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Development of a powder metallurgical self cooling forging die with inner cavities

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Abstract

Powder metallurgy is known for its high potential for producing near net-shape products. A material utilization of up to 95 %, paired with comparably low energy costs, allows powder metallurgy to fulfil the requirements of modern manufacturing processes. By combining different powders, a wide range of products can be manufactured. An innovative powder metallurgical method currently being investigated at the Institute of Forming Technology and Machines (IFUM) within the subproject E3 of the Collaborative Research Centre 653 is the generation of controlled cavities inside a sintered part. For this purpose, a foreign element with a lower melting point than the base powder is embedded inside the green body. Depending on the sintering temperature, the foreign element can be firmly bonded with or melted out of the base powder, creating a defined cavity. Being attached to an external cooling system, the cavity can be applied as a closed circuit for circulating a cooling medium within the tool. The approach in this work is the development of a sintered forging die, equipped with an active temperature regulation which can react autonomously to process variations. The cooling temperature is controlled by measuring the operating temperature within the forging die. For measuring purposes, the cavities can also be used for integrating temperature sensors.

The main aspect of these studies is the characterization of the compaction and melting behavior of the foreign material. Since the location of the foreign element within the base powder can differ due to the pressing force, the prediction of its final position based on the initial position and the process conditions is of high importance. For this aim, numerical simulations are employed to develop an optimized cooling layout. A numerical model is used to describe the compaction behaviour of the powder as an elastoplastic compressible continuum and its interdependency with the integrated elements. The studies also cover the influence of surface contours of the foreign elements (corrugated, plain) on their melting behavior as well as the resulting inner surface of the cooling channel.

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1. Introduction

Sub-project E3 arose from the Collaborative Research Centre 653 which mainly deals with “gentelligent components in their life cycle”. The aim of sub-project E3 is to develop a forging die which can “feel”, “learn” and “control” autonomous reactions to process variations. In the current early stage of the project (project start third quarter 2013) mainly preinvestigations and feasibility analysis were carried out. Furthermore, an outlook on future investigations is given (project end second quarter 2017).

Forging dies underlie high thermal and mechanical loads. Besides additional mechanical tool failures, varying temperatures also take influence on the gravure and as a consequence on the part accuracy. The thermal load of the tool is mainly influenced by forging temperature, forming rate, amount of friction, cycle time and heat flow caused by convection and radiation [1]. To counteract these thermal loads and hold the ground temperature steady, lubricants and spray cooling systems are applied [2].

The aim of this work is to provide a supplemental cooling system, besides a conventional spray cooling system, for thermal highly stressed areas by using internal cooling channels. The channels will accommodate the cooling medium which is pumped through the die body. The temperature of the cooling medium is regulated by means of an external recooling/heating aggregate. The channels can also be used for integrating temperature sensors. A possible solution is to apply fiberoptical sensors which enable continuous temperature measuring along the channels (Fig. 1). Based on the temperature measurements, the temperature of the cooling medium can be regulated in different directions (higher and lower).

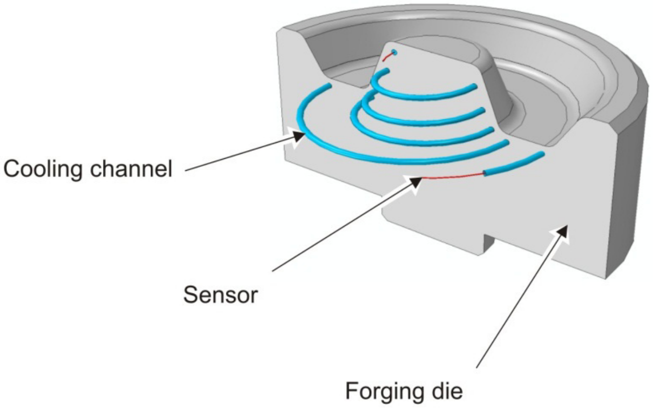


Fig. 1. Forging die with cooling channels and temperature sensor.

An effective temperature balance of forging tools results in an improved lifetime and higher part accuracy. A defined internal cooling system already exists for injection molding and pressure casting processes. The advantages are shorter cycle times, stable processes and higher accuracy [1]. These advantages have to be taken into consideration for designing the forging die, especially if highest accuracy is required. MUESSIG points out in his research when using a forging die equipped with drilled and milled cooling channels that the ground temperature of the die can be held constant by using tempered dies. Without a tempered die, failures can occur especially during starting times, process variations and after interruption, see Fig. 2 [1].

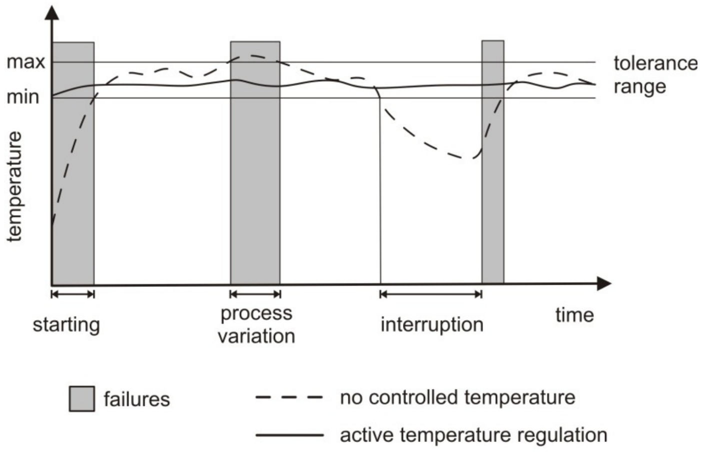


Fig. 2. Failures based on thermal variations of a forging process [2].

Current studies show promising results of powder-based forging dies. BEHRENS et al. investigated the wear mechanisms of generatively produced forging tools with integrated cooling channels out of DIN 1.2709 (X3NiCoMoTi18-9-5) hot – work steel powder. Even after 500 forging cycles almost no visible wear mechanism was detected, whereas a conventionally produced die out of DIN 1.2344 (X40CrMoV5-1) shows a significantly higher adhesive wear after the same procedure. In comparison to machined cooling channels, the selective laser sintering process allows manufacturing of cooling channels with different shapes and defined radii. Current disadvantages of generative processes are long process times and a limitation of the cooling channel diameter to values greater than or equal to 8 mm [3].

2. Experimental Setup

The objective of this project is to develop a forging die with integrated cooling channels consisting of hot - work tool steel powder. For this purpose it is planned to carry out the three process steps pressing, sintering and hot isostatic pressing (HIP) (Fig. 3). After pressing copper - tubes into the green body an equivalent channel system will be melted out by a sinter furnace. The shape of the cooling system is produced according to numerical process simulation of thermal loads and mechanical stresses. To achieve high density and mechanical strength, the sintered forging die will be subsequently compacted in a HIP-process.

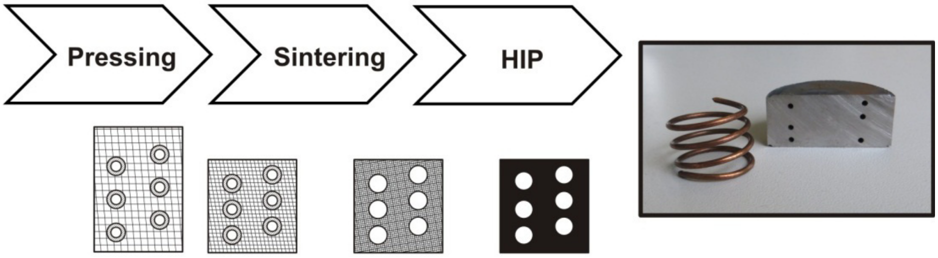


Fig. 3. Process-indicated diagram.

2.1. Materials

It is planned to manufacture the forging die from the hot-working steel DIN 1.2999 (X45MoCrV5-3-1). Table 1 shows the alloying elements and their content level for the material.

Table 1. Alloying elements of Thyrotherm 2999 EFS SUPRA.

	alloy content in mass.-%					
	C	Si	Mn	Cr	Mo	V
Thyrotherm 2999 EFS SUPRA	0.45	0.30	0.50	3.10	5.00	1.00

Besides its superb wear resistance, the chosen alloy has a high heat conductivity (35.2 W/(m•K) hardened), which is necessary for an effective heat dissipation combined with an internal cooling system [4]. In a first attempt the chosen alloy was water atomized by EPM Europowder Metallurgy. This production method delivers an irregular powder mould which increases the powder fixation during cold pressing. As opposed to this, spherically moulded gas - atomised powder of high alloyed tool steel is more difficult to compact to a green body [5]. For future investigations it is planned to examine gas - atomised powder, too. The particle size distribution of the used powder is located in the range of 50µm - 300µm. Due to the water-atomized production method the powder has a basic hardness of 720 HV 0.1 which causes that the powder isn't pressable. In Fig. 4 left, a martensitic structure can be recognized. After a subsequent heat treatment the powder was soft annealed in a vacuum sintering furnace (T = 800°C, t = 4.5 h), reflected by the fine grained structure and the decreased measured hardness of 230 HV 0.1 (Fig. 4 right). This conducted heat treatment led to pressable powder.

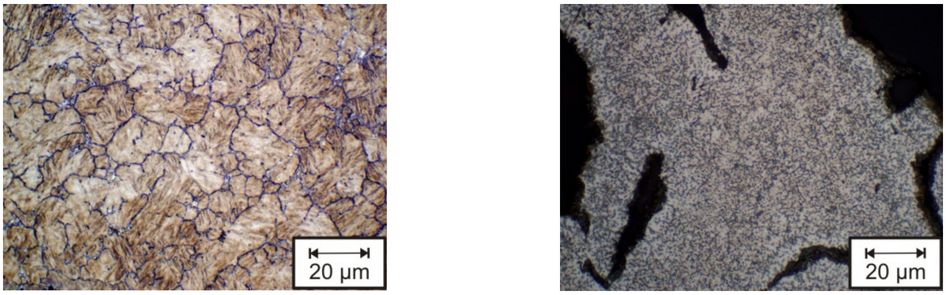


Fig. 4. Material structure of one powder particle of 1.2999 before (left) and after heat treatment (right).

The following integration of functional elements into the pressable powder requires a particular attention paid to the compaction process. 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. For the characterization of the compaction behavior of metallic powders within the scope of this project it is planned to carry out pressure strength tests and brazilian disc tests to characterize the powder by means of the Drucker Prager Cap Model [6].

2.2. Melting copper elements out of steel powder

During the sintering, copper liquefies and infiltrates the surrounding powder areas through capillary effects (cohesion and adhesion). 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. In case the solid element melts completely and infiltrates the surrounding areas, it leaves a cavity with the exact form of the primary element, see Fig. 5 [7].

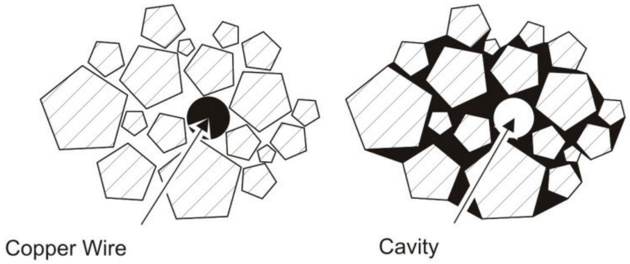


Fig. 5. Pore rearrangement by capillary penetration [7].

In preliminary investigations different elements (wire, cuboid) made of copper were molten out of steel powder. The fabricated samples are investigated in metallographic tests. A selection of micrographs is shown in Fig. 6. The figures indicate that the copper is thoroughly molten and has infiltrated the surrounding powder. The geometry of the cavity left by the molten element can be precisely controlled by a proper setting of the sintering temperature and duration.

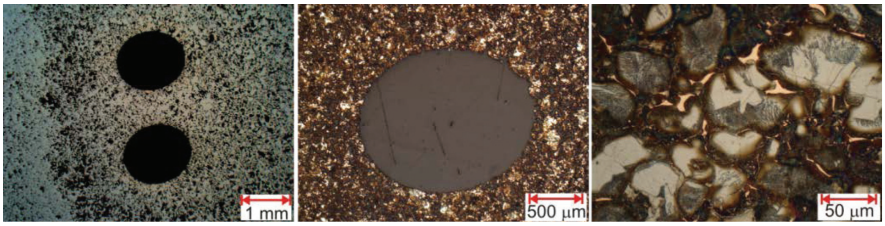


Fig. 6. Sintered part made of steel powder, infiltrated by an integrated copper element, left and middle, compound microstructure of steel and copper (right).

2.3. Design of cooling channels

Structured surface tubes offer an enhanced heat transfer to the cooling system (Fig. 7). Depending on the structure, a significantly higher thermo-conductivity can be achieved. Due to a strong vortex formation near the wall, a radial exchange process is strongly enhanced. However, at the same time the pressure loss increases significantly based on higher tube friction and turbulent flow within the structured channels [8].

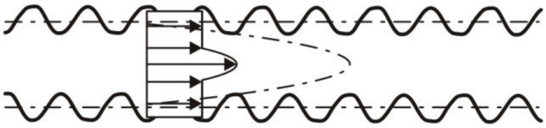


Fig. 7. Flow rates in dented tubes and in plain tubes (dashed line) [8].

Within this project, it is planned to compare differently designed channels as seen in Fig. 8 left. The structured channel can be made e.g. of a metric thread whereas the plain structure is represented by a slick tube wall or rod. In a first attempt it has been proven that even the structure of an embedded small metric copper thread (M2) can be molten out by a sintering process (Fig. 8 right).

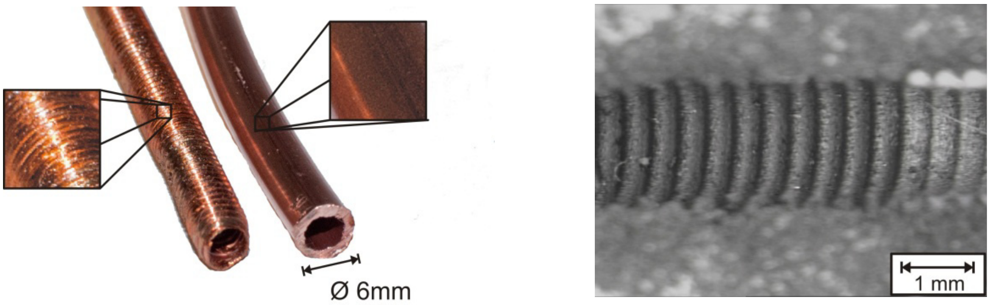


Fig. 8. Copper elements (left) and metric thread (M2) melted out in iron powder (right).

3. Numerical investigations

3.1. Numerical investigation of the forging die

To obtain knowledge about the material flow of the workpiece material, the temperatures in the surface layer of the forging dies, as well as a realistic tool analysis already in the concept phase of forging tools, computer-aided process design can be used. The nonlinear Finite Element (FE) Method has been established as a suitable calculation tool for process development and optimization [9, 10].

In order to indicate the optimal positions of cooling channels, as well as their dimensions, an FE based analysis of the temperature field at the end of a forging step is necessary. In the FE calculation the temperature increasing in the surface layer due to contact to the hot workpiece and as result of tribological load can be determined. The FE approach renders cost intensive experiments redundant. Another important point is the stress analysis of forging tools and especially the mechanical loads acting on the cooling channels. The goal is an estimation and assessment of the loads the tools are exposed to during the forming process. In order to determine the required process parameters such as temperature, stresses and strains of the tool, a thermo-mechanical tool analysis should be performed. In addition to the elastic material behavior this approach also takes into account the thermo-mechanical interactions between workpiece and tool. Thus, a realistic computation of the forging process is possible.

For the forging process, a stress analysis for forging tools is done. The FE model consists of upper die, lower die and billet. The lower die is modeled as rigid body. For the upper die an elasto-plastic material behavior and for the billet an elasto-viscoplastic material behavior is asigned. In a first approach the workpiece consists of the steel DIN 1.0503 (C45) and the tools are made of the hot work tool steel DIN 1.2343 (X37CrMoV 5-1). To achieve a good accuracy in the FE results the element size in the layer of the dies were set to 0.15 mm. The forging temperature of the raw part is 1.200 °C. As basic tool temperature, an operating temperature of 20°C is assumed. The heat transfer coefficient between billet and part is set to 50 W/m²K. For describing the friction the combined Coulomb-Tresca model is used. Based on ring compression tests the friction coefficient is set to 0.1 and the friction shear factor has been set to 0.3 [11]. For the modelling, the rotational symmetry is used. For purposes of clearer illustration, the model in Fig. 9 is expanded to 180°.

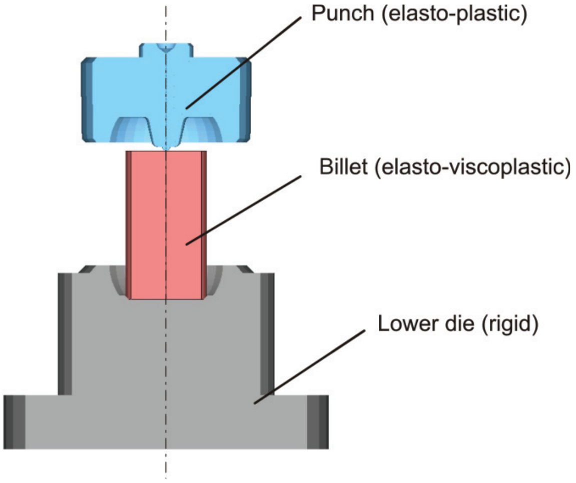


Fig. 9. Simulation model of forging process.

3.2. Calculated thermal and mechanical stresses of the forging tool

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 dies. For the tool design and the analysis of the mechanical loads, the mechanical properties have to be described as a function of temperature. In the following, the stress analysis for the upper die is carried out. Important process parameters for the assessment of the thermal and mechanical loads are the temperature distribution and the current state of stress. The plastic strain of the part is an important process variable to evaluate the formability. The plastic strain is in a middle range of 1.5 to 2. Only in the area of the mandrel a high plastic strain rate from 3 until 4.5 can be determined. The temperature distribution shows maximum values of about 670 °C at the upper mandrel of the die by the end of the forming process, see Fig. 10 right.

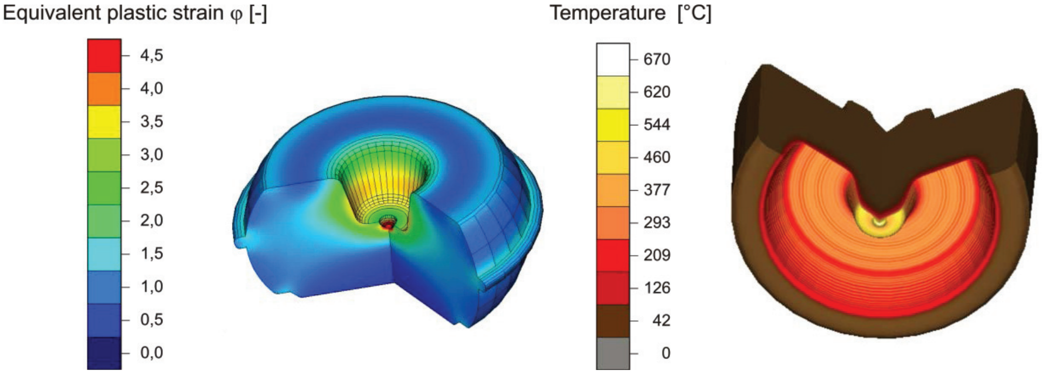
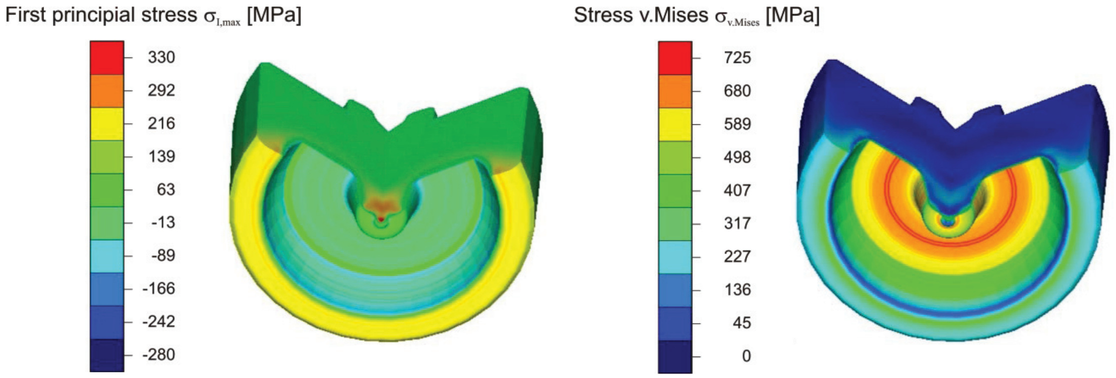


Fig. 10. Equivalent plastic strain of the part (left) and temperature distribution in the upper die (right).

For a comprehensive tool analysis of the mechanical loads the consideration of the von Mises stress $\sigma_{v.Mises}$ and the first principal stress $\sigma_{I,max}$ is of importance. The von Mises stress is independent of the direction and indicates the beginning of a plastification. If the calculated first principal stress in the tool reaches the ultimate tensile (normal) strength, tool failure is imminent. The first principal stress indicates the maximum tensile stress in the tool. Those tool regions exposed to high tensile stresses have a high risk of failure due to crack initiation. Fig. 11 reveals the highest tensile stress of 330 MPa, which is an indication that crack initiation does not develop.


First principial stress $\sigma_{I,max}$ [MPa]

Stress v.Mises $\sigma_{v.Mises}$ [MPa]

Fig. 11. Maximal principial stress (left) and von Mises stress in the Upper die (right).

In this example, the von Mises stress $\sigma_{v.Mises}$ has a local maximum value of 725 MPa. This stresses limited die areas at the upper mandrel and in the radius in transition to the plane surface in the die. The first principal stress $\sigma_{I,max}$ decreases to -280 MPa . The yield stress of the die material 1.2343 amount to 700 MPa at 600 °C [12]. This is below the maximum stress $\sigma_{v.Mises}$ and micro plastifications of the surface can be expected. The stresses in the other die areas are lower and plastifications will not occur. The critical stress value, the first principal stress $\sigma_{I,max}$ is below the mechanical limit. This shows that the geometrical dimensions of forging part and forming dies can be used without die failure.

4. Outlook

Based on numerical results an adapted cooling system will be developed. The results support the dimensioning of copper elements in terms of location, length and diameter. A further challenge is the production of defined cooling channels with various radii and their counteraction with the powder during pressing. Therefore the results of the planned simulation of the pressing process will deliver a reliable prediction. After manufacturing, the forging die will be installed in an automated mechanical power press and attached to a self-regulated cooling system.

5. Acknowledgement

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