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Numerical process design for the production of a hybrid die made of tool steel X38CrMoV5.3 and inconel 718

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Abstract. Dies used in hot forging are subjected to high cyclic thermo-mechanical loads, which lead to die failure. There are various options for increasing the service life of these dies, for example coatings or heat treatments. Another possibility is to adapt the choice of material, which is the focus of this work. For example, the nickel-based alloy Inconel has a higher strength at elevated temperatures compared to tool steel. However, Inconel is difficult to manufacture and has higher material costs. For this reason, a new process design for the production of a hybrid die consisting of Inconel 718 and tool steel X38CrMoV5.3 is presented within this work. To produce the hybrid dies, the two materials are first friction welded and then formed using hot forging. In addition to the numerical process design, experimental tests are also carried out to manufacture such hybrid dies. Furthermore, a numerical parameter study is done to determine the influence of the forging temperature, the forging speed and the initial Inconel thickness on the process parameters. It can be shown that the production of hybrid dies is possible by using the Tailored Forming process chain. The influencing factors investigated change the required press force and also the material distribution of the Inconel in the hybrid die produced. In the future, further experimental tests will be carried out to determine the service life of the hybrid dies.

Introduction

In hot forging, the dies are exposed to high thermal and mechanical cyclic loads. These can lead to failure, particular in the die surfaces [1]. Die failure causes high costs due to the replacement as well as production downtimes [2]. The total resulting costs depend not only on the failure of the die, but also on the logistics costs. Therefore, the aim should be to increase the service life, but not to generate higher logistics planning through complicated die production [3]. Various approaches exist to increase the die service life. On the one hand, the loads that occur can be reduced by improving the tribological conditions or adapting the die geometry [2]. On the other hand, the load resistance can be increased by surface modification [4] or choice of material [5].

A material with a high potential to increase the load resistance of forging dies is Inconel. Compared to tool steel, Inconel offers high mechanical properties, especially at elevated load temperatures. However, Inconel is more expensive than tool steel and difficult to manufacture [6]. Therefore, within this work a production process concept for the manufacturing of a hybrid forging die is presented and investigated. The hybrid die consists of the conventional tool steel X38CrMoV5.3 (AISI H10 / DIN: 1.2367) and the Inconel alloy 718 (EN NiCr19NbMo / 2.4668). Inconel is used for the near surface regions to increase the die life due to its high strength at elevated temperatures. The significantly less expensive tool steel is used in less critical areas as base material. To counteract the low machinability of Inconel, the hybrid dies are produced by means of die forging. According to the Tailored Forming concept [7], friction welding is used to join both materials before the forging process.

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Numerical simulation is used to design the manufacturing process for the hybrid dies. Due to the different material properties and the difficulty of reworking Inconel, it is essential to design the process close to the final geometry. In addition, it must be ensured that a sufficient Inconel layer is present locally in accordance with the expected loads. The usability of finite element (FE) simulation has already been demonstrated in the work of Bouguecha et al. [2] for the design of forging dies and Renhof [5] for the prediction of the material behaviour as well as for the dimensioning of hybrid forging processes by Behrens et al. [7].

The advantage of a hybrid material combination has been investigated by Landgrebe et al. [8]. Here, an Inconel layer was used to reduce the thermal and corrosive load as well as to improve frictional resistance on the component. The hybrid material combination was produced by selective laser melting (SLM) process. The potential of the process chain, consisting of joining the two materials and then combined forging, has already been partially investigated. For example, the process chain for the production of hybrid shafts [7] or bearing bushings [9] was analysed. In these investigations, the focus was on the material combination of steel and aluminium as well as on the production of hybrid components. The production of dies for application in hot forging processes using a forming process was investigated in the work of Behrens et al. [10]. However, only the use of mono-material was considered. The forming process results in a higher surface hardness compared to a conventionally manufactured die.

The general feasibility of the combined forging of pre-joined semi-finished workpiece made of tool steel and Inconel has already been demonstrated in initial numerical and experimental investigations for a simplified geometry [11]. However, the production of a specific die shape has not yet been analysed.

This paper focuses on the numerical design and analysis of a production process for a hybrid die using a mandrel. In particular, the material flow of the Inconel layer must be analysed in order to ensure a suitable distribution of Inconel in the final component. In this context, the differing deformation behaviour of the used tool steel and Inconel as well as the die geometry influences the final material distribution of the hybrid die. Furthermore, the higher strength of Inconel even at elevated temperatures leads to higher die loads, which also needs to be taken into account during process design. The numerical model was validated by experimental forging tests and subsequently used for a numerical parameter study. Within the numerical study, the influence of the initial Inconel layer thickness as well as process parameters like press speed or temperature on the final material distribution and the required process force were analysed. Based on the results a possible process parameter setup was defined. The focus was on realising the lowest possible Inconel thickness in order to keep the material costs as low as possible.

Procedure

This work focuses on the process design and analysis for the production of a hybrid mandrel die geometry. The hybrid dies are to be made of tool steel X38CrMoV5.3 and Inconel 718, whereby the Inconel is to cover the zone most affected by the temperature and thus reduce the loads on the softer tool steel. For an efficient process design FE simulation using Simufact Forming v16.0 is used.

Definition of required Inconel thickness. In order to determine the required Inconel thickness, an FE simulation of the forging process was carried out with the chosen die geometry consisting of the mono-material X38CrMoV5.3. An overview over the used numerical process model as well as the considered process conditions can be found in [12]. The material model used was taken from the work of [11]. Based on the calculated local temperature distribution in the near surface regions the Inconel layer thickness is defined.

Numerical setup and parameter study. Fig. 1b shows a schematic representation of the simulation model of the forging process for manufacturing the hybrid die. The punch, ejector, reinforcement ring and shoulder insert consist of X37CrMoV5.1. The dies are not heated during the forging process, therefore an initial die temperature of 20 °C was assumed for the simulation. Ejector and punch are modelled as rigid bodies with heat conduction. The highly stressed sections of the mould, the shoulder insert and the reinforcement ring were modelled as deformable parts. The hybrid semi-finished workpiece consisting of the tool steel X38CrMoV5.3 and the Inconel 718 was simulated with a tie contact in order to depict the material bonded connection produced by means of friction welding. Material data like temperature and strain rate dependent flow curves for both materials were experimental determined in previous work of the authors [11]. Before the simulation of the forging process, the hybrid semi-finished product was heated up and a subsequent cooling simulation with a duration of 20 s was carried out. It was heated up to the temperature corresponding to the subsequent furnace temperature. The individual simulations are used to reproduce the experimental process conditions, whereby a cooling time equal to the transfer time from the furnace to the press was selected. In all simulations (explicit time integration), the dies were meshed with "Quadtree" elements and the semi-finished product with "Advancing Front Quad" elements.

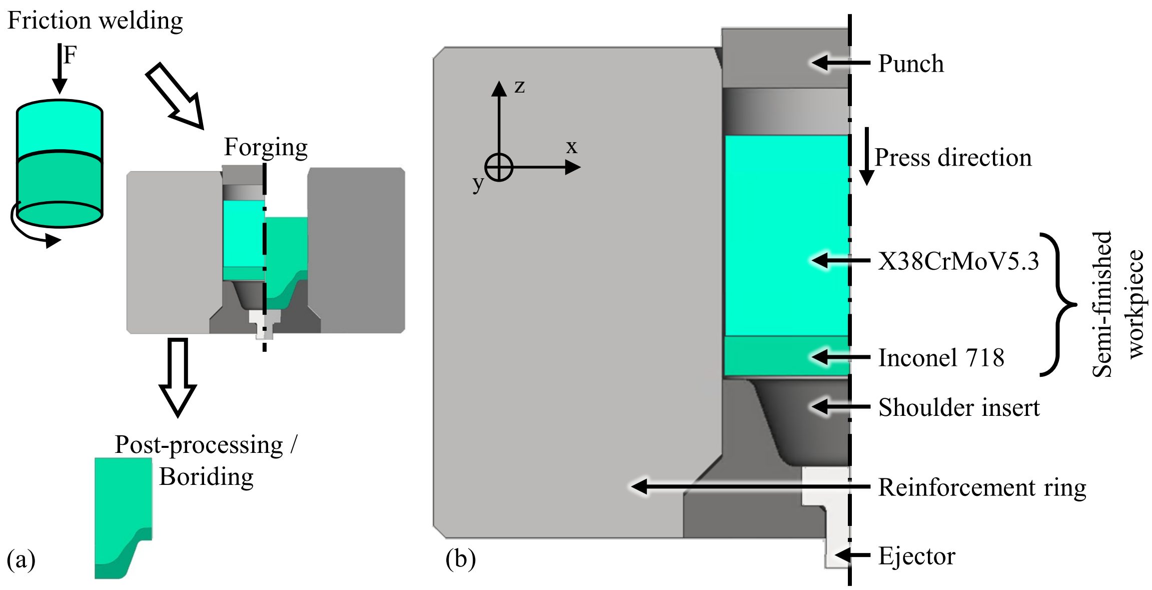


Fig. 1. (a) Schematic sequence of the process chain for producing a hybrid die and (b) Simulation model.

A combined friction model of Coulomb and Tresca was selected with a friction coefficient μ of 0.15 and a friction factor m of 0.3, which was defined in accordance with [2]. With these friction parameters, very good agreement between simulation and experiment was achieved in this project as well as in other projects. The heat transfer coefficient between Inconel and tool steel was set to 5 W/(m^{2}K) based on data from literature [13]. In order to take into account the different changes in length of the two materials both during the heating of the hybrid semi-finished workpiece and the subsequent hot forging the coefficient of thermal expansion was determined on the basis of literature values. For Inconel, a value averaged between the work of Agazhanov et al. [14] and Dye et al. [15] was defined. For tool steel X38CrMoV5.3 the value of [16] was used. Punch movement is modelled using a hydraulic press with a constant press speed, which will also be used for the experimental forging tests. As part of the full factorial parameter study, the press speed (5 / 10 / 15 mm/s) and the Inconel thickness (3 / 5 / 7 mm) were varied. The height of the tool steel is adjusted so that the overall height of the hybrid semi-finished workpiece remains constant at

33 mm. Furthermore, the selected furnace temperature (900 / 1,000 / 1,100 °C) was varied as part of the parameter study.

Experimental setup. Based on the numerical results experimental forging tests for the production of a hybrid die was carried out using friction-welded hybrid semi-finished workpieces. A schematic process chain for the manufacture of a hybrid die is shown in Fig. 1a. The pre-joined hybrid semi-finished workpiece consist of an Inconel layer with an initial thickness of 5 mm whereby the initial height of the tool steel was 28 mm. The hybrid semi-finished workpiece was preheated to a temperature of 1,000 °C within a furnace. Heating time was set to 15 min with a 5 min hold time to ensure homogenous temperature distribution. The transfer time between the furnace and the press was measured to 20 s. Tests were carried out on a hydraulic press and a constant press speed of 10 mm/s was set. After successful forging of the hybrid semi-finished workpiece, the hybrid die was measured optically. The optical measurement was converted into a digital model of the produced hybrid die and compared to the calculated geometry. For later use as a die in hot forging, the surface still needs to be reworked. The post-processing is based on the work of [17].

Results

The results are differentiated between the verification of the simulation results based on experimental data and the parameter study. Firstly, the comparison between simulation and experiment is discussed in more detail. After successful verification of the simulation model, the results from the parameter study are presented.

Minimum Inconel layer thickness. The numerical calculated temperature distribution shown in Fig. 2a indicates that the highest thermal loads occur at the mandrel. With increasing radius to the die centre, the temperatures near the surface decrease. In the centre of the mandrel, an increased temperature can be observed to a depth of 2.4 mm. Near the mandrel radius a temperature influence zone of up to 2.2 mm from the surface was determined. However, these region shows the highest temperature of up to 573 °C. Based on these findings, the final Inconel layer should have a thickness of at least 2.4 mm in the area of the highest thermal load after hybrid forging. At the same time, an Inconel layer is not required everywhere on the die surface. As a result, a separated die concept was developed (Fig. 2b). The hybrid die will consist of a conventional outer section and an inner hybrid section, whereby the inner hybrid mandrel is fixed (shrink fit and press-fit connection) in the conventional section. This will simplify the production of the hybrid inserts and any possible removal of the highly loaded mandrel can take place separately in the subsequent use. In addition, a material-efficient realisation can be carried out in the die.

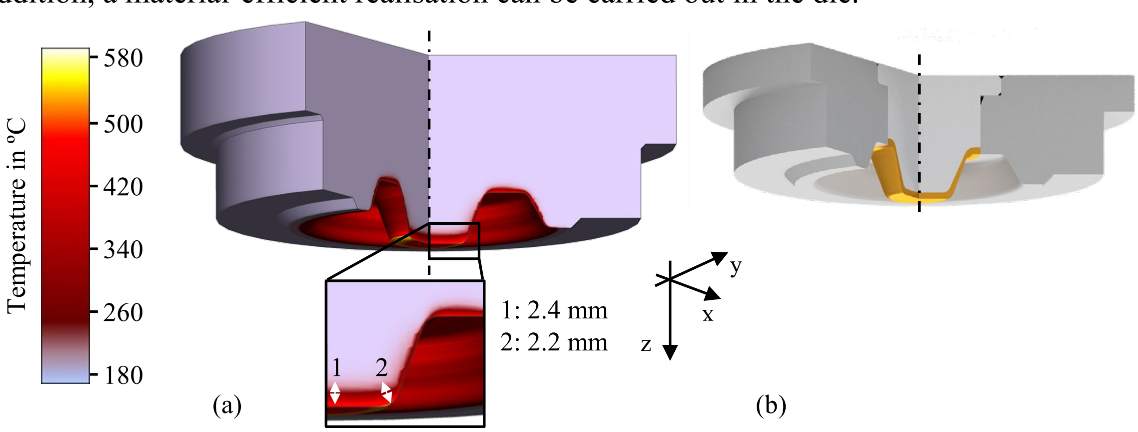


Fig. 2. Result of the temperature analysis of the mono-material die (a) and schematic illustration of the proposed hybrid die concept (b).

Numerical process design and validation. Using the described FE model, the process was numerical depicted. Initially, an Inconel layer thickness of 5 mm was considered. The temperature of the hybrid semi-finished workpiece was set to 1,000 °C and a press speed of 10 mm/s was assumed. The result of the simulation at 100 % forging with the punch released is shown in Fig. 3a. A complete filling of the die can be recognised. The Inconel shows the highest value of plastic strain of the hybrid semi-finished workpiece located in the upper area, where it is deformed by the shoulder insert. This plastic strain is evenly distributed in the tool steel at the point mentioned above. Within the tool steel, the plastic strain is rather low.

The load on the dies during the forging process is shown in Fig. 3b. It can be seen that the shoulder insert is subjected to the highest load. The maximum value of the equivalent stress v. Mises is almost 3,000 MPa. These values can be observed primarily in the upper radius, where the highest value of plastic strain of Inconel is located, and in the lower radius of the shoulder insert. The reinforcement ring shows equivalent stress values of 2,000-2,100 MPa. These are in the area where the hybrid semi-finished workpiece has contact and is upset. The numerical results show that the production of hybrid dies is possible using this set of parameters. These determined stress values are above the mechanical properties like yield strength of the material selected for the component [18]. This local exceeding of the yield strength can lead to plastic deformation of the die. As the hot forging process is intended to produce dies for later use in hot forging and as little material as possible should be used, it is necessary to produce the mandrels close to the final contour during forging. To ensure this, it is necessary to estimate the probability of plastic deformation in the die. For this reason, the equivalent stresses are analysed in this context. Due to the arrangement of a reinforcement ring around the shoulder insert, the material can be prevented from plastic deformation. Nevertheless, the aim of this process should be to minimise the load on the die sections.

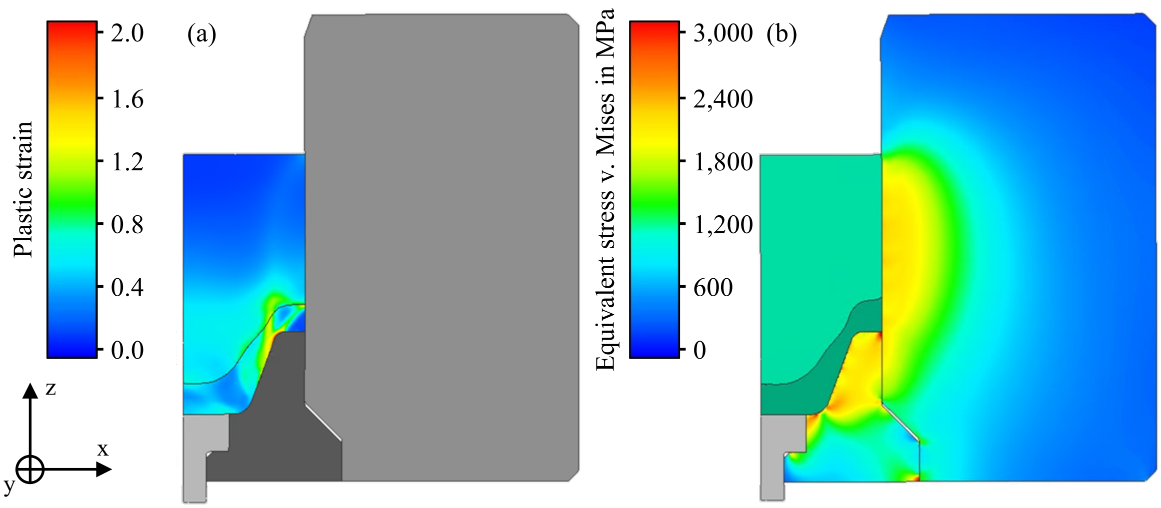


Fig. 3. Result of the numerical process design (a) and the die load at 5 mm Inconel thickness, 10 mm/s press speed and 1,000 °C furnace temperature (b).

Subsequently, experimental forging tests were performed. During the tests a maximum press force of 1,960-2,000 kN was reached. A nearly similar maximum force of 2,050 kN was calculated by numerical simulation. Overall, the experimental and numerical force-displacement curves show good agreement (Fig. 4a). The characteristic ranges and the maximum force are correctly depicted in the simulation. Deviations in the force curve at high stroke values can be attributed to elastic deflection of the press system in reality. Further, a geometric verification was carried out. For this purpose, the experimentally produced die was optically measured and a surface file was exported. A comparison between experimental measured and numerical calculated die geometry is shown in

Fig. 4b. Overall, there is a good agreement and only a small deviation of a maximum of 0.06 mm can be seen, which is particularly noticeable in the outer lower circumference (red region). Due to the good agreement between experiment and simulation, the FE model can be considered as validated.

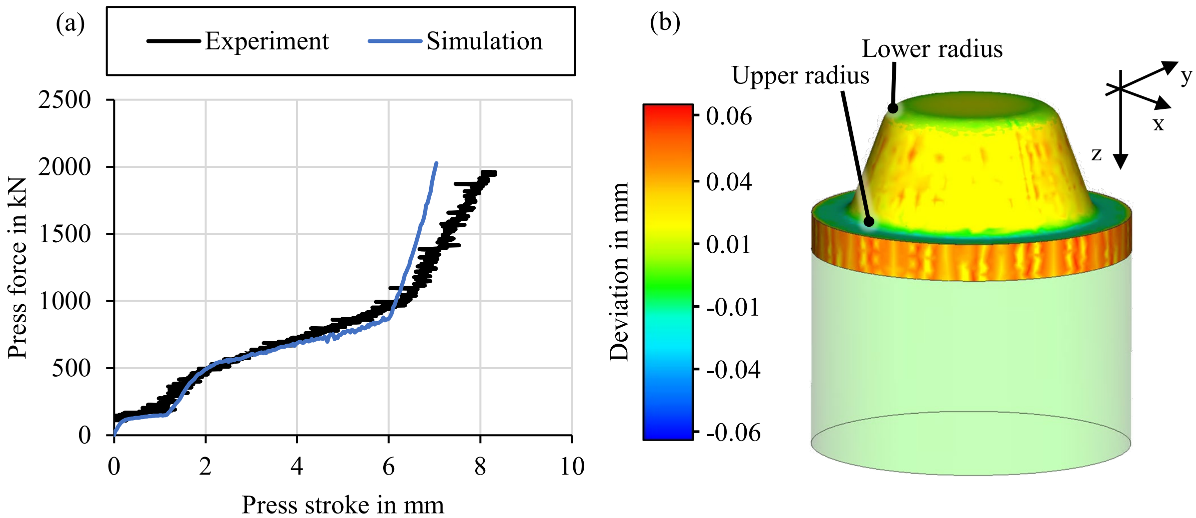
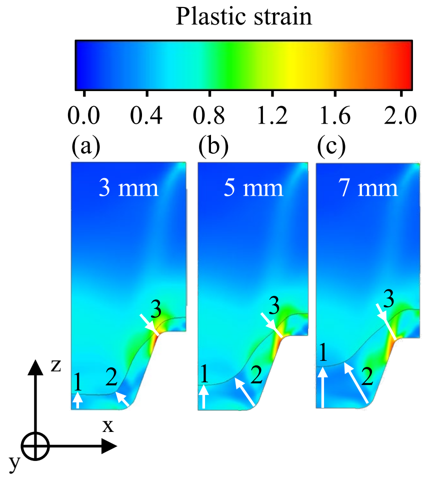


Fig. 4. Comparison between experimental and numerical force-displacement curves (a) and geometric comparison (b) (10 mm/s; 1,000 °C).

Numerical parameter study. Using the validated FE model, the influence of various process parameters was analysed. As shown in Fig. 5, at a press speed of 10 mm/s and a furnace temperature of 1,000 °C, the final Inconel distribution was significantly influenced by the choice of the initial Inconel layer thickness. With an initial Inconel thickness of 3 mm (Fig. 5a), the percentage deviations from the initial thickness are the highest compared to the other initial thicknesses, but the lowest upsetting to 3.2 mm (+6.7 %) of the Inconel can be observed in the lower radius (2). The strongest thinning to 0.6 mm (-80 %) can be observed in the area of the upper radius (3) and an initial thinning can already be recognised before complete forging. The highest value of plastic strain is also present at this point, which also extends into the tool steel at this initial layer thickness. Such a high value is not found in the tool steel for the other Inconel thicknesses. In contrast, the other Inconel thicknesses have a concentration of the higher plastic strain values on the Inconel layer, which is why the tool steel shows lower values. At the Inconel initial thickness of 5 mm (Fig. 5b), a kind of accumulation of the Inconel can be observed in the lower radius (2), resulting in an increase in Inconel up to a thickness of 5.6 mm (+12 %). In the area of the upper radius, a thinning to 1.6 mm (-68 %) can be seen (3). The accumulation of the Inconel in the lower radius (2) is even more clearly recognisable with an Inconel initial thickness of 7 mm (Fig. 5c). Here, the Inconel increases to a thickness of 8.3 mm (+18 %). During the forging process, it can be recognised that the Inconel is pushed towards the centre. For this reason, the smallest reduction to only 6.9 mm (-2 %) was calculated for this variant in the centre of the mandrel (1) at the end of the forging process. Comparison of relative changes show that an increase of the initial Inconel layer thickness leads to a stronger accumulation of Inconel in the lower region (2) and less reduction in the centre of the mandrel (1) and upper radius (3). Overall, the minimum Inconel thickness of 2.4 mm can be realised with each parameter variation investigated. With the lowest Inconel thickness, however, it is necessary to check how much material is lost through post-processing. From an ecological and cost point of view, the variant with the greatest Inconel thickness should not be favoured.



(d)

Initial Inconel layer thickness in mm		3	5	7
Position 1	Final thickness in mm	2.4	4.1	6.9
	Rel. change in %	-20	-18	-2
Position 2	Final thickness in mm	3.2	5.6	8.3
	Rel. change in %	+6.7	+12	+18
Position 3	Final thickness in mm	0.6	1.6	2.9
	Rel. change in %	-80	-68	-59

Fig. 5. Final material distribution of Inconel and tool steel for an initial layer thickness of 3 mm (a), 5 mm (b) and 7 mm (c) as well as comparison between specific regions regarding final thickness and relative change of thickness for the Inconel layer (d) (10 mm/s; 1,000 °C).

Fig. 6 shows the dependence of the required press force on the press speed and the selected furnace temperature for an initial Inconel layer thickness of 5 mm. As expected, the force requirement is strongly temperature-dependent and decreases with increasing semi-finished workpiece temperature. For the press speed, there is a slight increase in the press force with increasing speed, which can be attributed to the strain rate dependency of Inconel in particular. An increase in the press force with increasing layer thickness was observed for the variation of the layer thickness, as expected. Ultimately, all variants can be implemented with regard to the required press force. However, it should be noted that, on the one hand, the deformation capacity of the Inconel is reduced with decreasing temperature and, on the other hand, that the die load increases. Accordingly, the highest possible temperatures should be aimed for during forging. Also, from an economic point of view, only as much Inconel as necessary should be used.

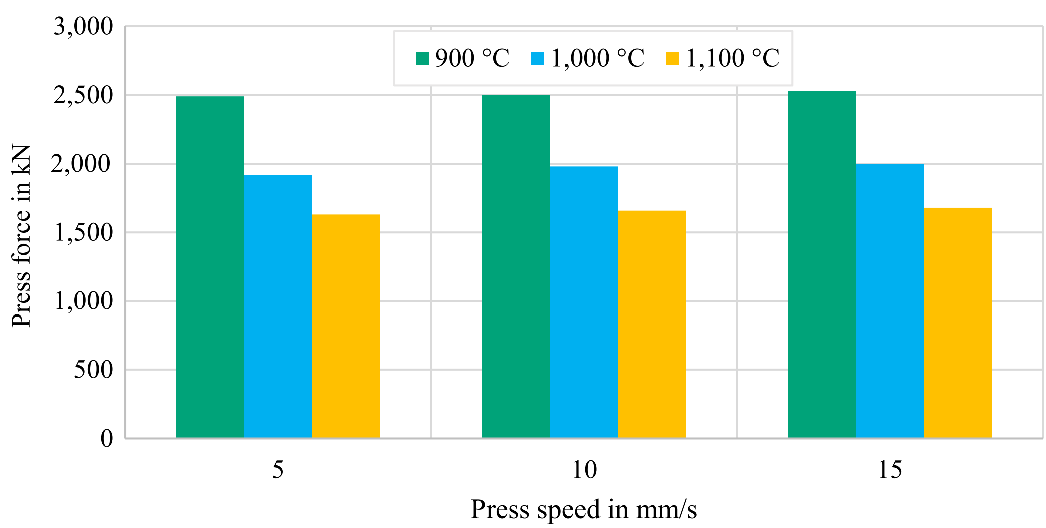


Fig. 6. Results from the full factorial parameter study: The influence of temperature and press speed on the press force with an initial Inconel thickness of 5 mm.

Conclusion

In this work, the numerical process design for the production of hybrid dies was presented. The focus was on the final Inconel distribution to ensure sufficient protection for the thermal high loaded near surface die areas. First, the thermal load on the die was analysed using numerical simulation in order to define a minimum layer thickness for the Inconel. The temperature distribution indicates that the die requires a coating thickness of at least approx. 2.4 mm to 3.0 mm. Subsequently the hybrid forging process was designed by FE-simulation. The simulation showed that equivalent stresses are above the mechanical properties like yield strength of the material selected for the component. By placing a reinforcement ring around the shoulder insert, plastic deformation of the material can be prevented. A reduction in the load can be achieved, for example, by reducing the thickness of the Inconel. Experimental tests were carried out and the FE model was validated by comparing experiment and simulation. Finally, the required Inconel distribution in the hybrid die was successfully achieved by adjusting the Inconel layer thickness.

After successful validation of the FE model, a numerical parameter study was performed on the influence of the forging temperature, the initial Inconel thickness and the selected press speed on the resulting material distribution as well as the required press force. The initial layer thickness influences clearly the final Inconel distribution. The layer thickness distribution is only influenced by the initial layer thickness and not by the investigated process parameters temperature as well as press speed. In order to achieve the minimum required Inconel thickness of 2.4 mm in thermally highly stressed area, an initial thickness of 3 mm is required. As the formed hybrid die must then be reworked, the Inconel thickness at the end of the forging process should be greater than 2.4 mm. Accordingly, a slightly greater initial Inconel thickness should be selected. An initial Inconel thickness of 7 mm leads to a layer distribution that fits the requirements. However, this results in higher die loads and also from an economic point of view, this initial Inconel thickness should not be selected. Overall, the initial thickness of 5 mm can therefore be recommended for the process. As expected, a reduced temperature leads to an increase in press force. Furthermore, required press force can be reduced by low press speeds. The conclusion for the tests was that a furnace temperature of 1,000 °C or 1,100 °C should be aimed for. At the same time, a medium to slow press speed should be aimed for during forging the hybrid semi-finished workpiece.

In the future, the experimentally produced dies should be tested in forging tests regarding their lifetime potential. The die life analysis in series forging tests should determine whether the hybrid dies have a longer service life than conventional dies due to the adapted material distribution. Fatigue phenomena such as crack formation or abrasive wear play a particularly important role here. On the basis of these further findings, the conclusion can be drawn as to whether the higher die manufacturing costs due to the more complex manufacturing process and the higher material can be compensated by a longer service life of the dies. In addition, further simulations and tests should be carried out regarding the transfer to larger cross-sections. Further investigations may include local tensile tests on hybrid friction-welded specimens to determine the properties of the joining zone and a cooling simulation with analysis of the stress relaxation in the hybrid forging die. In the cooling simulations, the influence of the different thermal expansion coefficients on the stresses in the joining zone is of interest.

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