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PROCESS AND TOOL DESIGN FOR PRECISION FORGING OF GEARED COMPONENTS

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ABSTRACT: Precision forging is an innovative manufacturing process for the flash less, near-net-shape production of high performance components. Outstanding material characteristics as well as a reduced process chain and a high material efficiency are the essential advantages of precision forging. Only defined functional surfaces need a finishing after the forging and integrated annealing process. The increased mechanical and dynamical component strength forward the trend of light weight construction. The requirements regarding accuracy in dimension demand high standards of process and tool design. An important part of the current research work is beyond the basic process design and tool construction the correction of geometry and material influences on the shrinking of the hot forged parts.

KEYWORDS: Massive Forming, Bulk Metal Forming, Near-Net-Shape Forming, Precision Forging

1 INTRODUCTION

The growing worldwide competition in the processing industries leads to a constant rise of cost pressure. Research and technological developments in manufacturing technologies are the basic prerequisites to meet cost and quality requirements to assert on the market. Forgings have outstanding material and component characteristics. They feature a high mechanical and dynamical strength due to the process-related grain refinement, the unbroken grain flow as well as the absolute freedom from cavities. An increased power density of forgings forwards the trend of light weight construction.

Germany is the number two producer of forgings world-wide. The production in 2006 amounted 2.6 million tons of forgings. 1.4 million tons accounted for drop forgings. Together with system producers the automotive sector receives more than 80 % of the total production [1].

Generally extensive casting and machining processes are used to manufacture filigree and complex components. Due to higher material usage and especially the inferior strength of casted and machined work pieces highly stressed components like gear wheels are at least rough-forged and finished by machining. Precision forging is an innovative manufacturing process for highly stressable near-net-shape components. It belongs to the category of drop forging and is performed flash less in a closed die. In exceptional cases fabrication tolerances up to IT 7 can be achieved by precision forging [1].

Figure 1 shows a selection of already precision forged parts by the Institute of Metal Forming and Metal-Forming Machines of the Leibniz Universitaet Hannover (IFUM).

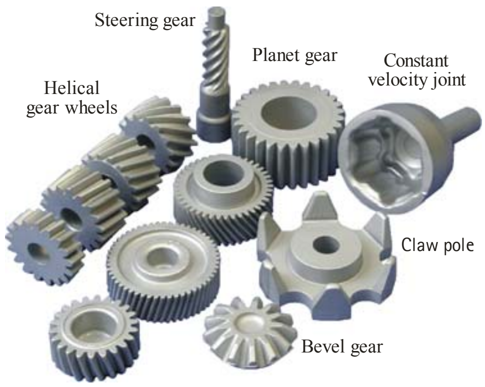

***Figure 1:** Selection of precision forged parts (IFUM)*

The IFUM develops precision forging processes using the example of geared parts like gear wheels, bevel or steering gears. Compared to conventional machining processes a strikingly reduced process chain and a high material efficiency are the advantages of precision forging. Only defined functional surfaces need a final machining after the forging and integrated annealing process in order to ensure the production accuracy and component functionality. The shape cutting and an additional annealing process can be cancelled (Figure 2).

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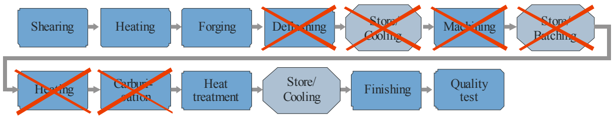

Figure 2: Reduced process chain

Process and cost analyses for conventional machined and precision forged gear wheels show a notable saving potential favouring the forged parts [2].
Within the Collaborative Research Centre 489 "Process Chain for Production of Precision-Forged High Performance Components" the development and qualification of innovative technological, logistical and economical methods for manufacturing precision forged high performance components is focused in current research work. The IFUM fundamentally elaborates the process design and process control of precision forging processes. The spectrum of researched parts from originally compact gear wheels was currently extended by a pinion shaft with a distinct mass distribution. The forged demonstration parts are shown in Figure 3 and Figure 4.

Tooth characteristics

Real pitch module	m_n	2
Number of teeth	z	37
Helix angle	β	20°
Addendum modification coefficient	x	0
Normal pressure angle	α_n	20°
Pitch circle diameter	d	78.75 mm
Tip diameter	d_t	82.75 mm
Root diameter	d_r	73.75 mm
Base diameter	d_b	74.33 mm
Grinding allowance	Δs	150 µm

Figure 3: Precison forged gear wheel

Tooth characteristics

Real pitch module	m_n	2
Number of teeth	z	30
Helix angle	β	20°
Addendum modification coefficient	x	0
Normal pressure angle	α_n	20°
Pitch circle diameter	d	63.85 mm
Tip diameter	d_t	67.85 mm
Root diameter	d_r	58.85 mm
Base diameter	d_b	59.54 mm
Grinding allowance	Δs	150 µm

Figure 4: Precision forged pinion shaft

The grinding allowance for the final machining of tooth flanks and bases is predefined to 150 µm.
To avoid adverse effects on root bearing and running smoothness due to skin-deep microcracks a constant grinding allowance has to be ensured by an adapted design of the forging contour (Figure 5).

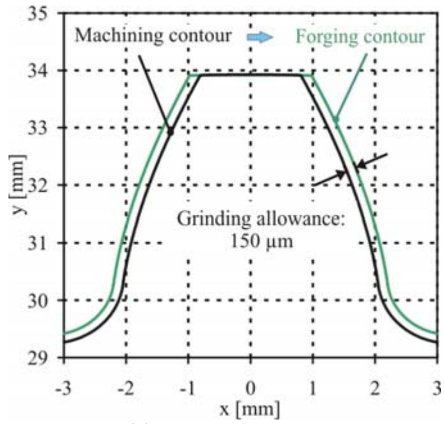

Figure 5: Design of forging contour

The requirements regarding accuracy in dimension demand high standards of process and tool design. An important part of the current research work is beyond the basic process design and tool construction the correction of geometry and material influences on the shrinking characteristics of the hot forged parts.

2 PROCESS AND TOOL DESIGN FOR PRECISION FORGING

For an increase of deformability steel parts are forged at process temperatures up to 1250 °C. During the forging process the work piece already cools down inhomogeneously. This is shown by the locally varying annealing colours of the gear wheel shortly after the forging process in Figure 6.

Figure 6: Inhomogeneous cool down of forging

Due to the local heightened contact pressures and the adverse surface-volume ratio the heat loss in teeth is increased. This leads to a local cool down during the forging process. Thermography investigations prove a decrease of surface temperature down to 700-800 °C in the toothing (Figure 7). This inhomogeneous cool down influences the subsequent shrinking of warm formed parts and has to be compensated by a geometric correction of the die.

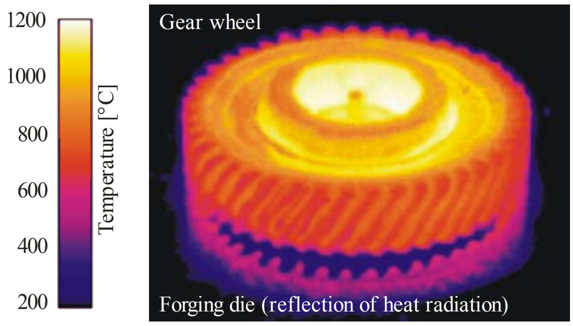

***Figure 7:** Thermography picture of a forged gear wheel*

2.1 GEOMETRIC CORRECTION OF DIE CONTOUR

To ensure the functionality of geared components the expectable shrinking of the formed teeth contour has to be compensated by a geometric correction of the forging die. In a variety of forging tests the IFUM empirically elaborated the following equation for die correction [3].

$$r_{corr} = r \times \left(1 + \frac{\frac{d_t - d}{d_t - d_r} \times (\Delta_r - \Delta_t) + \Delta_t}{100} \right) \quad (1)$$

The numeracy correction of die contour is dependent on the radius r or diameter d. The current component and tooth shape influences the cool down and resulting shrinking characteristics to a great extend. Hence the empirically elaborated correction factors Δ_t and Δ_r for tip and root diameter have to be adapted if necessary. The corrected tooth shape for the current pinion shaft gearing is shown in Figure 8.

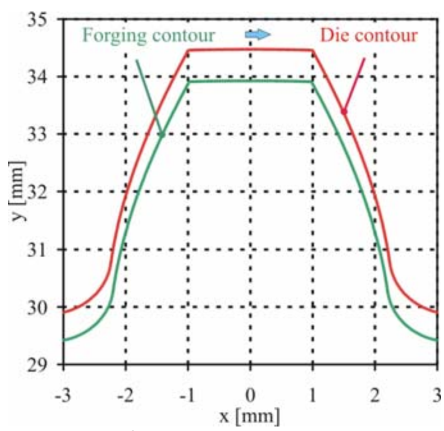

***Figure 8:** Design of die contour*

Apart from geometric component characteristics the used work piece material influences the cool down and resulting shrinking characteristics of forgings. Forging tests have shown that even the use of an alternative delivery batch can alter the shrinking characteristics and affect the achievable production accuracy.

To specify the material effect on shrinking consistently forged gear wheel made of 16MnCr5, 42CrMo4 and 100Cr6 were measured after cooling. The raw parts were heated up to 1150 °C, 1200 °C and 1250 °C. The used forging die was adjusted to 16MnCr5 and 1250 °C.

An abstract of the graphical analysis of measurement results is presented in Figure 9. The plot shows the measured root diameter depending on the alloy composition.

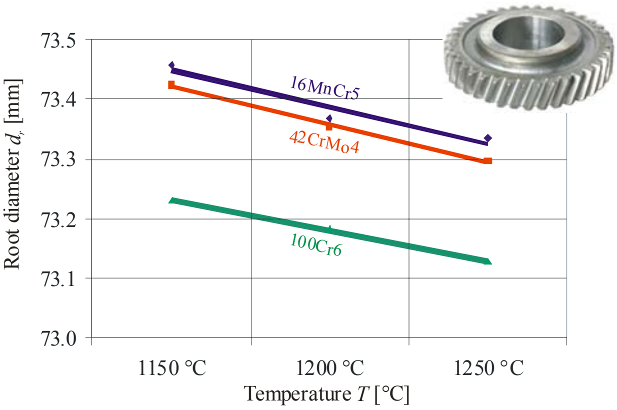

***Figure 9:** Component dimension over the course of carbon equivalent C_E*

Despite of constant forging conditions the gear wheels made of 100Cr6 feature the smallest part dimensions after cooling. This material influenced shrinking characteristic has to be compensated by an adapted process control, e. g. by regulation of raw part temperature. For this purpose the correlation between alloy composition and heat balance was fundamentally analysed for typical forging steels.

2.2 HEAT BALANCE OF FORGING STEELS

The observed loss of heat during the forging process is influenced by the material-specific thermo-physical characteristics heat capacity c_p and heat conductivity λ. Within material analysis and heating tests the density γ, heat capacity c_p and thermal diffusivity a of the typical used forging steels C45, C60, 16MnCr5, 42CrMo4 and 100Cr6 were analysed. For each steel grade two samples of different delivery batches were tested. The measured temperatures ranged between 900 °C to 1300 °C. The heat conductivity λ was determined using equation (2).

$$\lambda(T) = \gamma(T) \times c_p(T) \times a(T) \quad (2)$$

For the expression and comparison of the different alloy compositions the carbon equivalent C_E (3) of Ruhfus and Pflaume was used [4].

$$C_E = C + 0.2Mn + 0.25Cr + 0.33Mo + 0.1Ni + 0.2V + 0.2(Si - 0.5) + 0.2Ti + 0.1W + 0.1Al \quad (3)$$

(C, Mn, Cr, … = Content in mass percent)

Up to 1100 °C occurring phase transformations in steel interfere the measurement results of heat capacity c_p. Hence the determination of definitive physical correlations is not feasible. The graphical analysis of remaining measurement results above 1100 °C are presented in Figure 10 and Figure 11.

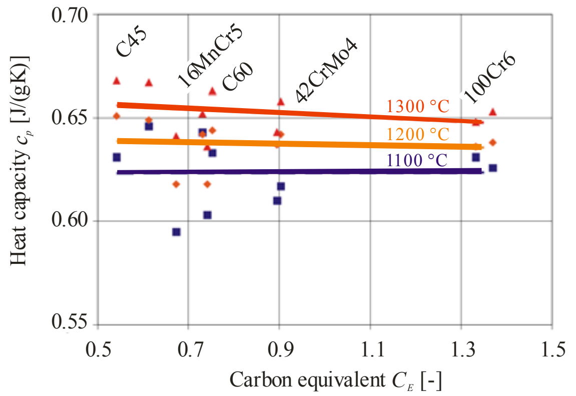

Figure 10: *Heat capacity c_p over the course of the carbon equivalent C_E*

The measured heat capacity c_p varies between 0.6-0.65 J/gK (1100 °C) and 0.64-0.67 J/gK (1300 °C) depending on temperature range. Higher temperatures tend to result in a slightly increased heat capacity c_p. All analysed steel samples show similar heat capacities. There is no correlation between heat capacity c_p and alloy composition ascertainable. Thus the influence of heat capacity c_p on the observed different shrinking characteristics is negligible within the assessed range of parameters.

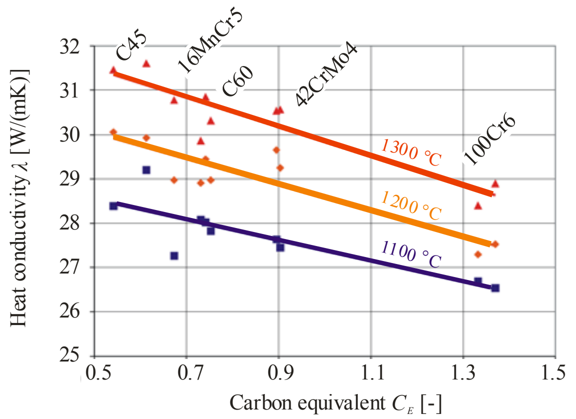

Figure 11: *Heat conductivity λ over the course of the carbon equivalent C_E*

The computed heat conductivity λ varies between 26.53 - 29.21 W/mK (1100 °C) and 28.4 - 31.6 W/mK (1300 °C) depending on temperature range. Higher temperatures tend to result in an increased heat conductivity λ. In contrast to the measured heat capacity c_p the graphical analysis of the heat conductivity λ shows a correlation to the alloy composite, expressed as carbon equivalent C_E. The heat conductivity λ decreases over the course of the carbon equivalent C_E.

The analysed samples of 100Cr6 with carbon equivalents of C_E=1.33 and C_E=1.37 show comparatively the lowest heat conductivity λ. In consequence of a reduced heat transfer and heat loss in work pieces during the forging process the forgings from 100Cr6 are formed at higher work piece temperatures and the subsequent shrinking during the cooling period is increased. Previously conducted forging tests affirm this assumption (Figure 9).

3 CONCLUSIONS

The material analyses and forging tests presented in this paper prove an influence of material on the shrinking characteristics of hot forged parts. It can be assumed that the material-specific thermo-physical heat conductivity λ determines the heat transfer and basic heat loss of the heated work pieces during the forging process. In consequence of material-specific varying work piece temperatures the formed forgings feature different shrinking characteristics during cool down. This observed material influence on the resulting part dimension is to be verified in further thermography and forging tests.
The challenge of the further research work will be the development of a material adapted process design and control, e. g. by an adapted regulation of raw part temperature, to improve the obtainable production accuracy of precision forged parts further.

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