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Best practice analysis of an industrial cogging process for a tool steel ingot

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An industrial cogging process for a 3.3-ton X38CrMoV5.1 tool steel ingot and the material properties of the ingot are comprehensively analyzed as part of the process validation, with an emphasis on studying the core deformation and gaining greater process knowledge. Material properties are obtained from a two-ton X38CrMoV5.1 ingot. The hot-working yield strength turned out to be quite homogeneous throughout the ingot and does not significantly differ from the yield strength of the forged material. A typical cast structure, free of shrink holes but with imperfections in the core, is observed in an ultrasonic analysis of the ingot. Traditional metallography provides a reference for the microstructure. In-depth process data are obtained from thermographic measurements and data logging during an industrial cogging trial on a 10-MN hydraulic open-die forging press. The FE-simulation of the 12-pass cogging process corresponds closely with the real process sequence. The calculated force shows only slight variations, and the final temperatures agree closely with the measurements. The quite homogeneous equivalent plastic strain in the core along the length of the block exceeds 1.5 throughout and is above the empirical limit required for void closure.

KEYWORDS: OPEN-DIE FORGING, COGGING, ULTRASONIC INSPECTION, FINITE ELEMENT SIMULATION, YIELD CURVE, CAST STRUCTURE

INTRODUCTION

Cogging is an incremental, open-die forging process that is used to produce rectangular, round or hexagonal semi-finished products with high demands in terms of mechanical properties and microstructure and is applied in many industrial fields, e.g. tool manufacturing, power generation machinery as well as heavy machinery.

Usually, the raw material used for cogging is an ingot. The ingot quality is closely linked to the solidification process, which depends on the mold and hot top design parameters, such as the height to diameter ratio, taper, shape, wall thickness, material, etc., and on other process parameters including the casting rate, temperature, material grade flux addition, etc. [5]. Various publications [1-4] report on alloy solidification processes and casting structure development. Cast macrostructures contain columnar crystals and globulites, and it is usually possible to differentiate between the various zones. Furthermore, ingot casting is subject to the many effects of heterogeneity due to the formation of macro-segregations, the unequal grain structure, core porosity, piping inclusion distribution etc. [5]. It is a well-known

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fact that heterogeneous cast structures affect the material properties, i.e. tensile strength and durability. What is not known, however, is the effect of the heterogeneous cast structure on the hot working yield stress of steel alloys under compression stress.

On the one hand, this study investigates the heterogeneity of a two-ton X38CrMoV5.1 ingot and its effect on the yield stress by examining the results of cylindrical upsetting experiments. On the other hand, a 12-pass industrial cogging process involving a 3.3-ton X38CrMoV5.1 tool steel ingot is simulated in order to investigate whether the deformation used to homogenize the material structure is equally distributed throughout the block and whether it reaches the core to a sufficient extent to ensure void closure.

SAMPLE MATERIAL PREPARATION

A two-ton X38CrMoV5.1 ingot is cut into one longitudinally sawn board and multiple transversally sawn discs (Fig. 1). The transversal discs are cut at the foot (F), middle (M) and head (K) ends of the ingot. These discs are 40 mm and 100 mm thick in order to enable the yield stress to be determined both axially and radially in relation to the ingot cogging directions. Furthermore, these boards are used for ultrasonic inspections to determine the macrostructure and heterogeneity, among other things.

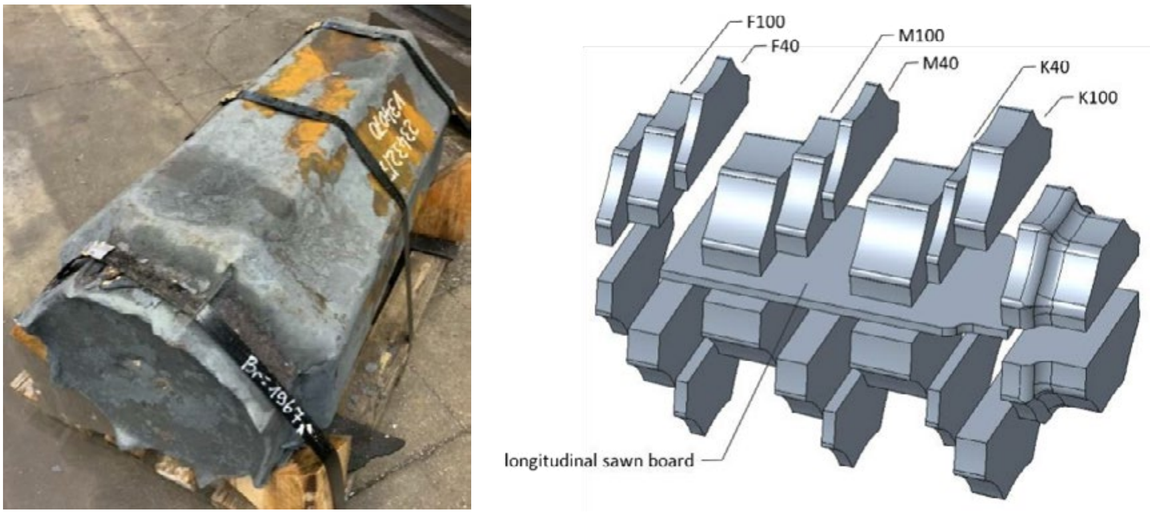

Fig.1 - Two-ton X38CrMoV5.1 ingot and its segmentation.

HOT WORKING MATERIAL PROPERTIES

The hot working material properties, the hot yield curves, are measured in cylindrical upsetting experiments conducted on a servo hydraulic testing machine (Servotest) at the Institute of Metal Forming (IBF) at RWTH Aachen University. Radial and axial ingot specimens are taken from the transversal discs, core, filet (¼R ≤ x ≤ ¾R), and outer edge. Additionally, radial specimens are taken from a transversal disc sawn out of a forged bar. To minimize frictional effects, the Rastegaev specimen geometry with a height-to-diameter ratio of 1.5 and a glass lubricant are applied. The cylindrical samples are homogenized at 1250°C for 15 minutes while using scale protection varnish and inert gas. Afterwards, the specimens are cooled down to testing temperature and compressed under isothermal conditions. Testing temperatures vary from 700 to 1200°C at strain rates of between 0.001 and 1.0 s^{-1}. The resulting yield curves are compensated for dissipative heating (fully isothermal).

From a comparison of the yield stress in the radial direction, measured on transversal disc K100 in the core, filet, and edge region, it is concluded that the differences between the yield curves of less than 5% are negligible. Comparison of the yield stress in the radial direction on transversal discs H, F and M in the filet (Fig. 2) shows that;

- yield curves obtained from the ingot foot (F) are on average 5.7% lower than those from the middle (M);
- yield curves obtained from the ingot head (H) are on average 3.0% lower than those from the middle (M); and
- the difference in the yield curves from the foot, middle and head is relatively minor.

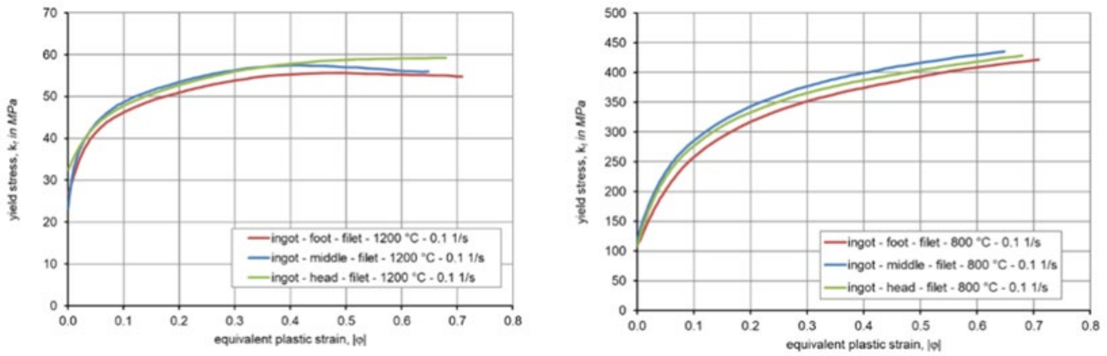

Fig.2 - Yield stress comparison for the foot – middle – head.

A comparison of the radial yield stress in the forged and cast material shows a deviation less than approx. 7%. This is relatively minor and may result from the fact that the ingot heterogeneity is lower than the relevant trade literature would suggest.

ULTRASONIC INSPECTION

The heterogeneity of the ingot is examined by conducting an ultrasonic inspection with HD scan, the quality inspection system for cast products developed by SMS group [6, 7]. It detects and visualizes defects (segregations, pores, macro-inclusions, cracks, etc.) in the material as well as the macrostructure.

Sample results of the measurement on the longitudinally sawn board and transversally sawn disc K40 are shown in Fig. 3. The plotted result combines the macrostructure (dendrites) and the imperfections (i.e. porosities, voids, segregations, and inclusions). A more detailed result analysis quantifies the area affected by imperfections (defects) in the core as being between 9 and 18%.

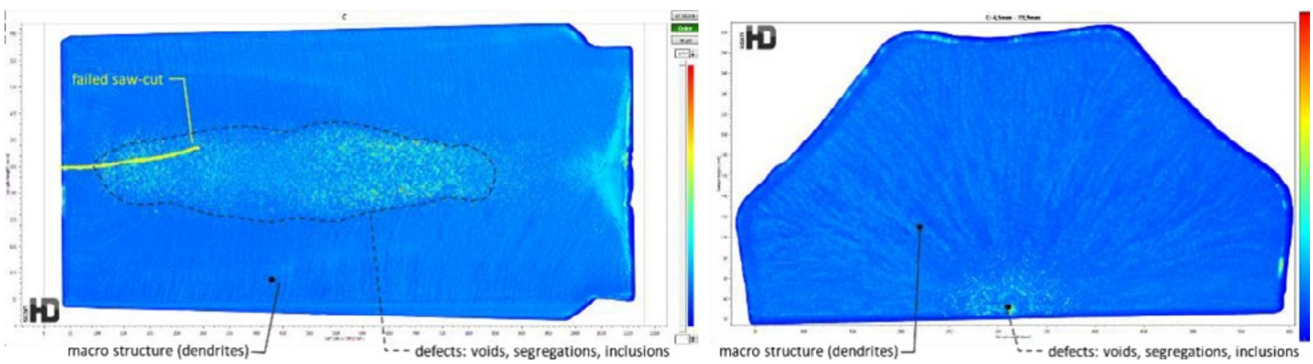

Fig.3 - Combined macrostructure and imperfections for the longitudinal board (left) and transversal disc K40 (right).

Taking all of this into consideration, the ultrasonic inspection proves that the ingot's macrostructure is quite homogeneous and that the heterogeneity is relatively low and concentrated in the core. This explains the minor differences in the hot yield curves at the different positions in the ingot.

MEASUREMENT DURING THE INDUSTRIAL COGGING TRIAL

In-depth process data were obtained from thermographic measurements and data logging during an industrial cogging trial process on the 10-MN hydraulic open-die forging press at Friedrich Lohmann GmbH. Among other things, the hydraulic pressure of the main press cylinder (press force), the ram position (stroke), as well as the position and rotation angle of the manipulator (feed) are logged during the whole cogging trial process. The forging temperature is measured by means of simultaneous thermographic measurements. In addition, the temperature of the dies and core temperature directly after cropping (indicatively) are recorded.

PROCESS SIMULATION

From the moment the ingot is drawn out of the forging furnace, the entire industrial cogging trial process is numerically simulated using the Simufact Forming finite element software, with the open-die forging application module applied for cogging [8]. Fig. 4 depicts the model set-up. It contains the clamps of the lift truck for furnace-press transport as well as the two clamps of the manipulator, the lower and upper die, and the forging itself. The X38CrMoV5.1 material properties stored in the Simufact Materials database are used. However, the yield curves are replaced by those determined on the two-ton ingot. The model accounts for all thermal effects. The cogging module considers all kinematic sequences in the cogging process. A single average constant velocity for the downstroke is calculated from the measurement data, as a way of simplifying the ram velocity as a function of the hydraulic press force. The other velocities (i.e. feeding, backstroke) are adapted accordingly to compensate for the resulting time deviations. Overall, the duration of each pass and that of the whole process corresponds with the industrial cogging trial.

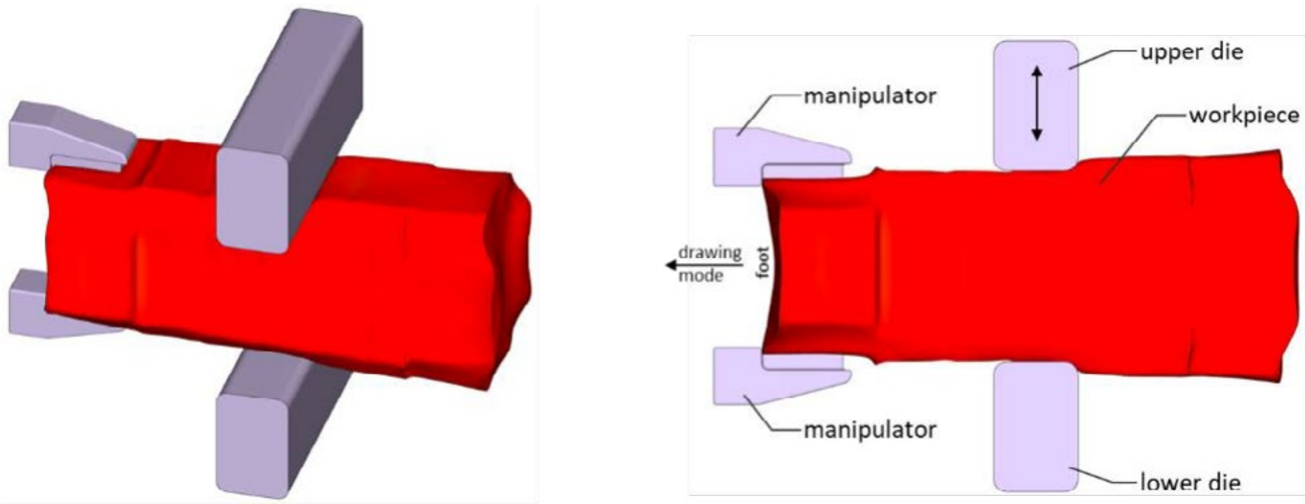

Fig.4 - Finite element model set-up.

The measurement data of the industrial cogging trial process are used to validate the FE model. The calculated surface temperature lies within the scattered range of the one measured. Although the calculated force does not precisely agree with the one measured, a qualitative conformity exists. In pass 1-6, the force is underestimated by approx. 7% on average. There is an average force difference of approx. 9% in pass 7-12 (Fig. 5).

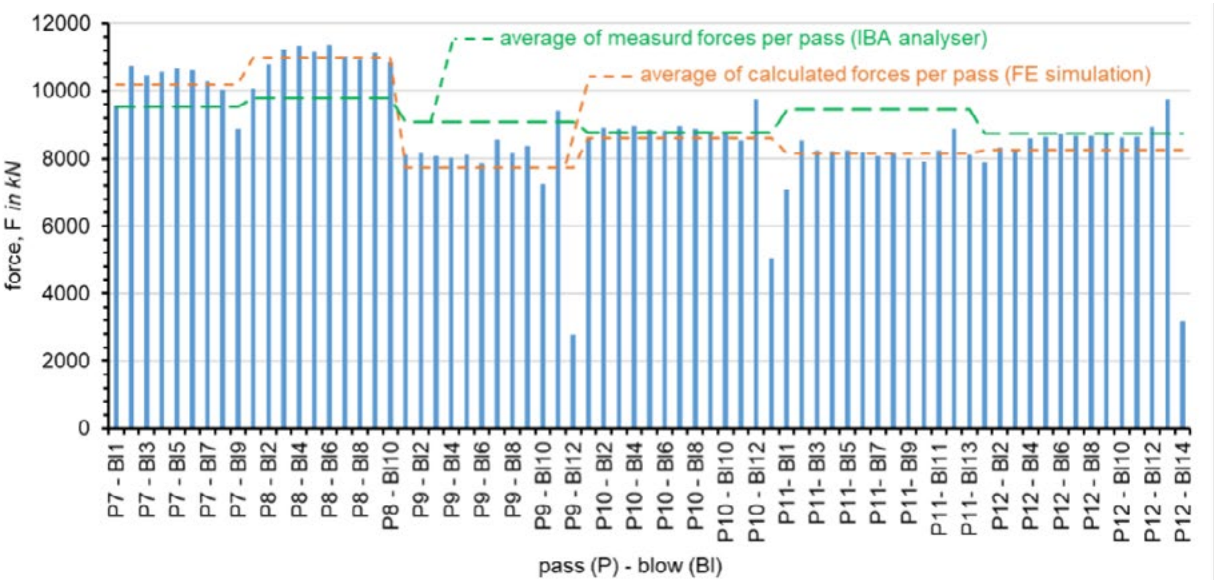

Fig.5 - Force during cogging pass 7-12.

The distribution of the equivalent plastic strain ($\varepsilon_{plastic}$) in Fig. 6 is heterogeneous. The equivalent plastic strain in the core along the length of the block exceeds 1.5 throughout and is more or less constant except for the block ends (Fig. 7). It exceeds the empirical lower limit of 1.4 that is required for void closure.

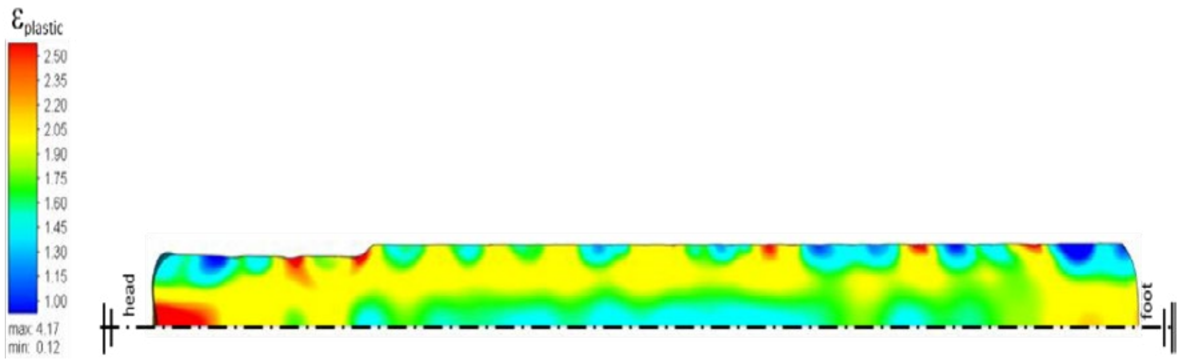

Fig.6 - $\varepsilon_{plastic}$ distribution in a quarter-symmetric longitudinal cut through the block center.

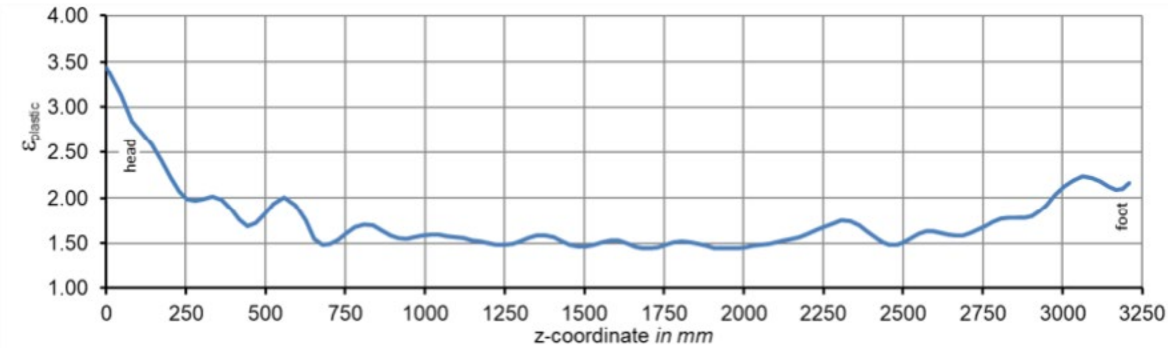

Fig.7 - $\varepsilon_{plastic}$ in the core along the block length.

CONCLUSIONS

The investigations presented prove that by applying in-depth process knowledge and adequate material properties, the numerical simulation of the cogging process provides realistic results and additional insights in both the process and the forging.

Material properties are obtained from a two-ton X38CrMoV5.1 ingot:

- Differences in the measured yield stresses at the different positions in the ingot are less than approx. 6%.
- The ultrasonic inspection shows a relatively homogeneous macrostructure and a relatively small number of defects.

In-depth process data are obtained from thermographic measurements and data logging during an industrial cogging trial process on the 10-MN hydraulic open-die forging press at Friedrich Lohmann GmbH as a validation of the FE simulations.

The entire industrial cogging trial process is numerically simulated:

- The yield curves measured on the two-ton ingot are implemented in the FE model.
- Boundary conditions for the FE model have been adapted according to the results obtained from the analysis of the industrial trial cogging process.
- The surface temperature shows a similar trend as the thermographic measurement.
- The calculated force corresponds with the measured force:
  - o Pass 1 – 6: the force is underestimated by an average of approx. 7%
  - o Pass 7 – 12: the force differs by an average of approx. 9%
- The equivalent plastic strain in the core along the length of the block exceeds 1.5 throughout and is fairly constant along the block length except for the block ends, which are cropped at the end of the cogging process.

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