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Numerical and experimental investigations on an extrusion process for a newly developed ultra-high-carbon lightweight steel for the automotive industry

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Abstract. In this study the material flow of a newly developed ultra-high-carbon lightweight steel (uhc-steel) with a high amount of aluminum was investigated in an extrusion process. Cylinder compression tests were performed for material characterization and frictional behaviour was determined by using ring compression tests. Numerical simulations were carried to determine the optimal die geometry as well as to calculate the process loads and dominated stresses in the die occurring during the process. Based on the numerical results, an extrusion process was designed and implemented. Experiments showed that the uhc-steel can be formed by extrusion however it is associated with a high wear rate.

1 Introduction

The demands on nowadays processes are focused on resource efficiency, like in example reducing the process chain, as well as lightweight [1,2].

Especially in the automotive sector the lightweight aspect is in focus of actual researches, where in example components of the powertrain are tried to be reduced by weight. Lightweight can either be reached by geometrically optimizing the components (topology optimization) or by new materials. With regard to lightweight ultra-high-carbon steels are potential lightweight steels, which can be used for massive formed parts in the automotive to reduce the weight. The research on uhc-steels began in the early 70´s, where studies were carried out to develop new thermo-mechanical processes for the creation of ultra-fine ferrite graine-sizes [3,4,5,]. In these studies about uhc-steels, the superplasticity of the uhc-steels were observed. In the following years, many studies were carried out investigating the superplasticity and the suerplastic flow of uhc-steels. According to recent investigations the carbon content has to be increased to meet the requirements for the superplasticity [6,7]. Uhc-steels contain about 1 - 2.1 % carbon. Besides the superplasticity at a certain temperature range, the characteristic mechanical properties of uhc-steels were found by low ductility and fracture toughness at ambient temperature, which is unusual for common steels in an intermediate carbon content of 0.1-1 %. Further researches focused on alloying elements stabilizing the occurring phases. One of the most important alloying element is aluminum. On the one hand it stabilizes the existing ferrite phase, but in terms of lightweight and resource efficiency it also reduces its weight due to the lower density in comparison with common steel.

Although these uhc-steels show a good formability at high temperatures, they are difficult to process, which results in high die wear [8,9]. The reason is the formation of thick networks of iron carbides or κ-carbides. These κ-carbides are formed, by cooling down high carbon steels from high temperatures to intermediate temperatures [10]. The carbide networks are areas, at which cracks can be initiated, primarily. In the last years in many researches the formation of these carbide networks aiming to create a homogeneous and fine-sized grain to avoid this critical formation was investigated.

In this study the flow behaviour of a newly developed uhc-steel is investigated on an extrusion process. A material characterization to determine flow curves and the temperature dependent friction coefficients was carried out. The data was implemented into the commercial software system Forge (Transvalor) and numerical simulations were carried out designing an extrusion process for different die geometries. Experiments were carried out, so that the numerical model was validated. The results showed a good agreement comparing the numerical with the experimental results.

2 Numerical and experimental investigations

2.1 Material characterization

To determine the strain-, strain-rate- and temperature dependent flow curves of the uhc-steel, cylindrical compression test were carried out on a servo-hydraulic plastometer, see Figure 1.

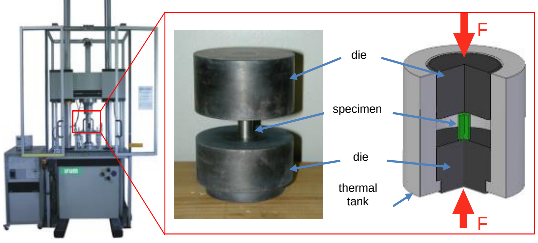

Figure 1. Servo-hydraulic plastometer (Instron).

Herefor specimens with Ø11x18 mm were used. The flow curves were determined at temperatures from 900 to 1200 °C in 100 degree steps. Strain rates of 1, 10 and 40s^{-1} were used, which cover a good range of strain rates occurring in most bulk metal forming processes. The compression tests were carried out up to a strain of 0.7, by which a homogeneous uniaxial forming can be assumed. To minimize the friction between the dies and the specimens, bornitrid was used as lubricant. The specimens were heated up in a furnace. To guarantee adiabatic conditions, the specimens were placed in a thermal tank.

In the figure 2 the exemplary flow curves of the uhc-steel are shown for the temperature range 900 – 1200 °C and the two strain-rates 1s^{-1} as well as 40s^{-1}. As can be observed, with increasing strain-rate, the flow stress level of the uhc-steel increases. At a temperature of 900 °C the flow stress increases from 280 MPa at a strain-rate of 1s^{-1} to 375 MPa at a strain-rate of 40s^{-1}. Furthermore, it can be observed that the flow curves at 900 °C, for both strain-rates, show a significant decrease over the strain. This is assumed to be linked with the high amount of aluminum in the uhc-steel.

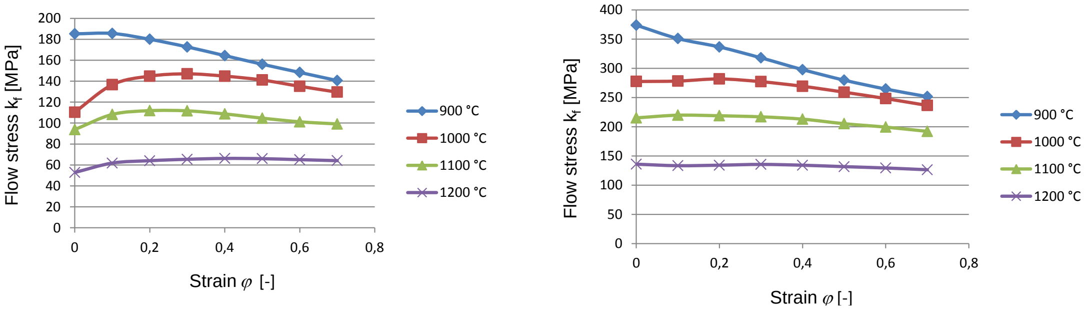

Figure 2. Uhc-steel flow curves at strain-rate 1s^{-1} (left) and 40s^{-1} (right).

To determine the friction behaviour of the uhc-steel, ring compression tests were performed using a screw press (Weingarten). Temperature dependent friction coefficients were determined. The billet temperature was varied between 800 and 1250 °C. The die temperature was varied between 150 and 250 °C, as die material the classic tool steel X40CrMoV5-1 (1.2344) was used. The dies were heated up with a heating jacket and the specimens were heated in a furnace. The tool setup for the ring compression tests is shown in figure 3, left. The specimen geometry, next to a forged part is shown in figure 3, left. As ratio for outer diameter to inner diameter to height, 6:3:2 was used. The geometry of the forged specimens were measured tactile and the friction factor was determined by avitzur method, calculating the friction coefficient with analytic approaches from the geometric dimensions after forging [11]. The results of the ring compression tests are shown in figure 3, right. As can be seen, the determined friction factors range between 0.26 and 0.44 depending on tool and specimen temperature. Furthermore, a significant influence of the die temperature can be observed at a die temperature of up to 200 °C. A dependency of the friction coefficient on rising specimen temperatures can be recognized at die temperatures above 225 °C.

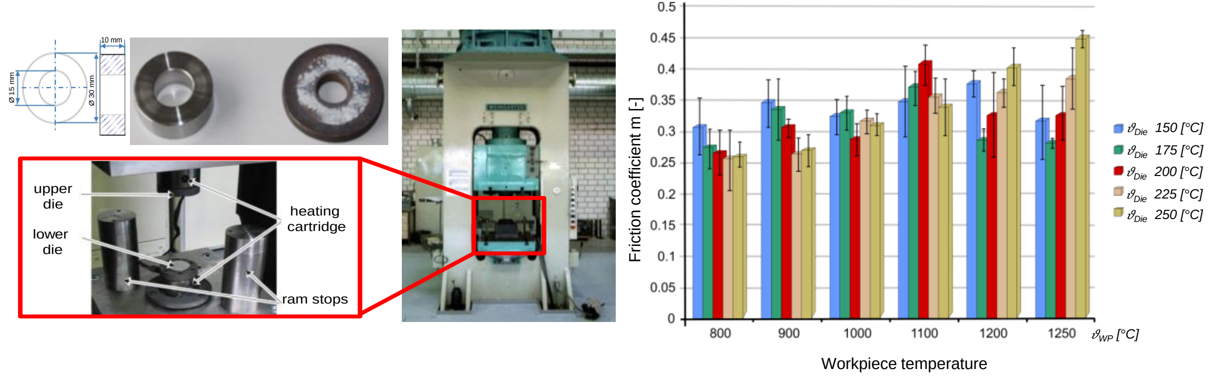

Figure 3. Tool setup for ring compression tests and specimen dimensions (left) with temperature dependent friction factors of the uhc-steel (right).

The data of the material characterization, which contains flow curves as well as temperature dependent friction coefficients were edited and implemented in the software system Forge (Transvalor) for carrying out numerical simulations.

2.2 *FE-aided design of the extrusion process and experiments*

Before carrying out the experimental investigations on the extrusion process, the tool system was numerically designed by carrying out simulations using the software system Forge (Transvalor).

To find the optimal die geometry geometric parameters, which were the tapering radius as well as the tapering, were varied and the stress state in the dies were determined. The tool system consists of an upper and a lower die, which are available in different geometries. The lower dies were investigated for two different taperings to reach local strains up to $\varphi = 1.5$ in the final part. In figure 4 the FE-model of the extrusion process next to forged part for the two different taperings is shown. The forging temperature was set to 1250 °C.

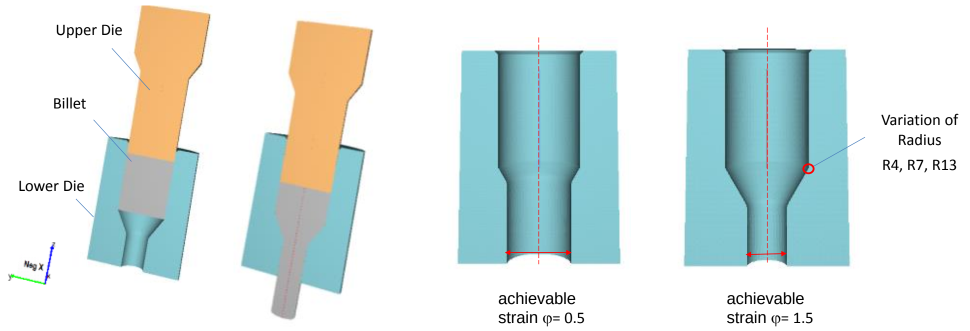

Figure 4. FE-model of the extrusion process

For the die stress analysis, the uncoupled method was used. In a first step a material flow simulation with rigid dies and an elasto-plastic material behavior is carried out. In a following step the loads from the material flow simulation are transferred and the real stress analysis is carried out using elastic modelled dies. Thus, the stress and strains within the dies can be determined and geometric changes of the dies can be performed if necessary. Regarding the die stress analysis results, only the exemplary results of the die with with the achievable strain of φ=1.5 in the part, which is more critical in terms of stresses, are shown in the following figure 5. To determine the optimal stress state for the dies, three different radii were investigated for the tapering of the lower tool, mentioned 13, 7 and 4 mm. To assess the loads on the dies, the von Mises stress as well as the first principal stress is taken into account. While the von Mises stress is an indicator for plastic deformations, the first principal stress shows the tension and compression stress and is an indicator for crack initiation. In figure 5 the results of the die stress analysis are shown for the lower die and the respective radii. As can be seen in figure 5 (left), the radii 4 mm as well as 13 mm show a high stress level up to 1000 MPa in the tapering area of the die. The die with the tapering radius of 7 mm show a comparatively lower stress level of about 900 MPa, which can be observed only in the upper tapering area. The comparison with the first principal stress, which is shown in figure 5 (right) shows qualitatively same results. The dies with 4 mm and 13 mm radii show stress levels of 950 MPa and 700 MPa. For the die with the radius of 7 mm a maximum stress of 520 MPa can be observed. In summary, the die with the radius of 7 mm showed the comparatively lowest stresses in the extrusion process, whereat all the stresses are under the tensile strength of the material. For further experimental investigations, the die with the 7 mm tapering radius was chosen.

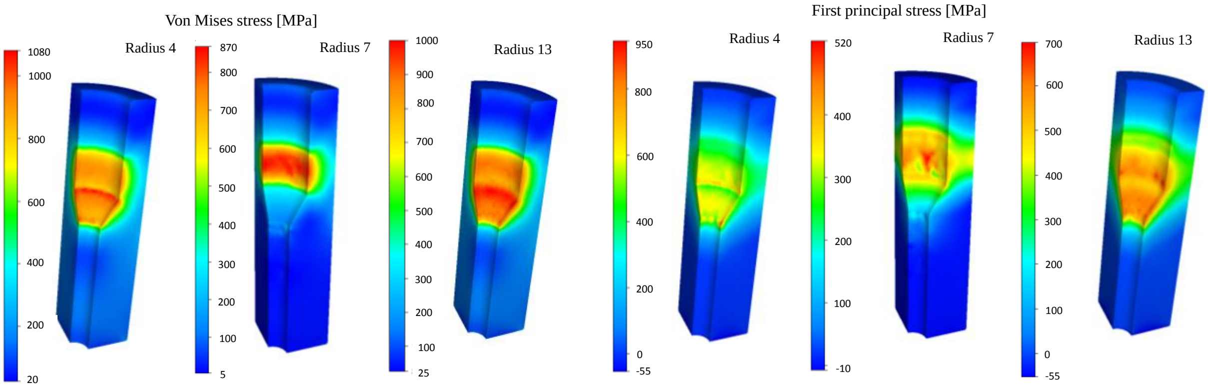

Figure 5. Von Mises stress (left) and first principal stress of the lower die for 3 different radii.

The experimental investigations were carried out on a screw press (Lasco), which is shown in figure 6. As lubricant the oil based lubricant Berulit 722 (Bechem) was used.

Figure 6. Screw press (Lasco).

Selected results and a comparison of the forged part with numerical simulations are shown in figure 7. In figure 7 (left) the numerically determined temperature distribution and the strain distribution are shown next to forged parts with the achievable strain of φ=0.5. The strain distribution in the center of the shaft is at the value of 0.5. At the outer areas of the shaft the plastic strain increase up to 1.6 due to the friction between the die and the billet. A comparison of the geometrical dimensions between the numerical results and the forged parts showed a good agreement. In figure 7 (right) the temperature distribution as well as the strain distribution of the part are shown next to forged parts with strain of φ=1.5. The strain in the shaft of the part is about 1.5 and increase up to 2.75 in the outer areas of the shaft due to friction.

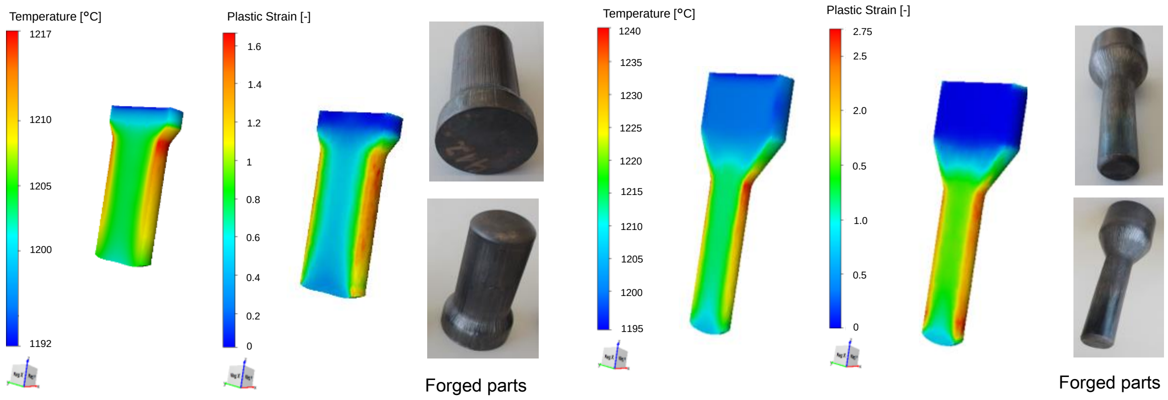

Figure 7. Temperature distribution, plastic strain and forged parts with the strains of φ=0.5 (left) and φ=1.5 (right).

The forged parts, shown in figure 7 indicate a high wear on the dies, which can be seen on the surface of the parts at their respective shafts. The numerical abrasive die wear determination, which is calculated from the sliding velocity and the normal stress applied on the surface, showed that a high die wear is expected. In figure 8 the numerical determined die wear is shown next to the dies after forging. An optical, qualitative evaluation of the die wear shows a good agreement of simulations with experiments. As can be seen, the dies show intense grooves at the tapering areas. This die wear behaviour is typical and one of the disadvantages of the uhc-steels. Here different lubricants and surface treatments of the dies should be investigated.

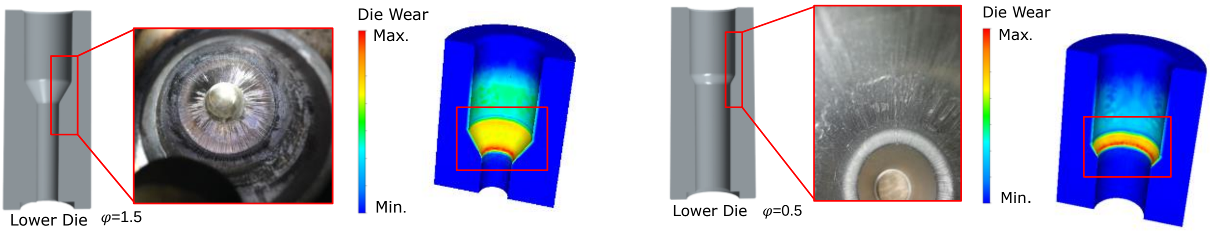

Figure 8. Die wear of the die with achievable strain of φ=1.5 (left) and the die with achievable strain of φ=0.5 (right).

The results show that the newly developed uhc-steel is suitable for processing. The properties of the forged parts are to be investigated in further investigations like tension test and metallographic investigations.

3 Summary and outlook

Uhc-steels are steels with a high amount of up to 2.1 % carbon.

In the hot forging temperature range uhc-steels show a high superplasticity, which was first observed and developed in the early 70´s. The alloying of elements like aluminum into the uhc-steel can reduce the density and thereby the weight of the material. In terms of lightweight bulk metal formed parts produced with the uhc-steel are in the focus of many investigations. Within this study a newly developed uhc-steel, which will be used for a process chain to produce piston pins, was investigated. A material characterization was carried out to determine the temperature-, strain- and strain-rate dependent flow curves via cylindrical compression tests. Furthermore, the temperature dependent friction behaviour was investigated using ring compression tests. An extrusion process with different taperings was numerically designed and experimental tests were carried out. The results show that the material can be processed at hot forging temperatures. The forged parts will be investigated for their mechanical properties with the help of tensile test and microsections. The knowledge gained, will be transferred to a process route for the production of piston pins in a backwards extrusion process. However, the high die wear has to be considered processing the investigated uhc-steel.

Acknowledgements

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