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Procedia Technology

Procedia Technology 26 (2016) 51 – 58

3rd International Conference on System-integrated Intelligence: New Challenges for Product and Production Engineering, SysInt 2016

Numerical Investigation for the Design of a Hot Forging Die with Integrated Cooling Channels

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Abstract

Ongoing research at the Institute of Forming Technology and Machines (IFUM) within the scope of sub-project E3 of the Collaborative Research Centre 653 deals with the generation of controlled cavities inside a sintered hot forging die. The primary objective of sub-project E3 is to develop a forging die which can "feel", "learn" and "control" autonomous reactions to process variations. The current project stage aims at developing a hot forging die with integrated cooling channels.

This paper presents the findings of numerical investigations carried out to analyze the hot forging die made of tool steel powder and equipped with internal cooling channels. Two different geometric variations have been numerically investigated in order to study the stress states within the die under process boundary conditions.

Peer-review under responsibility of the organizing committee of SysInt 2016

Keywords: powder metallurgy; cooling system; thermo-mechanical simulations; hot forging; numerical simulations

1. Introduction

Powder metallurgy has gained a significant importance in the metal processing industry in the recent years. It is known for its high potential for producing near net-shape products. Higher percentage of material utilization and comparably lower energy costs allows powder metallurgy to fulfil the requirements of modern manufacturing

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Peer-review under responsibility of the organizing committee of SysInt 2016
doi:10.1016/j.protcy.2016.08.008

processes. The Collaborative Research Centre 653 “gentelligent Components in their Lifecycle” aims at devising methods and techniques for manufacturing machine tools that can control themselves. The primary objective of sub-project E3 is to develop a forging die which can “feel”, “learn” and “control” process variations. In the ongoing project stage, the objective is to develop a hot forging die with integrated cooling channels as well as slots for fiber optic temperature sensors and a stab to induce a cooling effect in the die center and mandrel by conduction. Figure 1 shows the schematic of such a forging die.

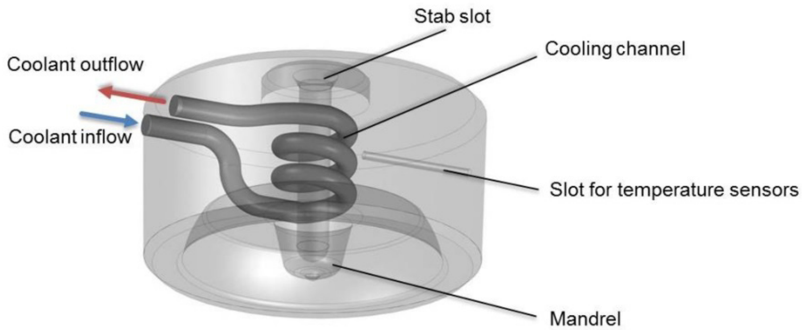

Figure 1: Forging die with integrated channels

Forging dies undergo high thermal and mechanical loads. Besides mechanical tool failures, variations in temperature also influence the die curvature and consequently part accuracy. The thermal load of a tool is mainly influenced by the forging temperature, forming rate, amount of friction, cycle time and heat flow caused by convection and radiation [1]. Lubricants and a spray cooling system help against these thermal loads to keep the basic temperature steady [2]. A supplementary cooling system based primarily on the concept of internal cooling channels in the areas with high thermal stresses is the focal point of this work. The channels will accommodate the cooling medium whose temperature is to be regulated by means of an external temperature control system. Temperature sensors can be integrated by application of fiber optic sensors hence enabling continuous temperature measurement along the length of the die. Based on these measurements, the temperature of the cooling medium can be regulated as per requirements.

Previous works by the authors present the preliminary work in this regard [3]. The present work deals with a numerical analysis of two different geometric variations of the said die in order to study the mechanical strength of the die, in particular the cooling channels, under operating conditions. Figure 2 presents concept diagrams for both of the variations. Left (Model A) is a die with integrated channels only whereas the right-side figure shows the variation with an additional vertical stab slot at the center (Model B). As mentioned earlier, this slot is designed with an aim to further extend the cooling effect to the mandrel by means of a high conductivity insert. The slot for the temperature sensors as shown in Figure 1 is omitted in the numerical analysis during this work but will be considered for the future investigations once the design of cooling channels is finalized.

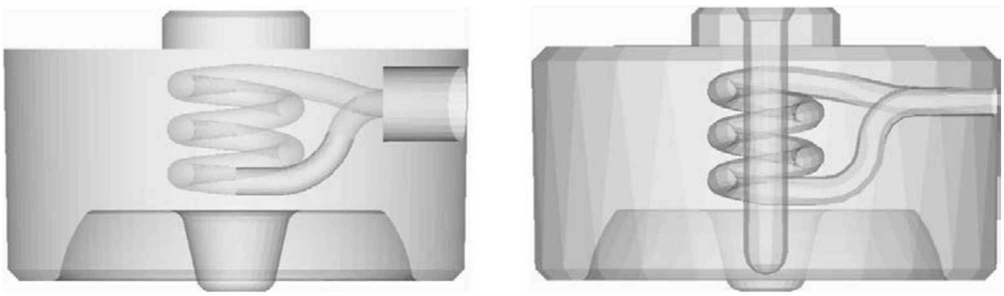

Figure 2: Geometric variations of the forging die; Model A (left) and Model B (right)

2. State of Research

Tools in hot forging processes undergo a combination of cyclic thermomechanical loads, thus the tool wear as well as the service life of the tools is of particular importance in these processes [4]. Behrens et al. have presented a numeric estimation of the abrasive tool wear as a major cause of tool failure in the hot forging processes [5].

Cooling system plays a crucial role in tool life, process productivity as well as product quality. Internal cooling systems already exist for injection moulding and pressure casting processes. Niu et al. developed an intelligent cooling channel system including automatic channel layout from the viewpoint of design as well as optimization, i.e. location, size and number of channels. They provided a criterion about cooling channel design and stated that interference between the cooling channels and other cavities in the mould are not allowed. Moreover, a proper distance is needed between the two. Too much distance decreases the cooling effect of channels whereas too short distances reduce the strength [6]. Yoneyama et al. fabricated cooling channels with different cross sections in the injection moulding using laser metal sintering. They argued that contrary to the conventional injection moulding which uses straight cooling channels created by drilling, the cross section of the laser sintered channels is not limited to circle only and can be oval, triangle or V-shaped as well [7]. Wang et. al. argued that minimum cooling time is imperative for high production rates. They presented an automated methodology to directly build a complex conformal cooling channel in 3D space [8]. Dimla et al. presented an efficient and optimum design for conformal cooling channels in an injection moulding tool using FEA and thermal heat transfer analysis. Their work presents the possibility to optimize and predict the best location for such channels, hence reducing the cooling time as compared to straight drilled channels [9]. Hassan et al. studied the effect of cooling channels' shape and their location on the temperature distribution of the mould. They showed that the position of the cooling channels has a great effect on the cooling process through the mould product [10]. As mentioned earlier, traditionally only straight channels could be manufactured by machining processes like drilling. A cooling system conforming to the shape of part in core and the cavity can be made possible with free-form fabrication or 3D printing. Saifullah et al. carried out numerical investigations to show that proper design and geometry of the conformal cooling channels can reduce cooling time by 40 % and total cycle time by 35 % thus greatly improving the production rate as well as the quality of injection moulded parts [11]. Thus cooling systems lead to advantages such as shorter cycle times, stable processes and higher accuracy. These advantages have to be taken into consideration for the design of forging dies, particularly if highest accuracy is required. Muessig used a forging die equipped with drilled and milled cooling channels in his research and argued that the basic temperature of the die can be kept constant by means of tempered dies [1]. Figure 3 shows that without a tempered die, failures can occur especially during starting times, process variations and after interruptions.

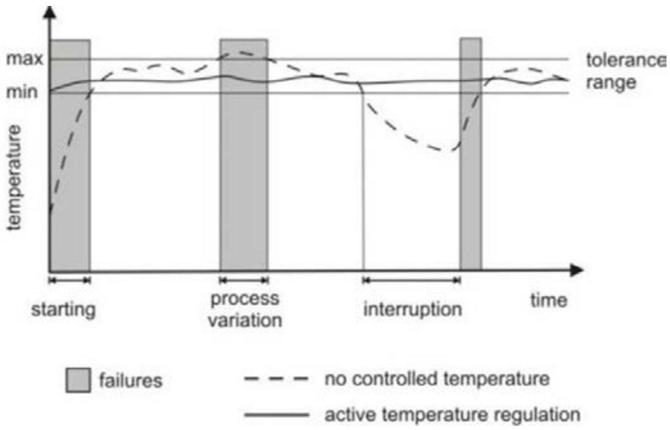

Figure 3: Failures based on thermal variations of a forging process [1]

3. Experimental Process

The production of a forging die with integrated channels is carried out in two process steps namely pressing and sintering (Figure 4). A copper spiral is used as a place-holder for creating the channels. During the pressing process, this copper spiral is pressed into the green compact. This compact is sintered in a sinter furnace in order to melt out the copper spiral by making use of the lower melting point of copper.

Earlier research by Behrens et al. presents a numeric as well as experimental investigation of compaction and sintering behavior for Aluminum powder [12]. For the characterization of the compaction behavior of metallic powders within the scope of the current project, cylindrical compression and brazilian disc tests have been carried out to characterize the powder by means of the Drucker Prager Cap Model. Particular attention must be paid to the compaction process for the integration of functional elements (e.g. copper spiral) into the base powder. There are frictional influences in the contact areas of the shaping tools and the powder body as well as between the powder and the integrated functional elements. This aspect is currently being investigated and will be presented in a later work.

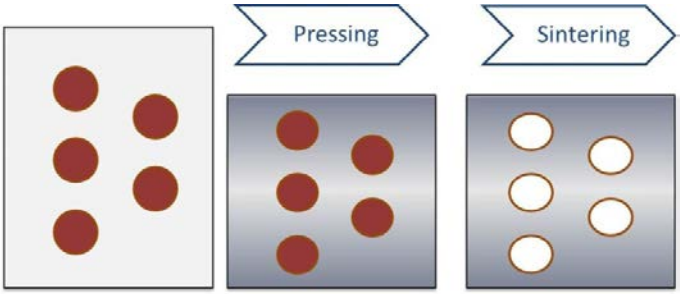

Figure 4: Production process of a forging die with integrated channels

3.1. Melting copper elements out of steel powder

During the sintering process, copper liquefies and infiltrates the surrounding powder areas through capillary effects. Therefore, the porosity of the base powder as well as the friction conditions existing between the two components have an influence on the penetration depth of the liquid phase. Danninger has argued that if the solid element melts completely and infiltrates the surrounding areas, it leaves a cavity with the exact form of the primary element as shown in Figure 5 [13]. In earlier investigations at the IFUM, different copper elements (wire, cuboid) were molten out of steel powder and the fabricated samples were investigated in metallographic tests (Figure 6) [14].

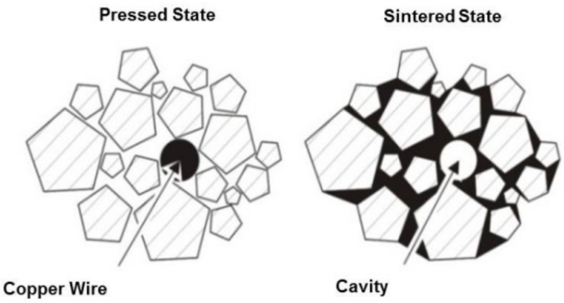

Figure 5: Schematic description of cavity creation by copper melting [13]

A laser-sintered prototype of the die is shown in Figure 7. The shape and size of the cooling system are optimized according to numerical process simulation of thermal loads and mechanical stresses in collaboration with the Institute of Product Development (iPEG) of the Leibniz Universitaet Hannover (LUH) [15].

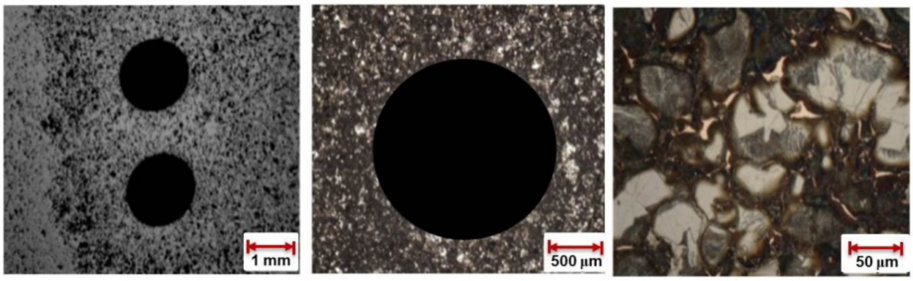

Figure 6: A sintered part made of steel powder, infiltrated by an integrated copper element (left), channels created by copper melting (center) and compound microstructure of steel and copper (right) [14]

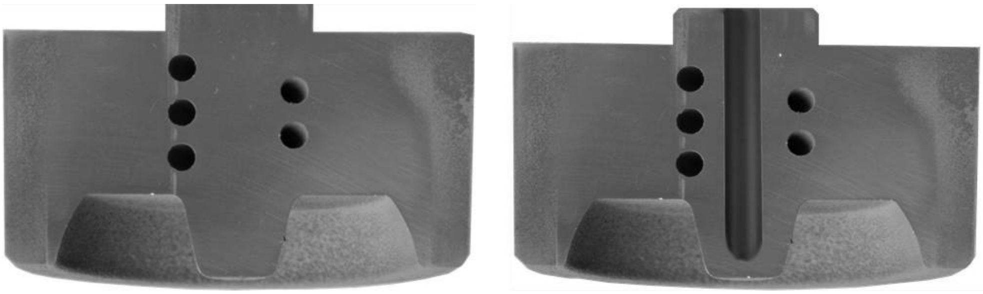

Figure 7: Laser-sintered prototypes of the forging die with integrated cooling channels; Model A (left) and Model B (right)

4. Numerical Investigations

4.1. FE-model of the process

In the metal forming industry, numerical investigations help to study the material flow as well as the behaviour of tools and parts. The Finite Element (FE) approach makes cost-intensive and time consuming experiments redundant. Nonlinear FE methods have been successfully employed as a suitable calculation tool for the simulation of forming processes [16]. In an earlier work, Behrens et al. have used FE methods as a tool for the process design as well as optimization of an industrial forging process [17]. Thus, a numerical investigation has been carried out to analyse the behaviour of a designed die under process boundary conditions.

In order to determine the mechanical loads in the forging die as well as the workpiece, a mechanical tool analysis has been performed. In addition to the elastic material behavior, the interactions between workpiece and tool have also been taken into account. The FE-model consists of a lower die, billet and an upper die (with channels) as presented in Figure 8 below. The lower die is modeled as a rigid body. The upper die is modelled as an elasto-plastic material and assigned work tool steel DIN 1.1545 (C105W1, AISI W1). The billet (workpiece) is assigned an elasto-viscoplastic material behaviour with steel 1.0503 (DIN C45, AISI 1045). Furthermore, model B also contains a stab insert which is modelled as elasto-plastic material and assigned DIN 1.1545 like the upper die.

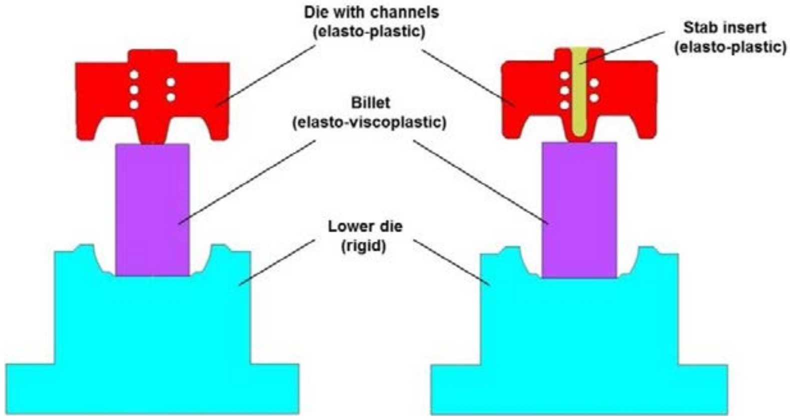

Figure 8: FE-model of the simulation process for both design variations; model A (left) and model B (right)

The FE mesh of the upper die was created with a maximum element length of 0.7 mm and refined in the lower part as well as around the channels (Figure 9). Model A has 17023 elements whereas model B comprises of 16652 elements. The billet was set to have a mesh with 4884 elements and a maximum element length of 0.4 mm. The forging temperature of the raw part (billet) is 1200 °C. An initial temperature of 250 °C is considered for the tool. The heat transfer coefficient between billet and upper die is set to 50 W/m²K, a value of 420 J/kgK is assigned to the heat capacity c_p and the thermal conductivity is set to 46 W/mK. The combined Coulomb-Tresca model is used to describe the friction with a friction coefficient 0.1 and a friction shear factor of 0.3 based on work done by Jeong et al. [18]. A hydraulic press with a downward (-Z direction) speed of 90 mm/s (0.09 m/s) was used to simulate the forging process.

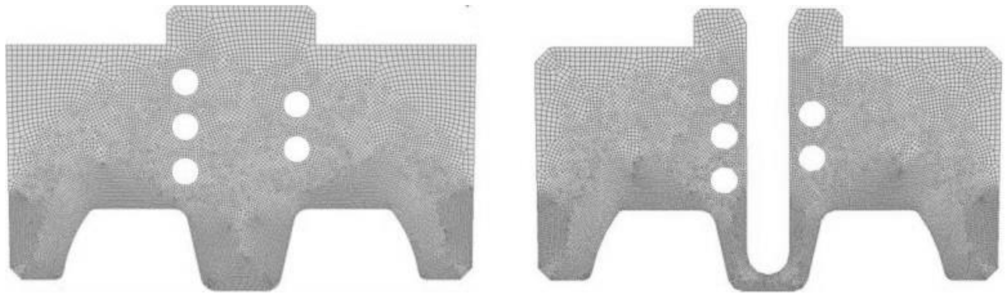

Figure 9: Mesh for both of the considered design variations; model A (left) and model B (right)

4.2. Calculated loadings on the forging tools

The thermo-mechanical tool analysis allows the calculation of the heat transfer from workpiece to tools during the forging process as well as of the mechanical loads acting on the tools. For tool design and the analysis of mechanical loads, the mechanical properties have to be described as a function of temperature. Important process parameters for the assessment of thermal and mechanical loads are temperature distribution and stress state. A consideration of the von Mises stress ($\sigma_{v.Mises}$) and the maximum principal stress ($\sigma_{I,max}$) is of particular importance for a detailed analysis of mechanical strengths. The von Mises stress is direction-independent and indicates the beginning of plasticity. If the calculated first principal stress (maximum principal stress) reaches the ultimate tensile (normal) strength, failure is imminent. The first principal stress indicates the maximum tensile stress in the component. Those tool regions exposed to high tensile stresses have a high risk of failure due to crack initiation.

Von Mises stress and maximum principle stress for both design variations are shown in Figure 10 and Figure 11 respectively. It is observed that high values exist only in the vicinity of channel cavities and the curved inner walls of the die (regions a and b, respectively). In the rest of the die, $\sigma_{v.Mises}$ exhibits values not higher than 500 MPa. The $\sigma_{I,max}$ decreases in the mandrel (-635 MPa for model A, whereas -775 MPa for model B) indicating a compression behavior contrary to the outer walls of the die and the channel cavities which experience tension. The yield stress of the die material 1.1545 is around 500 MPa and the ultimate tensile strength is 800 MPa at 700 °C [19]. Both investigated design variations exhibit higher local maximum values for $\sigma_{v.Mises}$ than the material yield stress thus micro plasticity of the surface can be expected in the respective regions. Contrarily, stresses in the other die areas are lower than the yield stress, hence, no large plasticization is observed. The critical stress value (maximum principal stress) is below the ultimate tensile strength of the material throughout the process. This investigation shows that the geometrical dimensions of the forging dies can be used without die failure, but an extended use can cause cracks in the vicinity of cavities. Furthermore, it is observed that due to the presence of vertical slot in the center of model B, it experiences higher stresses than the model A, particularly around the channel cavities. A variation in cavities' location at a greater distance from the slot can overcome this problem.

The effective plastic strain (ε) is an important process variable for evaluating formability. The plastic strain of the billet is less than 2 for most of the deformed part. A plastic strain higher than 3 is observed only in the area of the mandrel impact as shown in Figure 12.

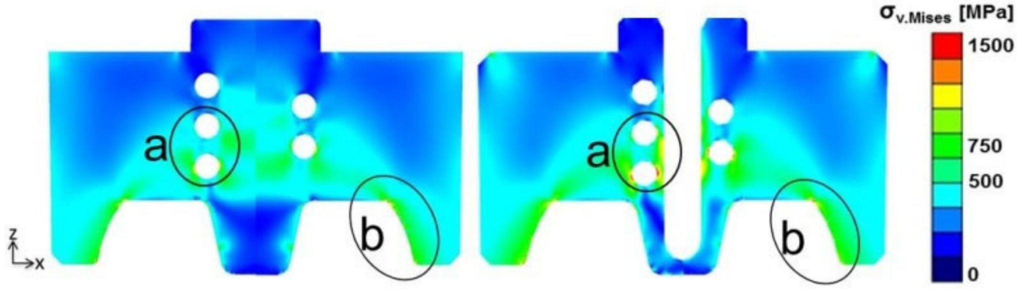

Figure 10: Mises stress distribution and regions of high stresses in the forging die; model A (left) and model B (right)

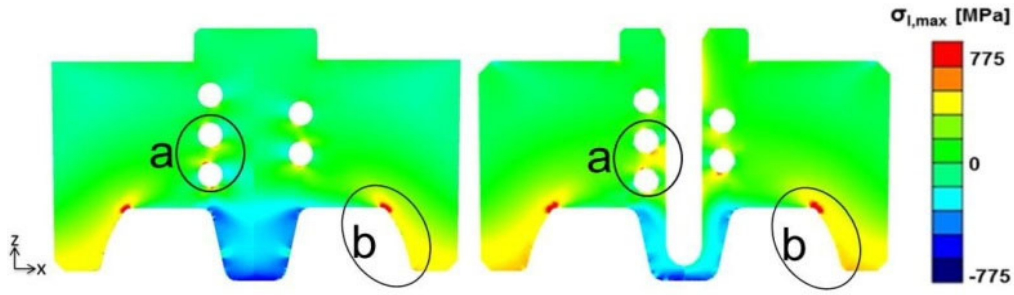

Figure 11: Maximum principle stress in in the forging die; model A (left) and model B (right)

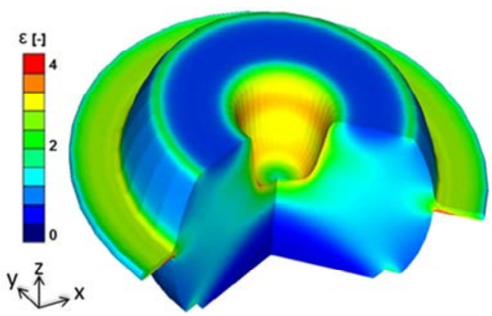

Figure 12: Effective plastic strain distribution in the billet

5. Conclusions and Outlook

The effects of channels in two different variations of forging dies have been investigated in terms of mechanical loads. It is shown that the geometrical dimensions of both forging dies can be used without die failure. However, high local stress values in the vicinity of cavities particularly in the case of model B (with a vertical slot) were observed which might lead to cracks and cause fracture in the longer run. Hence, a further design optimization is foreseen in order to improve the design efficiency of the cavities along with an improvement in the components' strength. Moreover, a detailed transient thermo-mechanical investigation to study time evolution of the loads will be carried out.

Acknowledgement

The results presented in this paper were obtained within the framework of the Collaborative Research Center 653 "Gentelligent Components in their Lifecycle" in the subproject E3 "Sintering gentelligent parts from metal powder". The authors would like to thank the German Research Foundation for the financial support of this project.

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