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ORIGINAL PAPER

Application of design of experiments to forging simulations to increase die life expectancy

Alessandro Alessio[1] · Dario Antonelli[1] · Roberto Doglione[2] · Gianfranco Genta[1]

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Abstract

Wear and fracture of steel dies employed in hot forging were evaluated through metallographic study with the aim of qualifying a Finite Element Simulation of the productive process. Apart from providing useful insights into the causes of die damaging, the simulation was exploited in a Design of Experiments to prevent fracture and to counter different mechanisms of wear. The objective is the optimization of die life acting only on process parameters that are directly adjustable in the actual industrial process. In the examination of stress distribution on the dies and the estimation of die wear, the complete forging cycle has been taken into consideration. Despite the considerable variability of the process, the study demonstrates that it is possible to prevent fracture insurgence and to increase the life expectancy of the die by a careful tuning of standard process parameters. Possible stakeholders of the study are not only process designers but also production managers, as most process parameters are modifiable during production.

Keywords Finite element method (FEM) · Forging · Design of experiments (DoE) · Wear

1 Introduction

Hot forging processes have a wide range of assets when employed in industrial mass production: high productivity, low costs, fairly good consistency with final shape. Forging techniques are consolidated by now and new innovations in the field mostly aim at optimising the process to further reduce costs. To achieve this goal, multiple challenges are faced. Optimisation can involve the forged part [1] (limiting the billet volume to the necessary amount to assure die filling avoiding wastes), the process [2–6] (limiting energy consumption and reducing lead times) and the tools [7] (reducing stresses and die wear). Dies in hot forging are likely the most expensive cost item, so efforts should be made to extend their working life to the maximum. However, prolonging their service life requires an analytical knowledge of their wear patterns, which depend on many factors, some of them not measured / measurable during ordinary production; therefore, research is still open and there is no universal predictive model of die life, as will be discussed in Sect. 2. If the goal is optimization of die life regardless of the estimate of its exact value, one can settle with less accurate information. Finite element analysis (FEA) proved to be a useful support to this aim: it allows to obtain reliable mathematical models that simplify the choice of the optimal process parameters, highlights the critical aspects of the process and allows to remedy them. In this study, a simulated Design of Experiments (DoE) was performed to determine the effect of process parameters on die wear and to estimate the amount of stresses developed in 32CrMoV12 steel die. Given the very high number of factors influencing the process and the high variability of some of them along all the working cycles, it was decided to focus on a robust method for the maximisation of die life rather than pursueing the exact prediction of its value. The analysis conducted was validated by metallurgical and topological tests on a worn die obtained from production.

✉ Dario Antonelli
dario.antonelli@polito.it

Alessandro Alessio
alessandro.alessio@polito.it

Roberto Doglione
roberto.doglione@polito.it

Gianfranco Genta
gianfranco.genta@polito.it

1 Department of Management and Production Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

2 INSTM, Via Giuseppe Giusti 9, 50121 Firenze, Italy

2 Models of die wear

Each forging process is in its own way unique and may show different damage mechanisms. The majority of die failures are attributed to abrasive wear [8–12] and only marginally to plastic deformation, thermomechanical fatigue cracks or fracture initiation caused by incorrect thermochemical treatments. Kim et al. [13] developed a method for estimating die life based on the most commonly encountered phenomena, i.e. wear and plastic deformation, the latter being aggravated by a strength reduction caused by high temperature. However, experimental evidence divided the opinion of researchers on this issue. Kchaou et al. [14] state that, given the wide variety of cases, different phenomena can be detected as the most severe. It depends on the situation and the geometry of the die has a considerable influence on the type of damage [15]: the lateral surfaces of the die are subject to fatigue damage; with respect to the direction of deformation, both normal and tangential surfaces are affected by mechanical fatigue and wear, but the latter are more prone to deep cracks. Kchaou's results are also supported by those of Behrens and Schaefer [16], who determined a predictive model for the life of a die that depends on its hardness and geometry, and demonstrates the strong dependence of wear on contact conditions. A similar study, with a focus on the dependence of wear on geometric parameters, was also conducted by Davoudi et al. [17] who revealed that increasing the surface angle not only does not improve the wear life of the die but also makes the wear deeper due to more severe conditions with high pressure and temperature. The studies carried out by Gronostajski et al. [10,18] raise strong doubts on whether dies deteriorate due to a single predominant effect; on the contrary, they state that more phenomena occur simultaneously during the process and that they interact with each other creating a chain action that complicates the identification of a wear model. In order to decouple the phenomena and to study them individually, M. Hawryluk et al. [11] purposely built a test station; they assessed that thermomechanical fatigue and oxidation often appear concurrently and act synergically leading to abrasive wear, which is the most easily measurable phenomenon. In order to simplify the problem, one could therefore narrow down the field to the most significant factors [19]. It is also helpful to assess the role of process temperature, which can influence a number of factors: a deviation in the initial temperature of the billet can lead to greater wear due to abrasion or plastic deformation and a hotter surface favours a reduction in the hardness of the die [20,21]. Tanaka et al. [22] derived a correlation model of die temperature and wear by means of a cooling model that considers the Reynolds number of the lubricant jets. It is the lubricant itself, with its application time and temperature, that plays a key role in promoting the formation of a homogeneous and effective layer that can reduce the risk of heat cracking and surface softening [23]. Safeguarding the microstructure and surface integrity is therefore extremely important for prolonging the life of the die. To this end, besides the classical nitriding treatment, special coatings and die processing techniques are being investigated [24]. For example, Behrens et al. [25] added a layer of nano-sized ceramic particles to a fine-grained microstructure to increase strength, ductility, fatigue and wear resistance without affecting surface friction. Gronostajski et al. [12,15] also tested different types of surface coatings in order to assess, also with the use of 3D scanner and hardness tests, which of them showed the best behaviour against damage mechanisms. Moreover, in relation to the surface integrity of the die and the degradation of the coating layer due to advancing wear, Behrens et al. [26] developed a method for calculating the die life as a function of the surface hardness of the die. Among the die production methods, EDM has proved to be the most valid for the surface resistance results obtained: thanks to the martensitic microstructure reinforced with extremely hard iron carbides and the lower presence of surface defects compared to cutting processes, it offers excellent resistance to wear; failure, in this case, is due to the underlying layer that softens with repeated high-temperature cycles [27]. In the first phase of use of the die, therefore, it can be assumed that the weakening effect due to thermal cycles is secondary to wear (the latter acts immediately while several cycles are needed before the microstructure is significantly altered). This behaviour motivated the study by Kim and Choi [28], which consists of determining a wear model by quantifying the volume of material removed from the test profiles and comparing it with numerical simulations (as in Andersson et al. [29]) and supporting it with fatigue stress analysis. The state of the art shows that it is possible to model die wear, but it is very difficult to consider the interrelations of the multiple damage phenomena involved (wear, plasticity, fatigue, fracture) and also of the many process parameters, which vary from one study to another and are difficult to compare. As the final objective of process designers is not the individuation of correlations among parameters but the optimization of die life, present paper proposes a numerical approach, corroborated by experimental evidence from an actual industrial processes, which take into account the only parameters that can be modified by the designer. Present method substitute the prediction of damage on the die with a sensitivity analysis that allows to search for an optimal configuration of process parameters that lead to the maximization of die life giving up knowing its exact value.

3 Identification of damage mechanisms on the die

The analysis of the durability model was carried out on a die (the lower part) used for the two-steps forging of a large axle nut, shown in Fig. 1 together which its finishing die. The particular shape of the part, and the forging problems arising from it, condition the die's structure that is composed by two elements: an outer ring and an interference fitted central pin. The analysis of wear and stress was carried out over a period of approximately 7500 working cycles, ended because of the premature discard of the die caused by fracture. The FEM analysis made it possible to obtain the specific wear model of the die over this period and, as proof of the validity of the extrapolated results, the simulated failure of the die at the same point where the real die breaks. This failure did not allow the campaign of experiments to be extended over a longer period as the resulting defect did not allow to meet design requirements. Given that the usual lifespan of hot forging dies is up to 20,000 cycles, the limited lifespan of this case study prompts an investigation of the causes, to solve them and to find the optimum combination of process parameters to extend lifespan beyond 7500 cycles.

3.1 Fracture analysis

The study starts from the investigation of the causes for the fracture, in order to identify an adequate correction. The damaged section of the die, highlited in Fig. 2, was subjected to fractographic and metallographic analysis.

Primary and secondary cracks were discovered using a scanning electron microscope (SEM) (Fig. 3): the former start under the surface and propagate parallel to it creating spalling (Fig. 3b) and delamination (Fig. 3c), the latter propagate perpendicularly to the surface along grain boundaries (Fig. 3f). Fig. 3d shows an example of initiation of damage. Primary and secondary cracks are commonly found in close proximity due to damage propagation, as can be seen in the overview in Fig. 3a and e. Thermal treatment was ruled out as a cause of fracture by metallographic analysis. They also revealed (Fig. 3i) a thin nitrided layer that had not been totally worn away during use. The shrink-fitted parts constituting the die are subjected to elastic subsidence under the repeated action of intense stresses. In FEM simulations, the amount of elastic deformation is equal to a 0.3 millimetres step between the pin and the ring (Fig. 4).

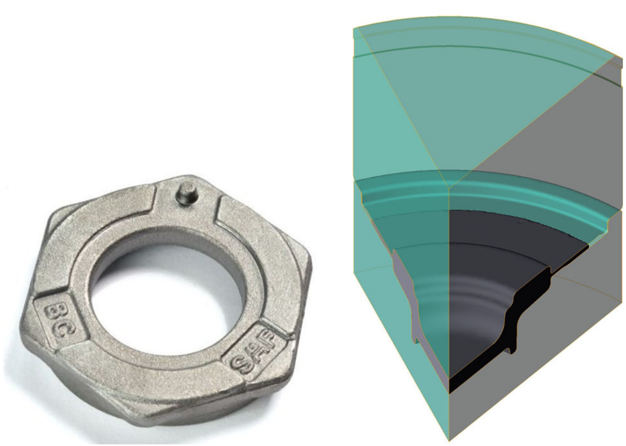


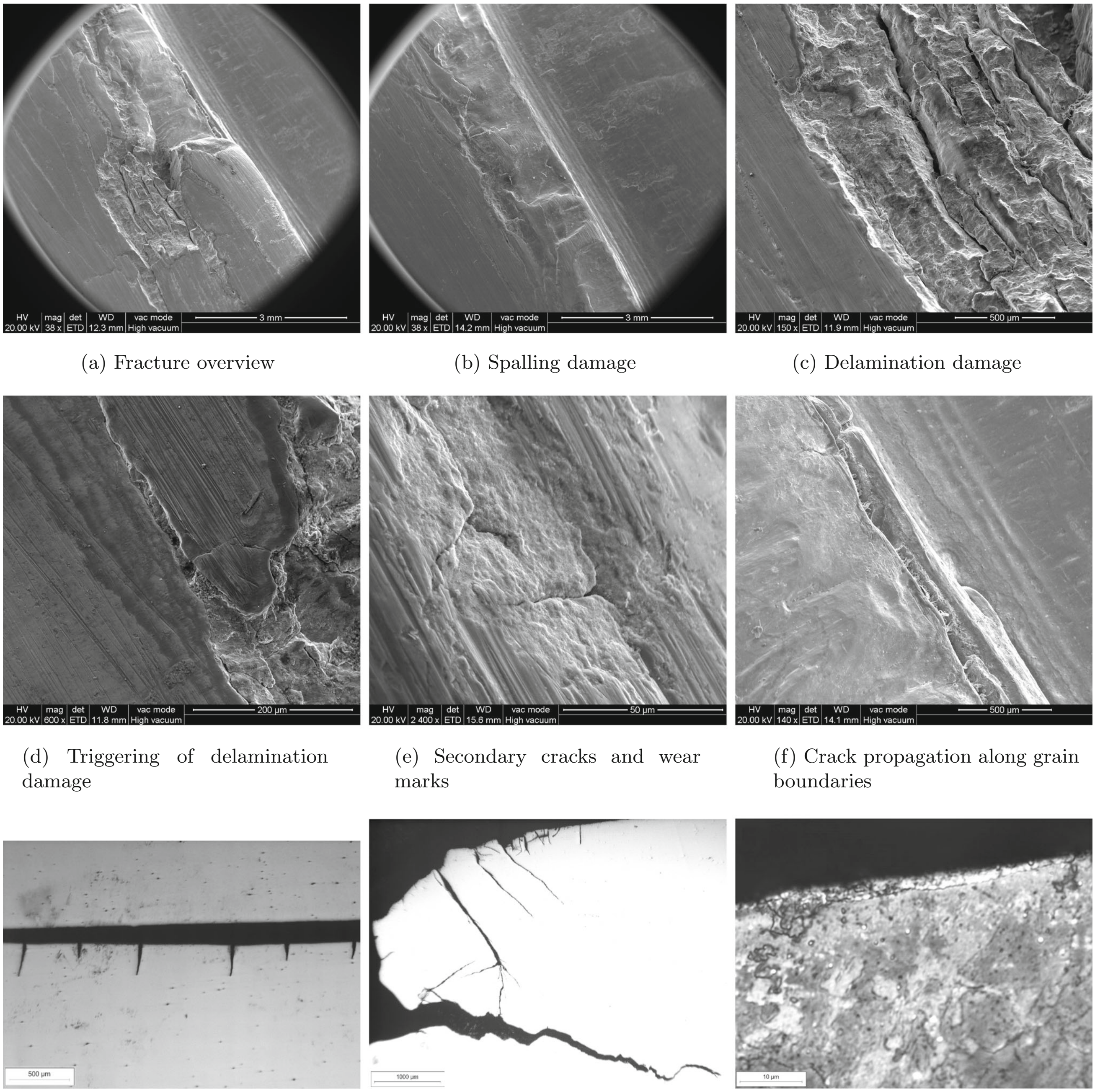
Fig. 1 Forged part and finishing impression

Fig. 2 The damaged section of the die

This causes a significant stress intensification at the edge of the ring, which is both the source of the main fracture and the cause of a forged part defect that prevents an extended use of the die (Fig. 5).

Moreover, long fractures (Fig. 3h) start at the junction of the hexagonal cavity of the lower ring, according to the metallographic cross-sections (Fig. 2, inset). This shows that large loads are applied which exceed the structural capabilities of the material. Excessive stress along the longitudinal direction of the die generates a sequence of periodic fractures, consistent with metallography performed on vertical surfaces in a plane of radial and longitudinal coordinates (Fig. 3g). In addition, the spalling phenomenon was observed (Fig. 3b), which indicates high shear forces [31].The die surface was originally nitrided with an approximately 300 μm thick layer. As a result of the forging cycles, in the most critical areas of the die, a considerable reduction of this layer was observed. The following phenomena resulted from abnormal operating conditions:

- The elastic subsidence of die components;
- Axial stress beyond the material limit;
- Cracks;
- Spalling.



(a) Fracture overview

(b) Spalling damage

(c) Delamination damage

(d) Triggering of delamination damage

(e) Secondary cracks and wear marks

(f) Crack propagation along grain boundaries

(g) Periodic fractures on vertical surfaces

(h) Long cracks running deep into the die due to heavy loads

(i) Residual nitrided layer

Fig. 3 Crack analysis using SEM

3.2 Wear analysis

A 3D scanner was used to measure the worn die profile, which was then compared to the nominal CAD model (Fig. 6). It has been proven that this method brings excellent results in the comparison of geometry with considerable advantages over other traditional methods [32].

The wear-to-cycle ratio for each point was computed assuming that the amount of material worn in each cycle was the same. The well-known Archard model for wear prediction was implemented in this study (Eq. (1)). In particular, it allows the use of accurate information provided by FEM simulations concerning local stresses at the interface between the die and the workpiece [29]:

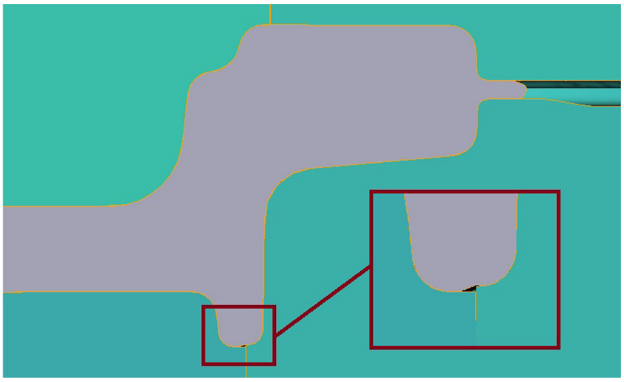


Fig. 4 Elastic subsidence of the die in simulated process

Fig. 5 Effects of elastic subsidence of the die on the forged part

$$W_\tau = K_\tau \int_0^t \frac{\tau v_\tau}{\bar{\sigma}} dt. \quad (1)$$

where W_τ is the wear due to shear stress, τ is the shear stress at the contact point, K_τ is an empirical coefficient, v_τ is the tangential velocity at the interface between the die and the part, $\bar{\sigma}$ is the yield strength of the die material, and t is the contact time between the die and the part. The points of industrial importance include those where the die cracks or the die wear is excessive compared to the specifications of the forged parts; these are indicated by the letters A, B, C and D in Fig. 7.

The status of the other points d1, d2, d3, d4, d5 and d6 were also studied for a better understanding of the wear phenomenon. Under the previously explained hypothesis, K_τ was calculated as in Eq. (2):

$$K_\tau = \frac{wear_{measured}}{n_{cycles}} \left(\int_0^t \frac{\tau v_\tau}{\bar{\sigma}} dt \right)^{-1}. \quad (2)$$

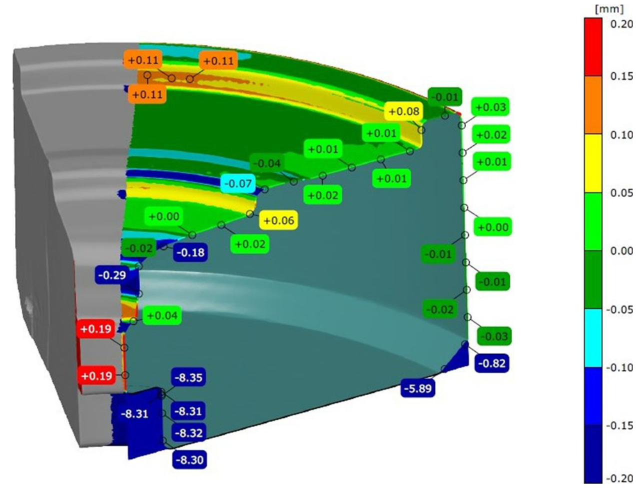


Fig. 6 Comparison of scanned 3D surface of the die with CAD model. Positive values in the bottom part are simply due to a production change from the original design

The results for points with detectable wear are shown in Table 1. Because several of the examined points have very little wear, the values are dispersed, but the most worn points, C, D, and d2, are in good agreement.

4 Identification of production factors affecting die life

DoE analysis can be used to understand how output variables are influenced by input variables and how the latter interact. Experiments are used to determine which factors influence most production and to predict the effects of their changes on process outputs. Through the metrics R^2 and p-value, analysis of variance (ANOVA) applied to a DoE allows the amount of variation caused by a controlled input to be distinguished from unmeasured perturbations of the system and random errors. The p-value is used to assess the significance of the effects of the input factors and their mutual interactions, while R^2 measures the goodness of fit of the regression equation. The fundamental distinction between simulated and experimental DoE is that the former does not require replication of the experiment.

4.1 Choice of production factors

Investigating the nature of the phenomena encountered in forging and deriving models that allow global optimisation of the parameters involves high computational costs due to the amount of simulations required for the entire campaign of experiments. Some researchers, D'Addona and Antonelli [30] adopted a neural network model to limit the growth of the number of tests as the number of variables increases.

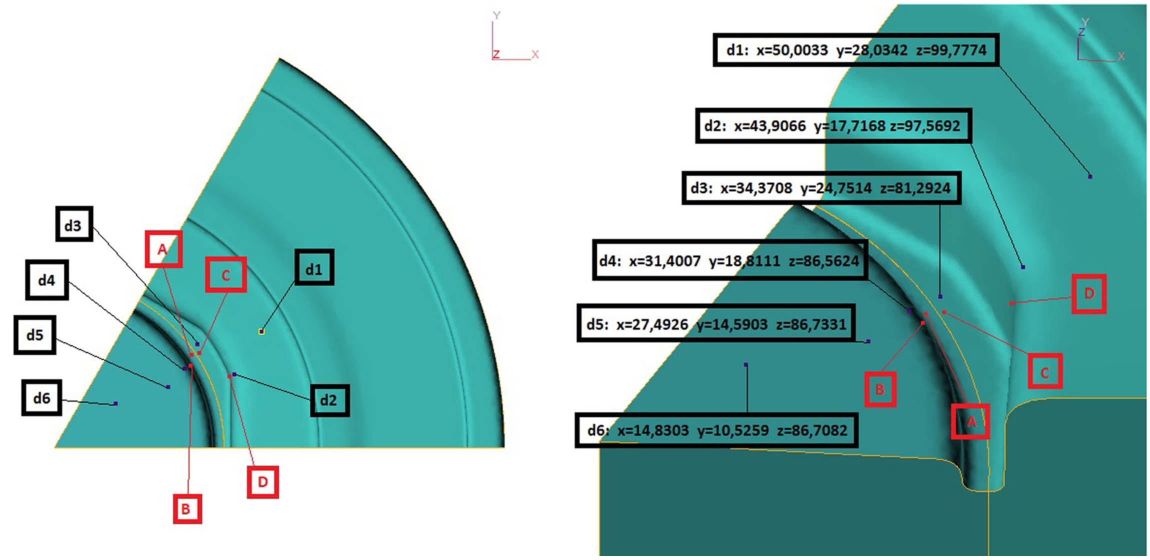


Fig. 7 Points of the die monitored

Table 1 K_τ values in the points with measurable wear

Point	Wear measured [mm]	Measured wear/cycle [mm/cycle]	Simulated wear/cycle [mm/cycle]	K_τ
C	0.16	2.13E-05	7.03E-05	0.30
D	0.16	2.13E-05	6.01E-05	0.35
d1	0.03	4.00E-06	3.13E-05	0.13
d2	0.18	2.40E-05	7.07E-05	0.34
d3	0.08	1.07E-05	5.12E-05	0.21

In present study the number of variables are intrinsecally limited to the only ones that can be easily modified during production. QForm-3D software was used to simulate a full factorial Design of Experiments in this work. The variables were chosen from those that can be straightforwardly changed during the manufacturing process: the mould preheating temperature (T), the lubricant friction factor (m) and the billet height after upsetting operation (h). The expected shape of the response surface determines the minimum number of levels for each factor: as the response surface is likely to be non-linear, the minimum number of levels required is three. Also in this case 3 levels were considered for each variable; this resulted in a total number of 27 trials. The height of a billet is limited to 16–20 mm due to production limitations. Thermal softening causes faster abrasive wear and plastic deformation of the tool, however, a higher die temperature also favours the reduction of forming stresses and thus the same wear and deformation. It is therefore necessary to identify the optimum die temperature. Practice suggests a value of 300 °C, in the range from room temperature (20 °C) to a maximum of 400 °C. Lubricants have several effects on the process, but their primary function is to reduce friction. The friction model proposed by Levanov was used to predict this phenomenon (Eq. (3)):

Table 2 The chosen factors and their levels

Factor	Minimum	Intermediate	Maximum
Initial die temperature [°C]	20	210	400
Workpiece height [mm]	16	18	20
Friction factor	0.15	0.4	0.8

$$\tau_{Levanov} = m\frac{\bar{\sigma}}{\sqrt{3}}\left(1 - e^{-n\frac{\sigma_n}{\bar{\sigma}}}\right) \tag{3}$$

where m is the friction factor, n is the Levanov coefficient (n=1.25), σ_n is the normal stress at the interface and $\bar{\sigma}$ is the yield stress of the workpiece. The friction factor levels were chosen to extend the range of the parameter between the best available lubrication (m=0.15) and its absence (m=0.8). Factors and levels are summarized as follow (Table 2).

Table 3 Significant and non-significant models obtained

Point	Average stress model	Equivalent stress model	Wear model
A	NO	NO	NO
B	NO	YES ($R^2 = 95.48\%$)	NO
C	NO	YES ($R^2 = 89.22\%$)	NO
D	YES ($R^2 = 84.30\%$)	YES ($R^2 = 92.06\%$)	YES ($R^2 = 96.99\%$)
d1	YES ($R^2 = 87.80\%$)	YES ($R^2 = 92.75\%$)	YES ($R^2 = 97.57\%$)
d2	YES ($R^2 = 91.78\%$)	YES ($R^2 = 92.07\%$)	NO
d3	NO	NO	NO
d4	YES ($R^2 = 89.82\%$)	YES ($R^2 = 98.43\%$)	YES ($R^2 = 94.93\%$)
d5	YES ($R^2 = 90.13\%$)	YES ($R^2 = 99.39\%$)	YES ($R^2 = 99.90\%$)
d6	NO	YES ($R^2 = 98.66\%$)	YES ($R^2 = 99.71\%$)

4.2 Choice of output variables

In order to identify a correlation between die damage phenomena and their causes, several outputs were monitored: abrasion wear, equivalent stress and mean stress. The latter was evaluated as an indicator of the probability of fracture occurrence. It is expressed by Eq. (4):

$$\sigma_{average} = \frac{\sigma_{ii}}{3}. \tag{4}$$

In Eq. (4) σ_{ii} are the principal stresses of the stress tensor.
Stresses generated during forging can exceed the yield strength of the mould material and, in such a situation, local deformations can lead to non-conformities in forged parts. This phenomenon is particularly present where the temperature is higher, due to thermal softening. For this reason, it was necessary to monitor the equivalent stress of the die throughout the process. The calculation criterion adopted is the Von Mises one (Eq. (5)):

$$\bar{\sigma} = \sqrt{\frac{3}{2}\sigma_{ij}\sigma_{ij}} \tag{5}$$

where σ_{ij} are the components of the stress tensor.
Abrasion wear is calculated as in Eq. (1) using the wear coefficient (K_τ) identified in Table 1.

4.3 Analysis of the results

Since the lower die of this process was the most critical, being affected by failure and significant wear, it was investigated in this study. In the attempt to derive a correlation between the quantities examined in Sect. 3.2 and the input parameters described in Sect. 3.1, a first-order linear regression analysis was carried out. The results obtained were inconclusive due to the very low R^2 values; therefore the models were discarded and a linear relationship excluded. Second-order regression models were therefore examined for each point in the following form (Eq. (6)):

$$y = const + \beta_i x_i + \beta_{ij} x_i x_j, \tag{6}$$

where *const* is the intercept of the model, x_i and x_j are the indipendent variables, β_i are the coefficient of first-order terms, and β_{ij} are the coefficient of second-order terms. Minitab software was used as support in the analysis to calculate the coefficients. Figure 7 shows the examinated points. All the models obtained are summarised in Table 3, which distinguishes between significant and non-significant models. In each model only some variables or interactions are relevant.

The low R^2 in the simulations is attributed to:

- Interpolation errors introduced by automatic remeshing;
- Mould deformation, which changes the position of the stress concentrations with respect to the chosen points on the unformed die;
- Alternating tensile and compressive stresses in the annular part of the mould: interference fit produces an initial tensile state in the outer part of the mould; during the forging process, the stress state is reversed at different process times.

The significance of the production factors was assessed by the corresponding *p*-values obtained from the ANOVA, carried out for each point and for each output. Although there are some exceptions, the order of significance is as follows:

1. *m*, friction coefficient,
2. *h*, billet height,
3. *T*, initial mould temperature.

Strong differences were seen across areas of different orientation, in particular comparing horizontal and vertical surfaces. As a result, point D, the only one among those analysed that is placed on the mould's vertical surface, shows the overall

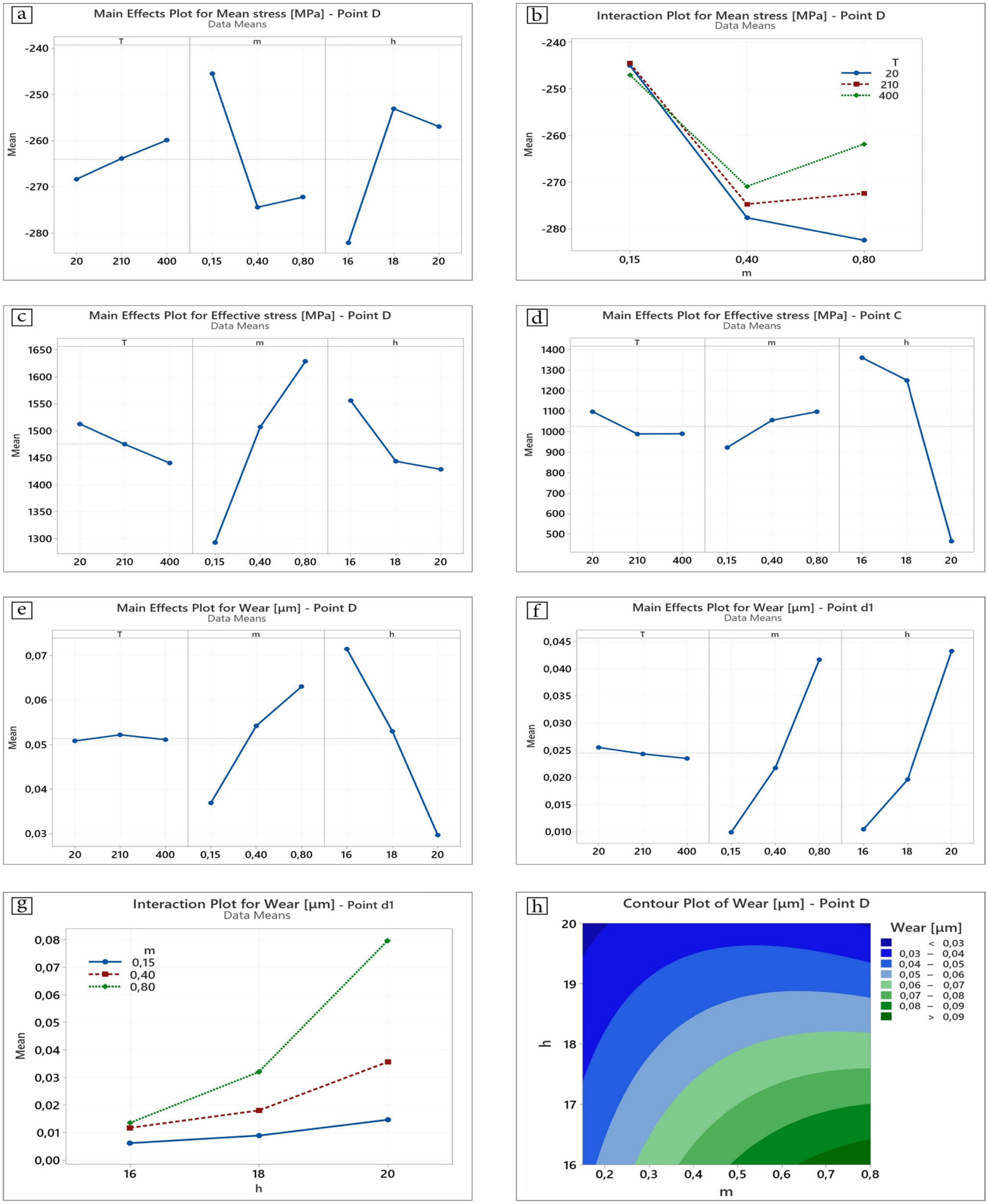


Fig. 8 **a** Mean stress trends for vertical surfaces (point D); **b** example of positive effect of increasing die temperature as the lubricant efficiency decreases (point D); **c** typical effective stress trend (point D); **d** effective stress trend in zone subjected to fracture (point C); **e** wear trend for vertical surfaces (point D); **f** typical wear trend (point d1); **g** example of threshold value for parameter h (point d1); **h** contour plots of wear for vertical surfaces (point D)

behaviour differently than the other points. Analysing the average stress, the graphs of the main effects referring to the vertical surface of the hexagon (point D) showed considerable non-linearity in relation to the friction factor and the height of the billet (Fig. 8a). The rest of the investigated points (d1, d2, d4 and d5) behave uniformly: the average stress modulus decreases with increasing mould temperature and billet height, with the inverse trend observed for high values of the friction factor. The interaction graphs for the mean stress support the previous results and show that increasing die temperature has a positive influence when the lubricant efficiency decreases, as can be seen in Fig. 8b. Analysing the equivalent stress, the main effect plots showed a similar behaviour in all die zones (Fig. 8c) with the exception of the fracture area: the general tendency revealed the friction factor as the most significant parameter (points B, D, d1, d2, d4, d5 and d6), while for the fracture zone (point C) the billet height was the most significant one (Fig. 8d). With regard to abrasive wear, the graphs show that the mould reacts differently for each surface analysed: the same patterns (Fig. 8f) were noted for horizontal surfaces and outward curvature radii, while the trends for vertical surfaces of the hexagon (point D) are different (Fig. 8e). It is generally true that wear increases as the quality of lubrication decreases and is barely affected by the initial mould temperature. The wear ratio related to the height of the billet is negative for the vertical surfaces (point D) and positive for the rest of the die. The interaction diagrams reveal a changing sensitivity to different operating conditions (Fig. 8g). Consequently, they allow the identification of threshold values for input factors to reduce wear and maximum stress.

5 Die life prediction

The DoE analysis revealed an unexpected result: the optimisation of die life depends more on the friction coefficient and the height of the billet than on its temperature. Contour plots illustrate the stress and wear patterns as the input parameters change (see, for example, Fig. 8h) and help to determine their ideal configuration. The recommended setup of the process parameters differs depending on the damage mechanism to be controlled:

- To minimise stress a higher billet, higher die temperature and a high quality lubricant (minimum m) are recommended.
- To reduce wear it is advantageous to have higher preheating temperatures, a good quality lubricant but a lower billet;

However, there are exceptions, such as for point D (the one on a vertical surface) and d4 (on the outward curvature radius), which showed minimal wear for the highest value of the billet height. The optimised parameters are shown in Table 4.

Table 4 Optimised parameters

Model	Point(s)	T [°C]	m	h [mm]
Average stress	D	400	0.15	18.42
	d1,d2, d4,d5	400	0.15	20
Effective stress	B	–	0.15	–
	C	400	0.8	20
	D	400	0.15	19.84
	d1,d2	400	0.15	20
	d4	–	0.15	20
	d5	400	0.15	19.19
	d6	400	0.15	19.6
Wear	D,d4	–	0.15	20
	d1	–	0.15	17.62
	d5,d6	400	0.15	16

Two actions are required to optimise the life of the die: preventing the occurrence of fracture and containing the two main damage mechanisms: wear and plastic deformation. With the exception of the area affected by the fracture, the stresses do not exceed the limit of plastic deformation, so the process has only been optimised for the containment of abrasive wear. To prevent the primary cause of the fracture, the composite mould can be assembled differently in order to compensate for elastic failure. According to the design requirements of the part, the acceptable wear threshold on the most critical surface (point D) is 0.43 mm. From the wear model obtained for point D and using the parameters adopted by the company, the estimated wear per cycle is $2.13E-05$ mm/cycle, which allows 9986 work cycles. By adopting the optimised factors from Table 4, the maximum mould life can be extended to 22156 cycles. This is the optimum value since the calculation does not consider the actual wear rate progression: a strong increase in the wear rate is expected with the removal of the last nitride coating layer. But even so, optimisation could bring considerable economic benefits.

6 Conclusion

Estimating the service life of hot forging dies is still an open challenge. The reason lies in the number of factors involved, some of which are hardly controllable during the process. However, the main mechanisms leading to irreversible die damage are well understood, and this work demonstrates that it is possible to limit and delay their impact as much as possible. As the aim of this work was to analyse and contain plastic deformation and abrasive wear, mathematical models known from literature were used to find the response of the die for optimisation purposes. Although it is difficult to actually implement all the recommended improvements, a selection of optimisations gave a measurable increasing in the life of the die. This work could be further improved with future studies: the polynomial response surface obtained from the DoE could be replaced by kriging regression. This will allow the simulations to be thickened around the expected optimum. Another relevant step is including in the experiment the main disturbance factors, whose variation can influence the quality of the result. As an example, the initial volume of the billet, the centering of the part on the die and the time between consecutive strokes could be considered as disturbing factors because their values cannot be determined with accuracy. The former two determine the amount of material flowing through the flash and its shape, the latter influences the working temperatures of the part. Finally, targeted analyses should be carried out with respect to the angle between die surfaces and forging direction, in order to quantify their actual relevance to wear and deformation.

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Availability of data and materials The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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Ethics approval Not applicable.

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