in a biaxial compression state close to the surfaces and in a triaxial tension state at the center (around B and H). The maximal tensile RS is found close to B for the axial component as indicated in Figs. 7a and 8.

As-Quenched Residual Stresses in a Premachined Forging

Based on the good agreement between measurement and calculation for the axisymmetric forging, the procedure illustrated above was applied to a larger but premachined forging with a central through-hole along the axis. All heat and stress calculations were done with a three-dimensional (3-D) model consisting of a cyclic symmetric pie segment of the premachined forging. The calculated RS for the as-quenched forging are shown in Fig. 9.

The stress distributions are quite different from the ones in the axisymmetric forging, and the absolute stress maxima are higher. This is attributed to the bigger size of the forging and to differences in the cooling behavior, which is affected by the heat transfer along the central hole and on the roughly contoured impeller blades acting as cooling fins. In general, it can be stated that forging premachining has two beneficial impacts on the cooling behavior: it accelerates cooling due to the reduced massive cross section of the part and it increases the effective surface for the heat transfer into the quenching medium. Both effects lead to an increase of the cooling rate, which is beneficial for the material properties. Depending on the effective premachined heat-treatment contour, the resulting stress distribution and level can be modified significantly as further stress calculations with different

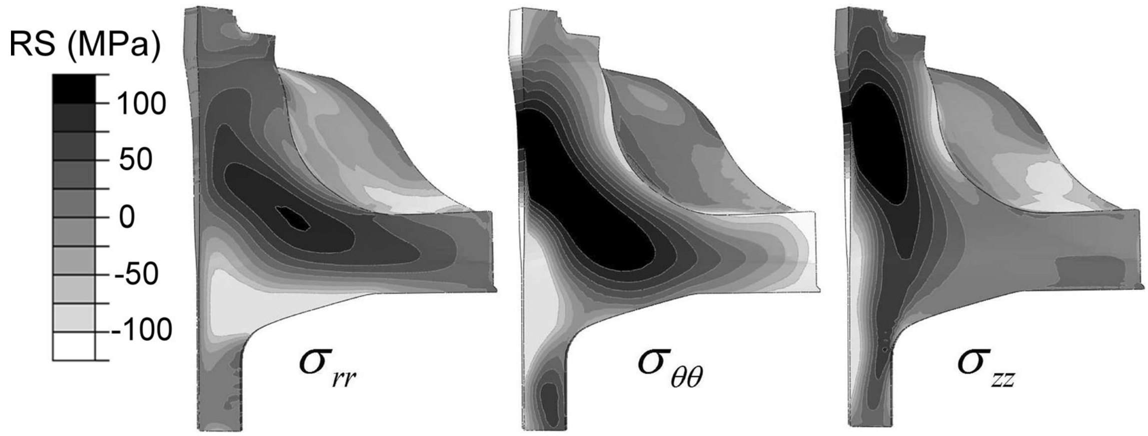

Fig. 9. Residual radial (left), hoop (middle), and axial (right) as-quenched stress components in premachined forging.

contours clearly showed. The prediction of RS by simulation is therefore a key issue in the design of heat-treatment contours of forgings.

CONCLUSION

A thermomechanical model is associated with Gleeble-interrupted tests to account for precipitation in a simple but realistic way. Instead of modeling precipitation that occurs during quenching, the model parameters are identified using a limited number of tensile tests achieved after representative interrupted cooling paths in a Gleeble machine. This approach appears to be sufficient to study the generation of stresses during quenching of large forgings. Stresses are further modified through the subsequent processing steps such as aging, machining, and spinning. The amount of premachining can be optimized using the current approach because quench-induced stresses are correctly assessed.

ACKNOWLEDGEMENTS

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