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Experimental Characterisation of Service-Degraded H13 Tool Steel and Numerical Assessment of Die Plasticity Risk in Hot Forging of Nickel-Based Superalloys

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Abstract. Hot forging of nickel-based superalloys involves severe thermo-mechanical loading of the forming dies due to the high strength of these materials, even at elevated temperatures. Under industrial production conditions, forging dies are subjected to repeated heating-cooling cycles, which progressively degrade the mechanical properties of the tool steel and increase the risk of die plastic deformation. Reliable assessment of die performance therefore requires material characterisation that accounts for both temperature effects and service-induced degradation. In this work, an H13 tool steel used in an industrial hot forging application (nickel-based superalloy case study), was experimentally and numerically investigated in both its raw and service-degraded conditions. Hardness measurements, microstructural analysis, uniaxial compression tests, and quasi-static tensile tests were carried out from room temperature up to 600 °C. An artificial degrading heat treatment was applied to reproduce the mechanical state of the most degraded die regions, and the resulting data were used to quantify the temperature-dependent reduction in yield strength with service exposure. Finite element simulations of the industrial forging process were then carried out using deformable dies to evaluate temperature evolution and stress levels in critical die regions. The risk of die plastification was assessed by comparing simulated von Mises stresses with the experimentally determined temperature-dependent yield strengths for the raw and degraded conditions. The results show a significant reduction in yield strength due to both increasing temperature and service-induced degradation, leading to a substantially higher risk of die plastic deformation under production conditions. The study underlines the importance of incorporating degraded material properties into tool design and process assessment, and motivates improved cooling systems to enhance tool life and process stability.

Introduction

Hot forging under severe thermo-mechanical loading conditions, such as those found during the forming of nickel-based superalloys, poses significant challenges for forging die materials. Nickel-based superalloys are widely employed in advanced sectors such as aerospace and energy generation due to their exceptional strength and creep resistance at elevated temperatures. However, their high flow stress, even at forging temperatures, results in elevated contact pressures and substantial thermal exposure of the dies. During industrial hot forging, dies are subjected to repeated heating-cooling cycles, with local temperatures reaching up to 600 °C [1,2]. These conditions progressively degrade the mechanical properties of the tool steel, reducing its yield strength and, consequently, increasing the risk of die plastification [3,4].

Conventional tool design approaches often rely on the mechanical properties of tool steels in the raw, as-heat-treated state. Such methods do not account for service-induced degradation, which may lead to an overestimation of tool performance and non-conservative design. A more realistic understanding of the degraded mechanical behaviour of tool steels after industrial production is therefore essential to improve tool life prediction and enable the development of more robust tool design methodologies [4,5].

Although the temperature-dependent softening of H13 tool steel has been extensively reported in the literature [6–8], experimental studies directly linking service-induced degradation of industrial forging dies with temperature-dependent mechanical characterisation and numerical stress assessment remain limited. In particular, the combined investigation of a real service-degraded tool, controlled reproduction of the degraded material state, and thermo-mechanically coupled numerical analysis for plastification risk assessment has received comparatively little attention. The novelty of the present work lies in this integrated approach, bridging industrial degradation, laboratory characterisation, and numerical evaluation under representative forging conditions.

In this study, the mechanical properties and the microstructure of a H13 tool steel employed in an industrial hot forging application were analysed in both its raw and service-degraded states. First, the raw steel was characterised through quasi-static tensile tests carried out from room temperature up to 600 °C. In the second stage, a forging die that had been used in serial industrial production was examined to evaluate service-induced degradation. Micro-hardness measurements were carried out across the die cross-section to assess property gradients from the surface to the core. Cylindrical specimens were then extracted from three regions (near the surface, mid-depth, and the core), and uniaxial compression tests were performed at room temperature to analyse the yield strength gradient across the die cross-section.

In addition, based on the hardness reduction observed in the most degraded zone of the industrial die, a controlled degrading heat treatment was applied to the raw H13 steel to reproduce comparable mechanical properties [9,10]. Tensile specimens were subsequently extracted from the degraded material, and quasi-static tensile tests were performed from room temperature up to 600 °C, enabling experimental determination of the temperature-dependent yield strength of the degraded H13 tool steel.

Finally, thermo-mechanically coupled finite element simulations of an industrial hot forging process were carried out using deformable dies [11,12], with the die material model calibrated based on the experimental data obtained in this work. The stress state in the forging die was analysed for both the raw and degraded material conditions, and the risk of plastification was assessed through comparison between simulated stress levels and experimentally determined yield strengths. This approach provides insight into the influence of service-induced degradation on die performance under representative industrial forging conditions.

Experimental Procedure

An industrial forging die manufactured from H13 tool steel and previously employed in hot forging production was employed for the experimental analysis (Fig.1a). The exact number of forging cycles performed with the analysed die prior to specimen extraction was not provided by the industrial partner. However, the die had been used under regular industrial production conditions and exhibited clear evidence of service-induced thermal degradation in regions close to the contact interface. A 10 mm thick slice was extracted from the cross-section of the die by wire electrical discharge machining (EDM) to enable detailed experimental characterisation (Fig.1b).

Fig. 1. a) H13 hot forging die employed for the study, and b) slice cut from the die with wire EDM for experimental characterisation.

First, a hardness analysis of the die cross-section was carried out to evaluate the mechanical property gradients induced by service conditions. For this purpose, micro-Vickers hardness tests (HV0.5) were performed along three directions: longitudinal, radial-oblique, and radial-horizontal, as illustrated in Fig.2a. The hardness measurements were programmed and performed automatically using a Vickers QATM Qness 60A+ hardness testing machine. Indentations were spaced at intervals of 1 mm, allowing a detailed mapping of the hardness distribution across the die cross-section.

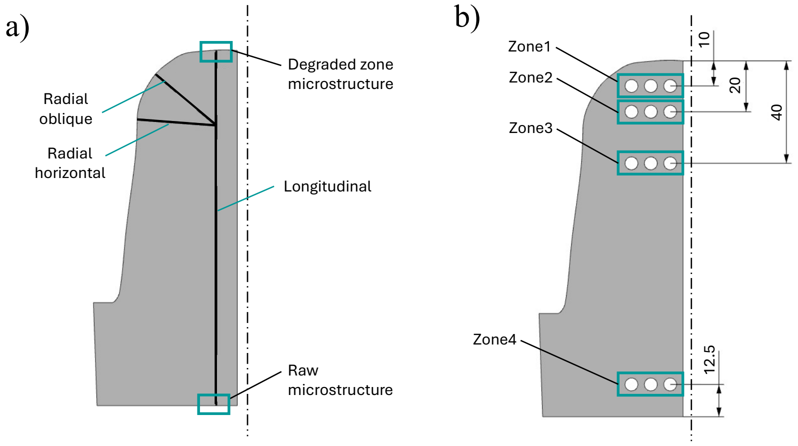

Fig. 2. a) Hardness test directions and microstructural analysis zones, and b) zones from which uniaxial compression samples were cut with wire EDM.

Optical microstructural analysis was subsequently conducted on the tool steel in two representative conditions: the as-heat-treated state at the base of the die, which was not affected by production-related degradation, and the degraded zone located at the die edge (Fig.2a). Standard metallographic sample preparation procedures were employed, followed by chemical etching using Nital. The microstructures were examined using a Leica DM i8C optical microscope to identify possible microstructural changes associated with service-induced degradation.

Cylindrical uniaxial compression specimens with dimensions Ø5×10 mm were extracted by wire EDM from four different locations across the die slice, ranging from the base region (non-affected zone) to the die edge (most affected zone), as shown in Fig.2b. Quasi-static uniaxial compression tests were performed at room temperature using an Instron 4206 universal testing machine to analyse the degradation of yield strength across the die cross-section resulting from industrial service (Fig.3). Zinc stearate lubricant was applied to the specimen-tool interfaces to minimise friction and reduce excessive barrelling. The force during the tests was acquired with the load cell integrated to the compression machine, and the displacement with a linear variable displacement transformer (LVDT) attached to the upper tool.

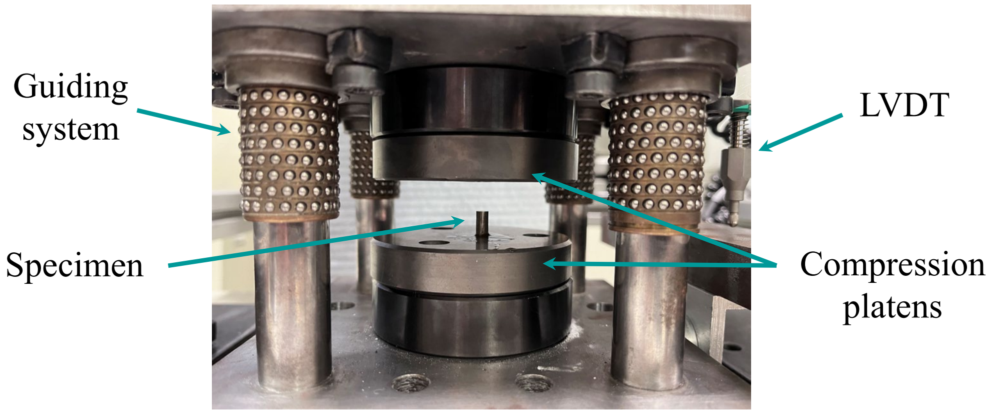

Fig. 3. Uniaxial compression test at room temperature conducted in the Instron 4206 universal machine.

To determine the temperature-dependent yield strength of the H13 tool steel in its initial, non-degraded state, tensile specimens were extracted by wire EDM from the base of the die (Fig.4). This zone was representative of the raw, as-heat-treated material condition, corresponding to forging dies at the beginning of production (Fig.4). Quasi-static tensile tests were carried out at room temperature, 300 °C, and 600 °C using the Instron 4206 universal testing machine. Prior to testing, the specimens were prepared for temperature and strain measurements. One side of each specimen was coated with a heat-resistant, high-emissivity paint to enable accurate temperature monitoring using an infrared (IR) thermal camera, while the opposite side was coated with a heat-resistant stochastic speckle pattern for strain measurement by Digital Image Correlation (DIC) (Fig.5a). Specimens were heated using an in-house developed Joule heating device, providing stable and uniform temperature control within the deformation zone, which was continuously monitored using the IR camera (Fig.5b). Strain in the gauge length was evaluated using GOM Correlate DIC software, employing a virtual extensometer.

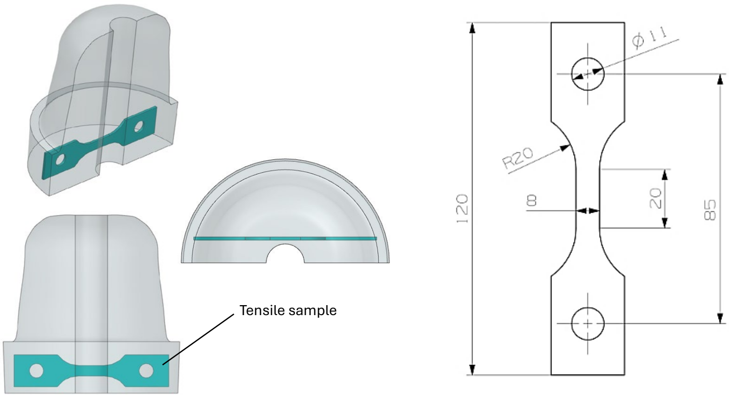

Fig. 4. Tensile samples extracted from the base of the die, representative of the raw, as-heat-treated material condition.

Based on the hardness values measured in the most degraded zone of the die cross-section, corresponding to the die edge, an artificial degrading heat treatment was applied to tensile specimens extracted from the non-affected zone of the die. The heat treatment consisted of exposure at 650 °C for 10 h in an electrical furnace, with the aim of reproducing mechanical properties comparable to those observed at the degraded die edge. This approach was adopted due to the insufficient material volume available at the die edge for direct extraction of tensile specimens.

After the tensile specimens were degraded using the aforementioned heat treatment, quasi-static tensile tests were performed at room temperature, 300 °C, and 600 °C to determine the temperature-dependent yield strength of the H13 tool steel in the degraded condition. The same experimental setup and Joule heating device as those used for the raw material tests were also employed in this case (Fig.5b).

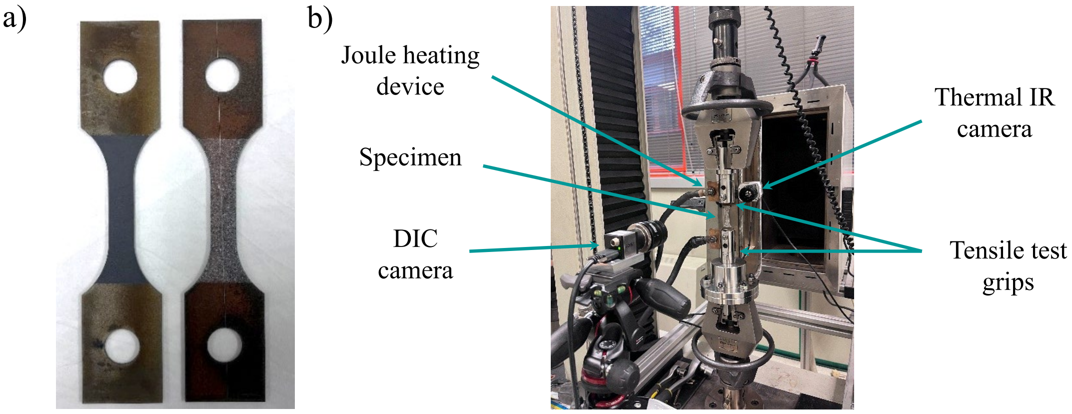

Fig. 5. a) Preparation of the tensile specimen for high-temperature testing, showing the high-emissivity coating for temperature measurement (left) and the stochastic speckle pattern for DIC strain measurement (right); and b) tensile testing setup with the in-house developed Joule heating device, the IR camera, and the DIC camera in the opposite side.

This experimental campaign enabled an extensive characterisation of the H13 tool steel in both its raw and degraded conditions, covering the full range of temperatures and material states observed under real industrial hot forging conditions. The combination of hardness measurements, microstructural analysis, and mechanical testing provided a comprehensive understanding of the evolution of mechanical behaviour across the die cross-section and with increasing temperature.

It should be noted that the mechanical characterisation performed in this study is limited to quasi-static uniaxial tensile and compression tests. In industrial forging operations, dies are subjected to multiaxial stress states and repeated thermo-mechanical cycles. Therefore, the yield strength values obtained here provide a conservative basis for assessing plastification risk, but they do not capture cyclic damage accumulation, fatigue effects, or stress-state sensitivity. The results should thus be interpreted as indicative of static plastification likelihood rather than a full representation of long-term die degradation mechanisms.

Results and Discussion

In this section the experimental and numerical results obtained from the characterisation of the H13 tool steel in both its raw and service-degraded conditions are presented. To begin with, Fig.6 presents the Vickers hardness distribution across the die cross-section from the edge to the base, measured along the longitudinal, radial-oblique, and radial-horizontal directions. From the base of the die up to a distance of approximately 80 mm from the edge, the hardness remains relatively constant, with values in the range of 500-550 HV0.5. This indicates that, in this region, the material is not affected by the cyclic heating-cooling experienced during production and retains its raw mechanical properties.

Beyond this distance, starting at approximately 80 mm from the edge, the hardness decreases progressively towards the die edge, reaching minimum values of around 225 HV0.5 at the surface. A similar hardness evolution is observed along the longitudinal, radial-oblique, and radial-horizontal directions, although slightly lower hardness values are measured in the radial-oblique direction.

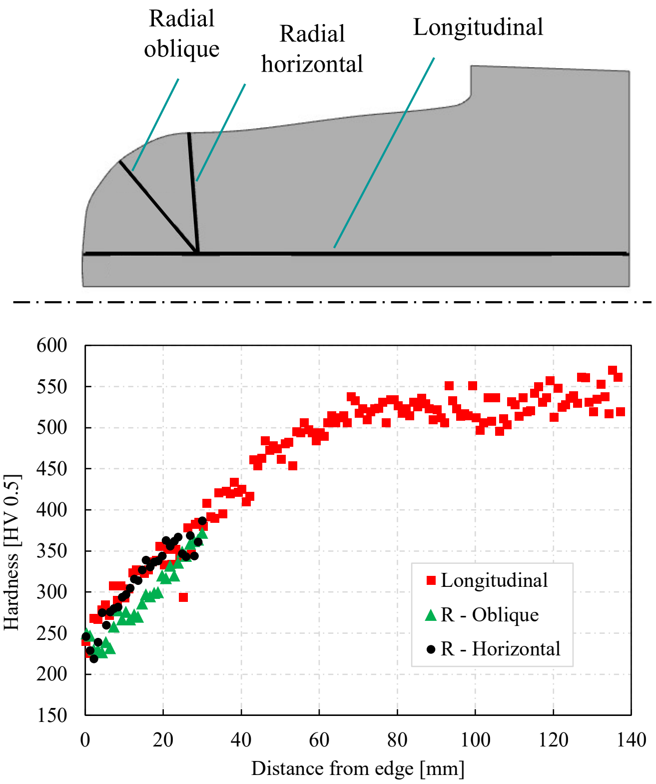

Fig. 6. Hardness evolution in the cross-section of the die from the edge to the base, in the horizontal, radial-oblique and radial-horizontal directions.

The microstructures of the non-affected zone at the base of the die and the service-degraded zone at the die edge are shown in Fig.7a and Fig.7b, respectively. The microstructure observed in the non-affected zone at the base of the die (Fig.7a) is characteristic of H13 tool steel in the as-heat-treated condition. The microstructure consists of a tempered martensitic matrix with a relatively uniform distribution of fine carbides, indicating that the original quenching and tempering treatment has been preserved in this region.

In contrast, the microstructure observed at the die edge (Fig.7b), corresponding to the most service-degraded zone, exhibits clear signs of thermal degradation. The microstructure appears more homogeneous and less defined, with evidence of carbide coarsening and a reduction in microstructural contrast compared to the base material. This microstructural evolution is indicative of over-tempering caused by prolonged exposure to elevated temperatures and repeated heating-cooling cycles during hot forging. Such changes are consistent with the significant reduction in hardness measured near the die edge.

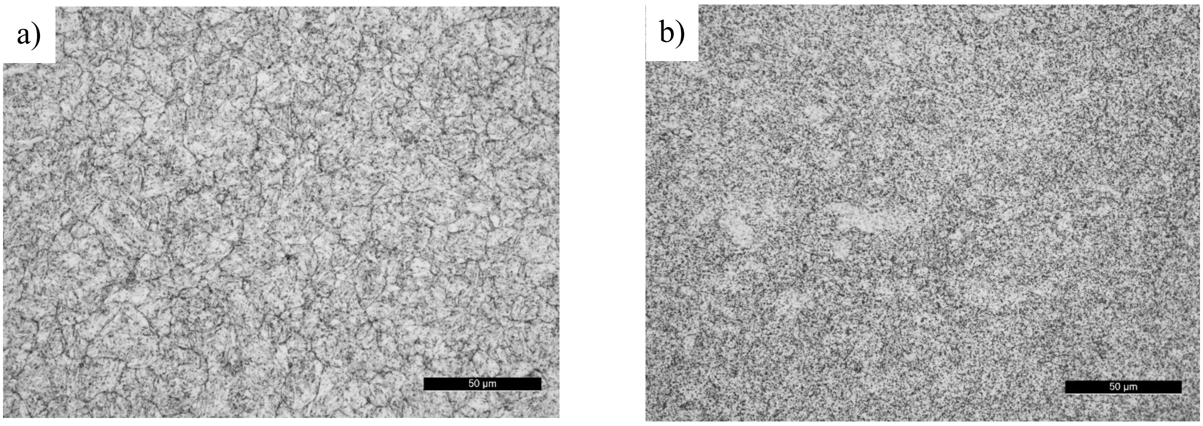

Fig. 7. a) The microstructures of the non-affected zone at the base of the die; and b) the service-degraded zone at the die edge.

Fig.8 shows the engineering stress–strain curves obtained from uniaxial compression tests performed at room temperature on specimens extracted from four different locations across the die cross-section, ranging from the base material (zone 4) to the die edge (zone 1), as indicated in Fig.2b. A clear degradation of mechanical properties is observed as the extraction location approaches the die edge.

Hardness measurements previously showed that the service-affected zone extends up to approximately 80 mm from the die edge. Accordingly, the uniaxial compression specimens extracted from zones 1, 2, and 3, located at distances of approximately 10 mm, 20 mm, and 40 mm from the edge, respectively, fall within this affected region. In contrast, specimens extracted from the base material (zone 4) are located outside the affected zone.

A noticeable scatter in the mechanical response is observed among specimens extracted from the same zone, particularly in the affected regions. This variability can be attributed to slight differences in the actual distance from the die edge, as specimens located closer to the edge are exposed to higher thermal and mechanical loads and therefore exhibit more pronounced degradation. Conversely, specimens extracted from the base material (zone 4) exhibit the highest mechanical strength and significantly lower scatter, with behaviour comparable to that of the original, as-heat-treated material. These results are in good agreement with the hardness measurements and further corroborate the observed mechanical property gradients across the die cross-section.

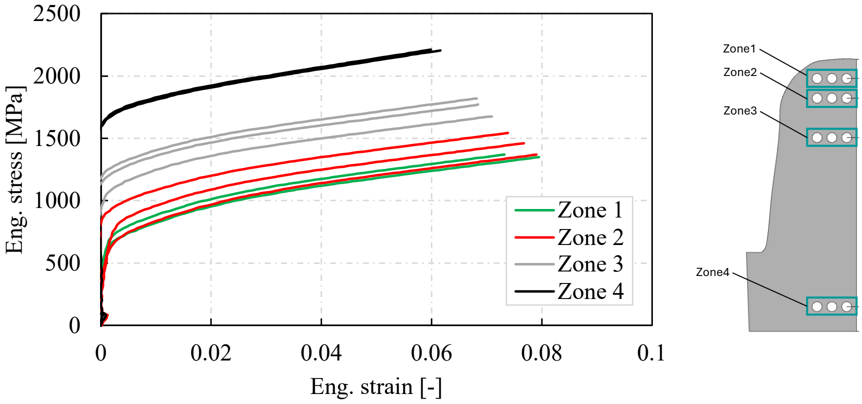

Fig. 8. Engineering stress-strain curves obtained from uniaxial compression tests at room temperature for specimens extracted from different locations across the die cross-section.

As described previously, to reproduce the mechanical properties observed in the degraded state at the die edge, an artificial degrading heat treatment of 10 h at 650 °C was applied to tensile specimens extracted from the base material in the raw condition. The hardness obtained after the degrading heat treatment was 288 HV0.5 (±7.3), which is very close to the hardness measured at the edge of the industrial die.

Fig.9 shows the microstructure of the H13 tool steel after the artificial degrading heat treatment. The microstructure exhibits strong similarities to that observed in the service-degraded zone at the die edge, characterised by a tempered martensitic matrix with reduced microstructural contrast and evidence of carbide coarsening. This close correspondence between hardness values and microstructural features confirms that the artificially degraded tensile specimens are representative of the service-degraded state of the industrial die and can therefore be reliably used to characterise the tensile properties of the tool steel after production.

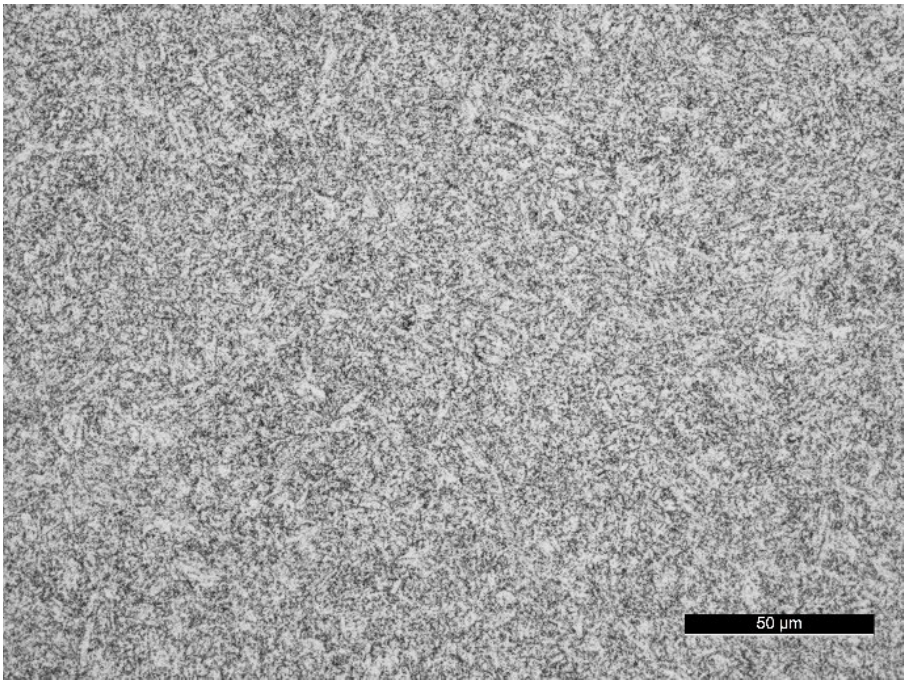

Fig. 9. Optical microstructure of the H13 tool steel in the artificially degraded condition after heat treatment at 650 °C for 10 h.

Fig.10 presents the engineering stress-strain curves obtained from tensile tests conducted at room temperature, 300 °C, and 600 °C on H13 tool steel specimens in both the raw and artificially degraded conditions. Two tests were performed for each temperature and material state, demonstrating good repeatability of the results. The corresponding yield strength values are summarised in Fig.11. For the raw material, the yield strengths were 1320 MPa at room temperature, 885 MPa at 300 °C, and 694 MPa at 600 °C. In contrast, the artificially degraded material exhibited significantly lower yield strength values of 653 MPa, 500 MPa, and 254 MPa at the same respective temperatures. In both conditions, a clear temperature dependence of the mechanical response is observed, with progressively decreasing stress levels at higher testing temperatures. Additionally, the degraded material shows an increased elongation capacity compared to the raw condition, consistent with its reduced strength and thermally softened state.

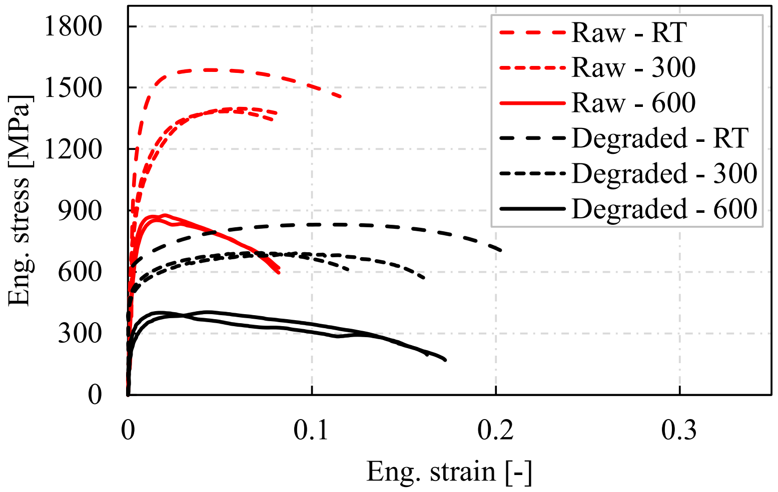

Fig. 10. Engineering stress-strain curves of the H13 steel in the raw and degraded conditions at room temperature, 300 ºC and 600 ºC.

The direct comparison of the yield strength evolution with temperature for the raw and degraded material conditions reveals a significant combined effect of thermal exposure and service-induced degradation (Fig.11). While the raw H13 tool steel already exhibits a significant reduction in yield strength with increasing temperature, this effect is amplified in the degraded condition. At all investigated temperatures, the degraded material shows markedly lower yield strength values than the raw state, with the difference becoming particularly critical at the highest tested temperature (600 ºC). This reduction in yield strength implies that, due to service-degradation, the forging die becomes increasingly prone to plastic deformation under the high contact stresses imposed by hot forging of nickel-based superalloys.

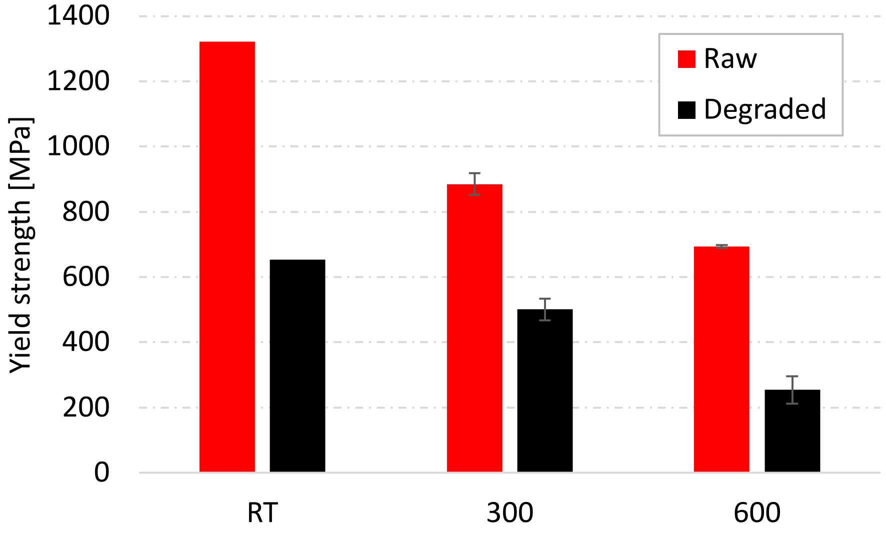

Fig. 11. Comparison of the yield strength of H13 tool steel in the raw and degraded conditions at room temperature, 300 ºC and 600 ºC.

Finally, a numerical study was conducted to assess the temperature evolution and stress levels reached in the analysed die during an industrial hot forging process. A thermo-mechanically coupled 2D finite element simulation of the forging process was carried out using the FORGE® simulation software. A full forging sequence of a real nickel-based superalloy component was simulated on a mechanical press. The billet material was modelled using a viscoplastic Hensel-Spittel constitutive model calibrated for Inconel 625, enabling accurate representation of its temperature- and strain-rate-dependent flow behaviour during forging.

The dies were modelled as deformable bodies using a purely elastic material model with a Young's modulus of 210 GPa. Plastic deformation of the dies was not directly simulated. Instead, the risk of die plastification was assessed by comparing the calculated von Mises equivalent stresses with the experimentally determined temperature-dependent yield strengths of the H13 tool steel in both the raw and service-degraded conditions.

The simulation was fully thermo-mechanically coupled. The initial billet temperature was set to 1150 °C, while the initial die temperatures were assumed to represent steady-state production conditions, with 250 °C for the upper die and 200 °C for the lower die. It should be noted that die temperatures were not experimentally measured during production. The simulated temperature evolution therefore represents an indicative assessment based on the assumed steady-state initial die temperatures and thermal boundary conditions. Consequently, the numerical results should be interpreted as qualitative rather than fully predictive.

Heat transfer between billet and die was modelled using a heat transfer coefficient of 10,000 W/m^2K. Contact conditions were defined using a Coulomb-limited Tresca friction model, with a Coulomb's friction coefficient of 0.15 and a Tresca's constant 0.3. The die mesh consisted of a general element size of 5 mm, refined to 1.25 mm in contact regions to improve stress resolution (Fig.12a). A single forging stroke was simulated, and intermediate stages of the stroke are presented to illustrate the evolution of temperature (Fig.12a) and stress fields (Fig.12b and Fig.12c).

Fig.12a illustrates the temperature distribution in the die at different stages of the forging stroke. Localised temperature increases are observed in regions close to the contact interface, with maximum temperatures reaching up to 400°C at the die edge by the end of the process. As demonstrated by the experimental results presented in this work, the yield strength of H13 tool steel decreases significantly with increasing temperature, an effect that is further intensified in the service-degraded condition.

Regarding the stress state, Fig.12b and Fig.12c present the von Mises equivalent stress distribution in the die at different stages of the forging sequence. Fig.12b and Fig.12c correspond to simulations assuming the die material in the raw state and in the degraded state, respectively. Localised regions near the die edge are subjected to high stress levels, reaching values of up to approximately 1000 MPa. These stress levels are critical, as the combination of elevated temperatures and high contact stresses in these regions significantly increases the likelihood of local plastic deformation of the die during production. This risk becomes particularly severe when the degraded material condition is considered, since a large portion of the die experiences stress levels exceeding the yield strength of the tool steel in the degraded state.

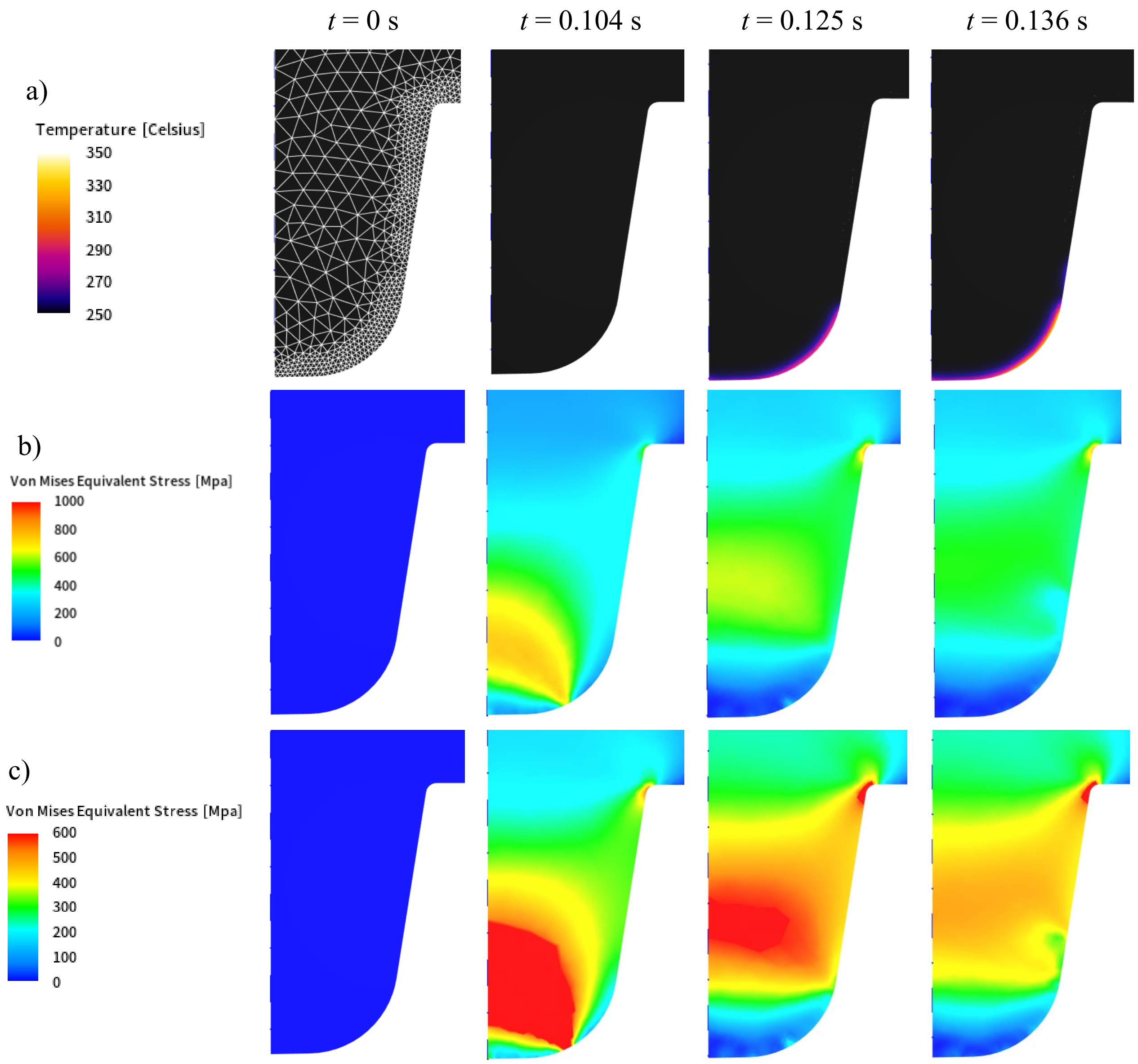

Fig. 12. a) Temperature distribution in the die at different stages of the forging sequence. von Mises equivalent stress distribution in the die at different stages of the forging sequence, b) assuming the die material in the raw state, and c) in the degraded state.

These results indicate that thermal exposure during hot forging significantly contributes to the degradation of die mechanical properties. Elevated temperatures reduce the yield strength of the tool steel, increasing the likelihood of die plastification under prolonged production conditions. From an industrial perspective, appropriate control of die thermal loading is therefore important for maintaining tool performance and dimensional stability. The present findings show that neglecting service-induced degradation in material modelling may lead to a non-conservative assessment of die behaviour, emphasising the need to incorporate temperature-dependent and degradation-sensitive properties into tool design.

It should be noted that, in the numerical simulations, the dies were modelled as purely elastic bodies and plastic deformation was not directly simulated. The risk of plastification was assessed by comparing the simulated von Mises stresses with the experimentally determined temperature-dependent yield strengths of the material. Accordingly, the numerical results should be interpreted as indicative of plastification likelihood rather than fully predictive of permanent die deformation.

In addition, die temperatures during industrial production were not experimentally monitored. The simulated temperature fields are therefore based on assumed steady-state initial conditions and prescribed thermal boundary parameters, and should be regarded as representative estimates of the thermal loading experienced during forging. Furthermore, while the experimentally observed material degradation results from repeated thermo-mechanical cycling during long-term industrial service, the simulation represents a single forging stroke under steady-state conditions. The numerical results thus provide a representative stress and temperature state for an individual forging cycle, whereas the experimentally characterised degradation reflects the cumulative effects of prolonged service exposure.

Conclusion

This study investigated the mechanical degradation of H13 tool steel under industrial hot forging conditions through combined experimental characterisation and numerical stress analysis. Based on the results obtained, the following conclusions can be drawn:

- A comprehensive experimental characterisation of H13 tool steel in both raw and service-degraded conditions was performed, covering the temperature range relevant for industrial hot forging (room temperature to 600 °C).
- Hardness measurements and microstructural analysis of an industrial forging die revealed a pronounced degradation of mechanical properties within approximately 80 mm from the die edge, consistent with thermal exposure during production.
- Uniaxial compression testing confirmed a significant reduction in yield strength in regions closer to the die edge, in agreement with the measured hardness gradients and observed microstructural changes.
- Quasi-static tensile testing demonstrated a strong temperature dependence of yield strength for H13 steel, with the degradation effect becoming particularly severe at elevated temperatures representative of forging conditions.
- An artificial degrading heat treatment successfully reproduced the mechanical and microstructural state of the service-degraded die edge, enabling controlled evaluation of temperature-dependent material behaviour.
- Thermo-mechanically coupled finite element simulations of a representative forging stroke showed that high von Mises stress levels are reached in critical die regions, particularly near the contact interface. Comparison of simulated stress levels with experimentally determined yield strengths indicates an increased risk of die plastification in the degraded condition.
- The results indicate that neglecting service-induced degradation in material modelling may lead to non-conservative assessment of die performance under industrial forging conditions.
- The findings highlight the importance of incorporating temperature-dependent and degradation-sensitive material properties into numerical tool design methodologies and support improved consideration of thermal loading in tool life assessment.

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