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Sensitivity analysis of near solidus forming (NSF) process with digital twin using Taguchi approach

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Abstract Forging at near solidus material state takes advantage of the high ductility of the material at the semi solid or soft-solid state while keeping most of the mechanical properties of a forged part. The technology is at maturity level ready for its industrial implementation. However, to implement the process for complex cases the development of an appropriate digital twin (DT) is necessary. While developing a material model, a strong experimental and DT is necessary to be able to evaluate the accuracy of the model. Aimed at having a reliable DT under control, for future material model validations, the main objective of this work is to develop a sensitivity analysis of three NSF industrial cases such as Hook, R spindle and H spindle to develop an adequate DT calibration procedure. Firstly, the benchmark experimentation process parameter noise and experimentation boundary conditions (BCs) parameter uncertainty are identified. Secondly, the three industrial benchmark DTs are constructed, and a Taguchi design of experiments (DoEs) methodology is put in place to develop the sensitivity analysis. Finally, after simulations the results are critically evaluated and the sensitivity of each benchmark to the different inputs (process parameter noise and BC parameter uncertainty) is studied. Lastly, the optimum DT calibration procedure is developed. Overall, the results stated the minimum impact of the material model in terms of dies filling. Nevertheless, even if the material model is the highest impacting factor for the forging forces other inputs, such as heat transfer and friction must be under control first.

Keywords Near solidus · Digital twin (DT) · Taguchi design · Sensitivity analysis · Heat transfer

1 Introduction

Forging is one of the oldest metal-forming techniques which is used from decades in the field of automobile and aerospace sectors due to its superior mechanical properties and ease in the fabrication of fairly complex parts. The process consists of deforming metals or alloys plastically to their desired shape by compressive force with a pair of dies, which is designed based on the shape of the final geometry. The process generally includes multiple deformation steps, in which the billet gradually transforms into its final desired shape. Due to their superior properties, forged parts are mostly used in high strength and high-performance applications where load, human safety, strength, and fatigue life are the critical considerations [1]. Despite all the advantages, the forging process has some limitations when it comes to the recent change in industrial technology. Reducing material consumption is a rising issue for manufacturers as stated by UN's Sustainable Development Goals and the European Union's Green New Deal to minimize carbon footprints [2]. More and more industries are moving towards sustainable and environmentally friendly processes. Traditional forging processes are lacking behind when it comes to the waste material as the volume of the initial billet is kept more to achieve better filling in the process (high flash percentage). Similarly, the forming forces are high in the case of manufacturing more complex parts which usually consists of multiple forming steps, resulting in the high consumption

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of energy which has a negative impact on the environment (since the process takes more time and energy to complete, the cost of manufacturing increases).

In this sense, different processes like semi-solid metal forming (SSM) or near solidus forming (NSF) are some of the possible choices to solve or at least reduce this problem. SSM is defined as the forming process at a temperature between the liquidus and solidus temperatures, as shown by Murali and Yong [3] in their work on the liquid forging of thin Al-Si structures. The advantage of this technology lies in its superior mechanical properties at a reasonable cost as presented by Bayramoglu et al. [4]. Nevertheless, the manufacturing process can be majorly affected by the process variables such as the temperature of the billet and dies, friction between dies and workpiece, press type, material, and the complexity of the desired part. The ideal forming techniques for the environment and the industries can be characterized by how well the die cavity is filled while keeping the forming forces as low and furthermore the mechanical properties of the final part.

A couple of early works of SSM (also referenced as semisolid forging) were presented by Kirkwood [5], where a description of the technologies available for producing non-dendritic structures are presented, and the SSM review presented by Fan [6]. The process takes the advantage of both classical hot forging and casting, where the part is manufactured at low forces while having good mechanical properties, which was demonstrated by Liu and Chen [7] for the mechanical behaviour of Al-Si-Cu 319 cast alloys. Another important aspect of the process is that even complex parts can be manufactured with a single step whereas three or more steps are necessary for traditional hot forging, hence reducing the energy cost and manufacturing time significantly. However, the mechanical properties are still below the forging standards.

According to Lozares et al. [8], the same benefits as those obtained in SSM can be achieved at conditions where no liquid is theoretically present using the near solidus forming (NSF) process. In his recent study, different automotive components of 42CrMo4 and S48C alloys were manufactured in a single stroke requiring between 6 and 10 times less forces in comparison with the conventional forging. In this case, unlike the SSM processes, the attained components exhibited as-forged mechanical properties. Furthermore, due to the high temperature of the billet the ductility of the material increases which gives advantages to the good filling by minimizing the raw material consumption stated by Plata et al. [9] in their work of manufacturing a complex uppercup shape attached to a long arm through NSF process.

Due to the nature of the NSF process, the design and optimization of the process based on real-time experiments are time-consuming and costly [10]. To overcome this, the digital twin (DT) approach can be implemented, where this technique is a crucial part of Industry 4.0. DTs provide insights into all aspects of the production line and manufacturing process [11]. The information can be used to make better decisions and even automate some choices by adjusting the equipment and processes such as used by Scaglioni and Ferretti [12] for the modelling of cutting process Turan et al. [2] implemented such technique for the design of the dies and industrial components which was used for the reduction of material consumption in the thermoforming process. However, a simulation-based DT approach can be implemented at NSF conditions, which is most suitable for manufacturing at high temperatures [13]. The technique can enable the parameter study of all inputs by means of numerical methods such as finite element method (FEM) tools in terms of physical based outputs. For this purpose, a numerical simulation tool FOGRGE NxT® was implemented which predicted the material flow behaviour stated by Knust et al. [14] for the investigation of input parameters in the filling in the multi-stage hot forging process. Despite all, the highest challenge creating a DT of the NSF process is the uncertainty of material behaviour during the process. The microstructure study carried out by Sołek et al. [15] showed that a small change in temperature caused a significant change in the flow stress of the material, hence wide parameters ranges were simulated to predict defects such as incomplete die filling. Similarly, Plata et al. [9] investigated the DT of the NSF process in 42CrMo4 steel grade, using a combination of X-ray fluorescence (XRF), optical microscopy and scanning electron microscopy (SEM) analysis revealing the deformation and material flow behaviour. Due to the high temperature, the material displayed semi-solid-like behaviour enabling the filling of complex shapes with less amount of force [8]. The high temperature of the process allows the microstructural refinement in the form of dynamic recrystallization, which results in the softening effect and causes a reduction in the press forces as shown by Refs. [16, 17] for nickel-based superalloy. Due to the high complexity of the material behaviour during NSF, this is still an open topic with further development needed to achieve an optimum model implementation.

Nevertheless, the material model plays a vital role in the NSF's DT but is not the only impacting factor [18], as stated by the previous authors by comparing the DT material models to their experiments. As in every forging DT, can also be influenced by process parameters, e.g., heat transfer coefficient (HTC), friction coefficient, emissivity, billet and dies characteristics. In addition, the knowledge of the rheological properties in a wide range of process parameters is also critical to understand the NSF process completely.

According to Malinowski et al. [19], the accuracy of DT in the forging process depended on the proper description of the boundary conditions where knowledge of HTC was one of the most critical boundary conditions (BCs) in their case, as it affected the quality of forged components. His study suggested the measurement of the temperature distributions within the dies and then proposed a finite-element simulation approach to understand the process deeply. From the previous studies, the ranges of HTC in the forging process could be found up to 1.5–18 kW/(m^2·K), as stated in Ref. [20] in the hot forging of flat H-13 tool steel dies. Similarly, in the investigation of friction behaviour in the ring compression test in AISI 304L material, HTC of 2–20 kW/(m^2·K) were presented by Sethy et al. [21]. It can be noticed that apart from HTC, friction stress can cause an intense deformation near the cylinder wall and dies surfaces. The value of friction coefficient was found between 0.2 and 0.5 in the presence of the Ceraspray layer lubricant in the semi-solid forming process by Becker et al. [22]. This value is strongly dependent on the type of lubricant and working conditions, especially the press velocity and forming temperature, as stated by Barrau et al. [23] during the investigation of friction and wear mechanism in steels. Furthermore, the emissivity value on the outside surface of the billet has been assumed to be a function of temperature and estimated at 0.35–1.0 presented by Bogdan [24] for AISI 4340 steel grade forging products. Again, the range of this parameter is influenced by the material and temperature properties of the billet and its surroundings presented by Traidi et al. [25] in the thermomechanical behaviour of steel at a semisolid temperature. Moreover, the ambient temperature can affect the temperature of the heated billet before and during the forging stand transport, due to which the process is performed in a controlled environment as stated by Andrade-Campos et al. [26], similar conclusion was presented by Tirth and Arabi [27]. Even if the experimental procedure is performed at room temperature, the ambient temperature in the vicinity of the hot workpiece is heated by radiation and that is why, mainly in the die cavity (where the air has difficulties to cool down between strokes) a temperature in the 50 °C and 70 °C range is usually assumed. Finally, the dies usually are preheated around 250–300 °C to minimize the heat loss from the billet, as presented by Lozares et al. [8] in the NSF process of 42CrMo4 steel component. Similarly, an identical temperature of 250 °C was presented by Koc et al. [28] for the dies during finite element simulations of semi-solid forging. The principal purpose is to prevent the surface roughness of the formed component which can occur due to the sudden decrease in the surface temperature. In short, all these parameters have a significant effect on the die filling and forming forces which are the key elements in the DT of the NSF process.

From the literature review there is no agreement on the HTC average value as this is strongly sensitive to material, roughness and other factors. An average of 2–20 kW/(m^2·K) range is appointed for the HTC from the collected works. Due to the temperature difference, the emissivity of the outside surfaces of the mould and that of the billet surface is assumed to be 0.35–1.0, as stated from Ref. [29]. Similarly, the friction coefficient is responsible for the material flow in the process and for that purpose many authors used various types of lubricants to minimize it and the typical range of friction coefficient can be found between 0.2–0.5. The dies temperature was decided differently by various authors based on the type of material used in the experimentation, in the approximated range between 250 °C and 300 °C.

At the actual maturity level of the NSF technology, it is critical to be able to have a reliable NSF-DT for process definition [30]. However, up to today, the optimal material modelling is the highest challenge, and it is still under development. As in most of the model development works, the experimental process data will have to be validated by experimental observation. Such as the comparison of the simulation data with the experiments, which is one way to verify the accuracy of the model. However, as shown in the literature review, there are other factors that could affect the outputs of the DT (mainly filling and forging forces) that must be under control or at least their impact evaluated prior to use the DT for material model validation purposes. A study of the input and output sensitivity could lead to, first the understanding of the impact on the different output measurements, and secondly the development of the optimum strategy to correctly evaluate the adequateness of the material model, as every other potential input will be under control.

In short, from the previous work of the authors it is clear that the material properties of the NSF are superior to the forging process. But there is a consensus that the actual material models do not represent the current material at NSF, because the numerical prediction of the forces are not in good agreement with the experimental forces. However, in order to be able to validate new material model developments, firstly, the other impacting factors in the NSF-DT have to be understood. Once a material model validation methodology can be developed. Having that as objective, in this work, first three different NSF benchmark cases have been selected (Hook, R spindle and H spindle). Then benchmark future experimentation process parameter noise and experimentation BC parameter uncertainty are identified. Next, the three industrial benchmark DTs are constructed, and a Taguchi design of experiments (DoEs) methodology is put in place to develop the sensitivity analysis. Sensibility analysis allows the deep understanding of the impact of each parameter/noise/BC in the main outputs of the DT, i.e., filling and forces. Finally, from the deep understanding of the NSF-DT behaviour the optimum material model validation strategy is defined.

2 Materials, experimental and numerical methods

For the sensitivity analysis of NSF process three industrial benchmarks were selected in this study. As presented in the introduction, all three benchmarks were experimentally tested by the research group prior to this study which shows the capability of NSF process. The benchmark cases are: (i) H spindle (see Fig. 1a), (ii) R spindle (see Fig. 1b) and (iii) Hook (see Fig. 1c). It must be clarified that even if some preliminary experimental testings have been performed (see Fig. 1), the presented work in this study is fully numerical as the objective is to deeply understand the NSF-DT behaviour and stablish the correct validation strategy.

H and R, both are automotive spindles which are used in the suspension system of the cars while the Hook is the weightlifting component. The weight of the H spindle is ~2.3 kg, the R Spindle ~3 kg, and ~2.4 kg for the Hook component. From the Fig. 1, a very low flash quantity resultant of each NSF process can be stated. The industrial components are developed using 42CrMo4 steel and its thermal properties are shown in Table 1.

2.1 Benchmark experimentation process parameter noise

In the introduction, the main DT's BC uncertainty ranges have been identified, i.e., friction coefficient, emissivity, heat transfer coefficient and ambient temperature. In some cases, the last one (ambient temperature) can be considered as a process parameter. However, due to the high complexity of experimentally measuring this value inside the die cavity, in this study it will be considered as DT's BC. In addition to the DT's BC, when comparing DT results with experimental, the process parameter noises must be considered.

Based on the experimental campaign developed by the research group on these benchmark workpieces as well as on other numerous industrial NSF experiments, in the last years, the following process parameter noises were identified.

Table 1 Thermal properties of 42CrMo4 steel

Density/ ($kg \cdot m^{-3}$)	Specific heat/ ($J \cdot (kg \cdot K)^{-1}$)	Conductivity/ ($W \cdot (m \cdot K)^{-1}$)	Thermal expansion/ K^{-1}
7850	778	35.5	13.2×10^{-6}

(i) Based on the billet manufacturing tolerances and the billet-to-billet measurement experience, a variability of ±0.5 mm in billet length and ±0.3 mm in diameter must be considered. With this uncertainty it will be evaluated if each billet must be measured at every test, or just the statistical measurement of the whole batch is sufficient.

(ii) For the studied NSF process the desired billet temperature of around 1 370 °C was selected which was used by Slater et al. [31] for the manufacturing of complex parts in the NSF process. To achieve this temperature, the billet is heated in a furnace to a higher temperature and then transferred using manipulation to the die cavity prior to the forging. As expected, during the transfer the billet cools down. From the conducted experiments measuring the transfer time and variability on the heating furnace, there was an uncertainty of +10 °C on the final temperature of the billet when arriving at the die cavity.

(iii) As in every forging process, the die cavity is slightly larger than the die diameter for easy placement of the billet. However, from one set-up of the process to the next one the location of the billet inside the die cavity can vary. To understand it clearly, if the circular die cavity is divided into 12 sections (like a clock ticks) and keeping in mind that the billet is slightly smaller,

(a) (b) (c)

Fig. 1 Industrial NSF benchmark **a** H spindle, **b** R spindle, **c** hook the assumption of contact between the die and the billet must be defined at some section from 1 to 12. By taking the extremes, four cases can be assumed, i.e., contact at 0/12, contact at 3/12, contact at 6/12 and contact at 9/12.

(iv) Furthermore, in order to reduce the thermal loss during the forging process, the dies were heated with an oil system during the trials. However, the experimental measurements (combined with some numerical thermal simulations) showed that a variation between 200 °C and 270 °C could be found between different tests.

As presented in the introduction, the material strength is the key aspect and challenge of the NSF-DT development. From the literature review and the past-experience of the group of NSF project [9], it can be assumed that going to the extreme a 50% of strength reduction can be assumed from the natural extrapolation of the hot forging material behaviour. The comparison of the impact of this input to others will guide to devise the optimum calibration strategy and material model suitability procedure.

2.2 Benchmark experimentation BC parameter uncertainty

As presented in the introduction, there is not an agreement on the BC for an optimum NSF simulation and in most cases, the values depend on the studied case.

(i) Even if there are methodologies to characterize the HTC under certain conditions [21], from the literature review a variation between 2 kW/(m^2·K) and 20 kW/(m^2·K) can be identified. Furthermore, numerous friction coefficient testing procedures are available in the literature. However, due to the complexity of some of them (and more at NSF temperatures), it is worth evaluating the impact of the BC on the results, before committing to the complex testing.

(ii) From the literature review a range between 0.2 and 0.5 for the friction coefficient has been identified and therefore this has been used in the study.

(iii) Lastly, a range between 50 °C and 70 °C has been used for ambient temperature, and the emissivity range between 0.35 and 1 has been taken for the sensitivity study based on the literature study.

Last but not least, a generic material model (taken from literature experimental data) has been taken as a reference. Then, a 50% of strength of the model variation has been studied in order to highlight the impact that the material model can have on the NSF-DT outputs.

2.3 Digital twin development

Forge NxT® finite element software was used in this study to develop the DT. In all cases, the dies and punch (tools) were assumed to be infinite rigid and the billet to be the only deformable body. The billets were heterogeneously meshed to optimize their performance (see Fig. 2a). The lower part of the billet was meshed in a finer mesh (see Fig. 2c) being this one the part of the material enduring a higher deformation. The top part of the billet was meshed with coarser elements to optimize simulation times (see Fig. 2b). This strategy was obtained by try and error to optimize the simulation time while assuring the necessary accuracy on the outputs. Furthermore, as a reference case, a Hansel-Spittel material model has been used

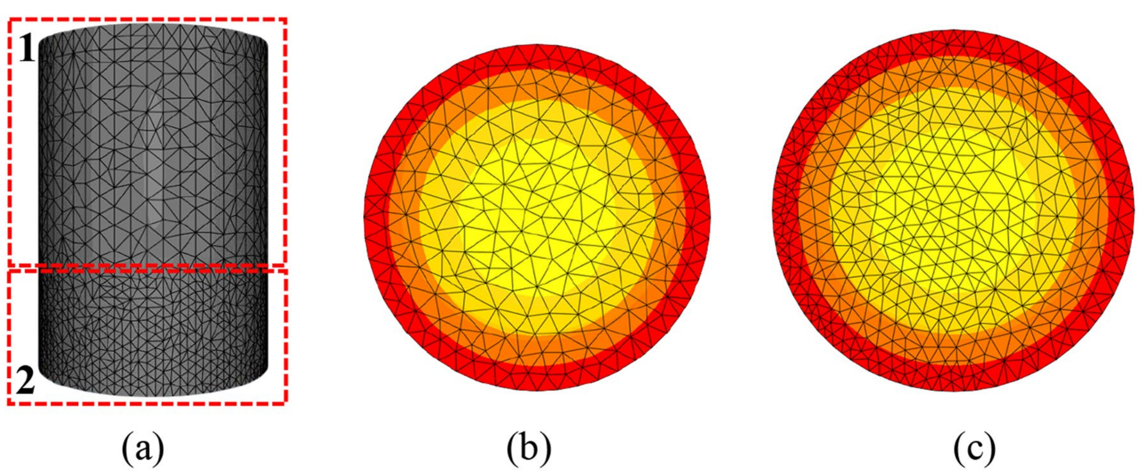

Fig. 2 Billet finite element mesh distribution **a** general view, **b** mesh setting 1, **c** mesh setting 2

$$\sigma = A\mathrm{e}^{m_1 T}\varepsilon^{m_2}\dot{\varepsilon}^{m_3}\mathrm{e}^{\frac{m_4}{\varepsilon}}(1+\varepsilon)^{m_5 T}\mathrm{e}^{\varepsilon m_7}\dot{\varepsilon}^{T m_8}T^{m_9}, \tag{1}$$

where σ is stress, ε strain, $\dot{\varepsilon}$ strain rate, T deformation temperature, and m_1 to m_9 material constants. The fitted parameters of Eq. (1) are derived from the literature generic compression test which are as follows: A 1 872.06, m_1 −0.002 89, m_2 0.112 3, m_3 0.143 6 and m_4 −0.048 7.

Due to the high strain developed during the process, an automatic remeshing rule was applied on the billet. The remeshing rule mesh size multiplier factor was defined according to Ref. [32] which was used in the study of close die forging for the manufacturing of a load bearing strut. The element type in the model is considered tetrahedron with the initial number of elements 35 276, on average the mesh number is increased to 155 634, due to the remeshing rule at the end of the deformation phase.

A servomechanical press was used with a capacity of 400 mm/s velocity in the simulation process of all three components, complete specifications of the press can be followed in the work presented by Ref. [8] in the NSF process of steel components. The position, speed and force response of a characteristic NSF industrial experimental trial is presented in Fig. 3b.

The contact on the NSF-DT was modelled by a Coulomb limited Tresca model implemented from the FORGE database, and the coefficient of the model is mathematically expressed as

$$\|\tau\| = \min\left(\mu\sigma_n;\overline{m}\frac{\sigma_0}{\sqrt{3}}\right), \tag{2}$$

where σ_n, σ_0, μ and $\overline{m}$ are the normal stress at contact, flow stress, Coulomb's friction coefficient and Tresca's friction coefficient, respectively. The values of Tresca's friction coefficient is defined between 0 and 1 (several studies have shown that it was generally possible to consider that ; $\overline{m} = 2\ \mu$), as implemented by Ref. [14] for a water graphite lubrication where $\mu = 0.15$ and $m = 0.3$, which is later fully explained by Ref. [33] in the study of friction models for skew rolling process.

2.4 Digital twin outputs

As in every forging operation, forming forces and die filling are the major factors to be industrially addresses. The case of NSF is not different and therefore, these two are the reference outputs in this study.

In the case of H spindle, based on the geometry of the component, five locations were decided from P_1–P_5 to calculate the filling values as shown in Fig. 4a. For the detailed study, the filling of these locations was measured at three different strokes such as 64%, 70%, and 90%, during the forging step. All these fillings were measured from the reference points, which is the distance between the reference point and the deformed material at each stroke during the forming step as depicted in Figs. 4a–c. The section view of the H spindle is stated in Fig. 4d, where two types of filling can be seen, vertical and one of the horizontal, the vertical filling (P_1) is also known as positive filling. As we know that, at the initial stages of the forming process the filling length can be very small. Hence the error of measurement can be quite high due to the small length of the filling, to avoid the error in the calculations, the higher values of strokes were selected (>60%).

Similarly, for the R spindle, five points were selected from P_1 to P_5, where P_1 represent the vertical filling and P_2–P_5 the horizontal filling to the punch displacement direction as shown in Figs. 4b, e, h. Again, filling lengths were

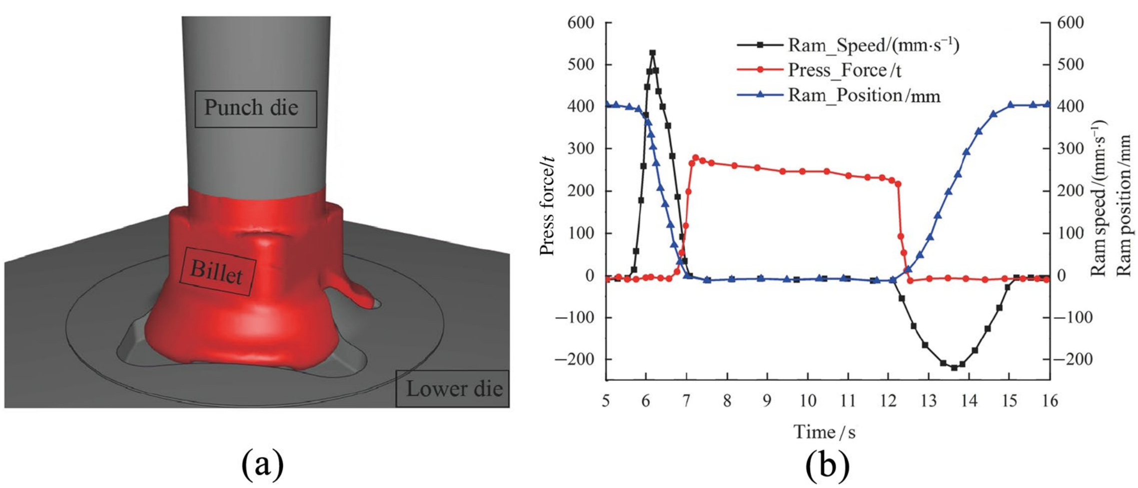

Fig. 3 Near solidus forming process **a** forging stage, **b** punch configuration

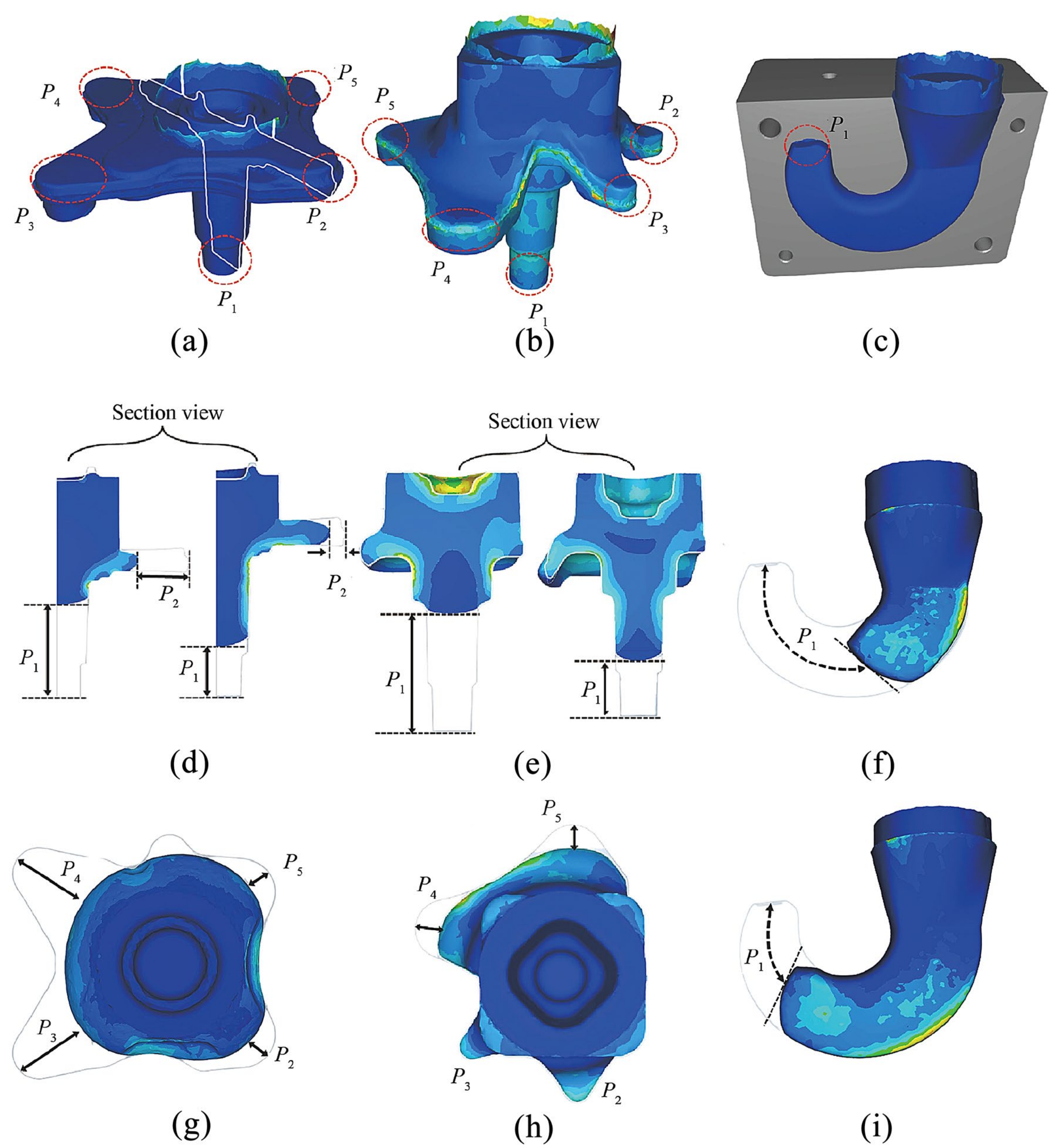

Fig. 4 Filling calculation of all geometries at various locations **a**, **d**, **g** H spindle horizontal and vertical filling at five different points (P_1–P_5), **b**, **e**, **h** R spindle horizontal and vertical filling at five different points (P_1–P_5), **c**, **f**, **i** hook filling at various strokes

calculated at three different stages 72%, 86%, and 97% of punch stroke.

As the material filling of the Hook components is circular as shown in Figs. 4c, f, i, all measurements were taken from a single reference point at three different stages, 74%, 80%, and 95% of the complete stroke (like the P_1 of the other two benchmarks). All these measurements were used in the NSF-DT, to identify the importance of each parameter in the three industrial components' filling.

Similar to the filling measurements, the forces were also computed at the three different stroke levels previously defined. Overall, all these measurements were used in the sensitivity analysis of the NSF-DT, which would be explained further in the upcoming sections.

2.5 Design of experiment

As previously presented, there are numerous input parameters that could impact the filling and force outputs and therefore the difficult validation of the material model. Therefore, in this work a DoE methodology has been used to analyse the sensitivity of the NSF-DT. Since the traditional design approach requires a large number of experiments, as stated by Ref. [34] for the study of the electrodeposition of copper on titanium wires, a Taguchi method has been implemented in this work. The Taguchi method uses a design of orthogonal arrays to study the entire parameter space with a small number of experiments. Similar technique was used by Zhang et al. [35] in a forging process of AA7050 material, and by Equbal et al. [36] for the AISI 1035 alloy steel spring saddle study. As presented in the introduction, the main objective of the design of experiment is to understand the impact of the different inputs (process parameter uncertainty and process parameter noise) on the main two outputs (filling and forces). This understanding will lead to the development of the optimum strategy to evaluate the material model suitability for the NSF-DT. In this work, a two-level Taguchi design of experiment has been developed. Table 2 summarises the selected inputs and levels for the study. The table also shows the graphical representation of each parameter, which will be further used in the figures to easily understand the results.

Thus, using table data, from the available Taguchi design, the L16 orthogonal array was selected by using Minitab®, and the independent variables were assigned. At this point, a total of 44 simulations were run at different configurations of input parameters, and their respective values of forming forces and die filling for each simulation case were evaluated.

3 Results and discussions

3.1 Sensitivity analysis results

For the sensitivity analysis of NSF-DT, the collected data from the Taguchi design table are simulated in FOGRGE NxT® with respect to each case and their results are presented in nominal value variation (percentage effect) (see Figs. 5–7).

In this section, the sensitivity analysis of vertical filling (P_1) in R spindle and H spindle and Hook components is discussed. Figure 5 shows the nominal value variation (NVV) of filling on the vertical axis and process parameters on the horizontal axis. Here Figs. 5a–c represent the results of the industrial components H spindle, R spindle and Hook respectively. Furthermore, NVV is shown per stroke value. In addition, the arrow on the top of the bar representation shows if the relation is directly proportional or inversely proportional, i.e., if the parameter value increases, the NVV values increase or get reduced. Furthermore, the individual stroke data for each parameter are presented in

Table 2 Input parameters for the DOE study of all samples and their levels

Parameters	Parameter levels for each geometry					
	R spindle		H spindle		Hook	
	L_1	L_2	L_1	L_2	L_1	L_2
* Billet diameter/mm	68.70	69.30	64.70	65.30	64.70	65.30
* Billet length/mm	92.50	93.50	89.50	90.50	92.50	93.50
* Strength of 42CrMo4 steel	50.0%	100%	50.0%	100%	50.0%	100%
* Billet temperature/°C	1360	1370	1360	1370	1360	1370
* Dies temperature/°C	200	270	200	270	200	270
◆ Heat-transfer coefficient/ $(kW\cdot(m^2\cdot K)^{-1})$	2.0	20	2.0	20	2.0	20
◆ Emissivity	0.35	1.00	0.35	1.00	0.35	1.00
◆ Ambient temperature/°C	50.0	70.0	50.0	70.0	50.0	70.0
◆ Friction coefficient	0.25	0.45	0.25	0.45	0.25	0.45
* Billet location	Considered		Considered		Excluded	

* Experimentation process parameter noise; ◆ BC parameter uncertainty

different colours and patterns for the easy understanding of the readers.

It is clear that in the initial stages of the forming process the filling length can be noted very small. Hence the error of measurement can be quite high due to the small length of the filling at this stage. To avoid the error in the calculations, the higher values of stroke were selected. Furthermore, from Fig. 5 it can be observed that all nominal value variations are below 10% for the vertical filing (P_1) output. The maximum range for the H Spindle is around 3% (corresponding to the HTC) while the average value for the Hook is 3% with some inputs showing and impact of around 5%–9%. The R spindle shows low values of NVV, below the 2% in general with the exception of a couple of items that are on the 3%−4%.

Furthermore, the NVV of filling in the horizontal direction from P_2−P_5 for H and R spindles is shown in Fig. 6 (as previously introduced, not horizontal filling has been measured for the Hook benchmark). Similar to the previous filling (P_1), these graphs also have a parameters representation on their *x*-axis and NVV on the *y*-axis, while the graphical representation of the filling locations is done, as shown in Fig. 6.

First thing to be noticed on the horizontal filling NVV (see Fig. 6) is the increased amplitude of the NVV with a maximum range of 36%, compared to the 10% of the vertical filling, being P_2 and P_3 of the R spindle benchmark the most sensitive filling outputs. It has to be stressed out that even if some items are above the 10% of NVV, other remain below the 5% of impact. This trend is shown for both benchmarks.

The NVV of all parameters with respect to press-force are presented in Fig. 7. Figures 7a, c, e illustrate the forces at each stroke and Figs. 7b, d, f represent the max forces achieved during the process. The values of the maximum forces were noticed at the stage when the dies were completely filled, which were typically above 90% of the total stroke.

According to Fig. 7, the first thing to notice is the sensitivity of the NSF-DT's forging forces to the different inputs as the range is increased this time up to 70%. Even if not all inputs reach those NVV values, a few are above the 10%−20%. In addition, it is worth to note that most trends are constant between the intermediate stroke values and the maximum final value.

Furthermore, the strokes value for filling calculation is different in each geometry. For example, in the case of H Spindle it starts at 64% and ends at 90%, similarly for R Spindle and Hook these values are ranged between 72%−97% and 68%−93%, respectively. The main reason for considering variable ranges, is due to the filling behaviour of the material in different geometries and also the dimensions of the specimen itself. For example, in H spindle the horizontal filling starts quiet early compared to the R spindle, which is due to difference in the dimension and shape of the components (see Figs. 4a,b).

3.2 Critical discussion of the study

From the sensitivity analysis results in Fig. 5, it can be seen that the NVV follows almost an identical pattern for the individual parameter in all three strokes. Furthermore, the billet length and diameter, HTC, emissivity, and friction coefficient had a significant effect on the vertical filling in all three benchmarks, whereas location in the H spindle and ambient temperature in the hook geometry only. Other parameters such as the material of the billet, temperature of the billet and dies had a minor effect on the vertical filling. As expected, billet length and diameter have a direct relation with the vertical filling as increasing the material of the billet, the vertical filing is increased. On the contrary, an increase on the HTC or on the friction will make the material flow difficult (one due to a faster cool down and the other due to the frictional force increase) reducing the vertical filling, as presented by Ref. [37]. Even if a similar trend is shown for the studied three stages, the global picture is only obtained with the analysis of the three stages and therefore further studies are recommended. Among the different studied inputs, both billet length and diameter are variables that can be taken under control by unitary measurement. However, by having these under control, the NVV of the impacting inputs is below or around 5% and this makes the experimental comparison difficult as the experimental vertical filling measurement error must be taken into account as well.

Similarly in Fig. 6, for the H spindle, it is clear that the filling is greatly affected by the location as stated in Ref. [38], also diameter of the billet, die temperature, HTC and emissivity, which is ranged between 5% and 28.5%, indicated in Figs. 6a, c, e, g. In the R spindle, these parameters are the location, diameter, length, heat transfer coefficient and friction coefficient.

The relation between the increase of billet volume and filling and the increase of HTC and/or friction and filling show generally the same trend shown in the vertical filling. Die temperature helps the material keep the thermal energy and in most cases basically is the antagonist to the HTC [39]. If a unitary billet measurement is assured, there are factors leading to a NVV higher than 10%. These are the die temperature, HTC and emissivity for P_3 on the H spindle benchmark and HTC and friction on the R spindle benchmark. Between both benchmarks, R spindle looks more sensitive then the H spindle one and therefore a better candidate for model calibration. However, the most critical outcome of the filling sensitivity is the fact that the impact of the material strength on the NVV is bellow 3% in all cases.

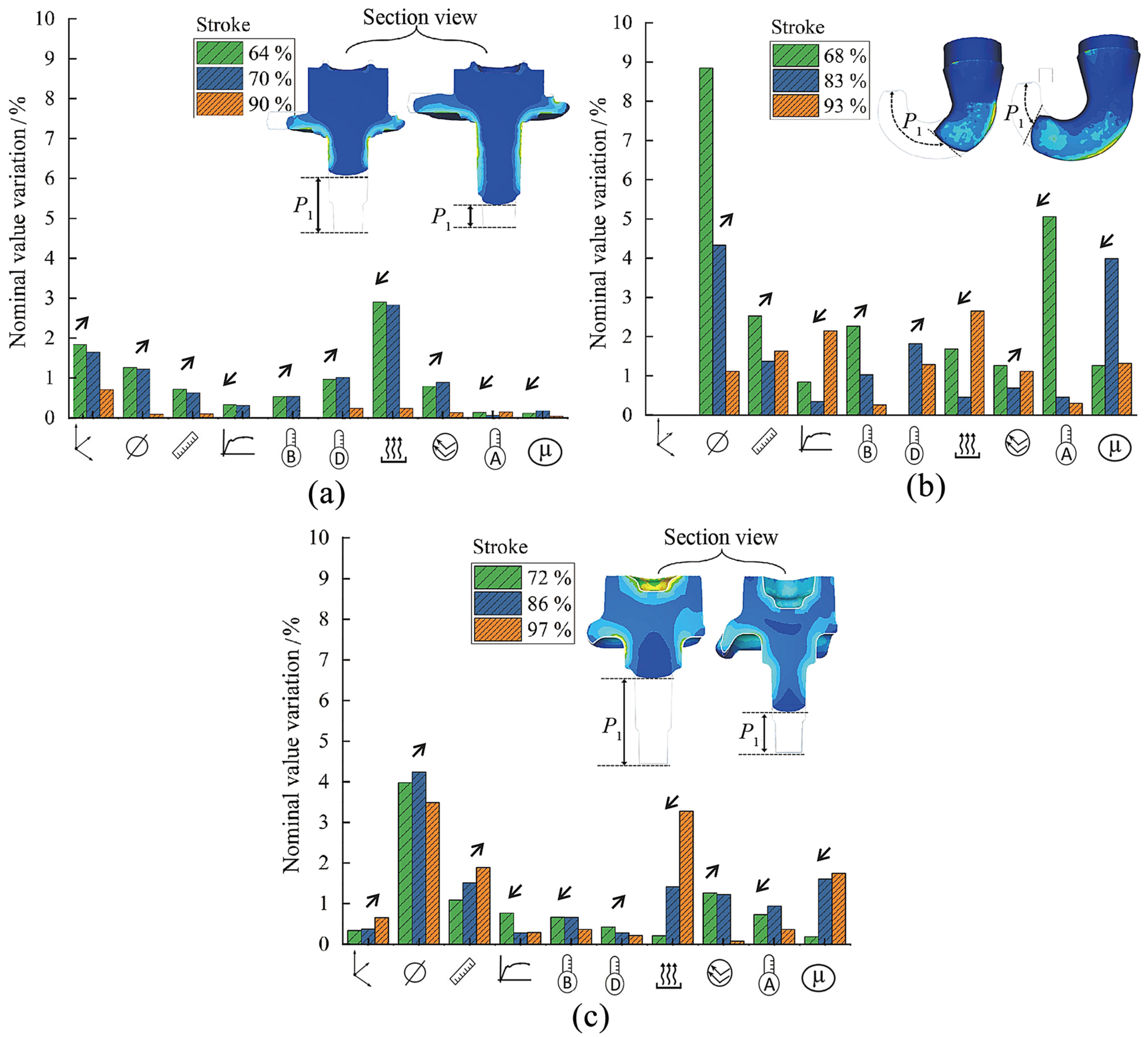

Fig. 5 Percentage effect of all input parameters **a** filling of H Spindle at 64%, 70% and 90% of stroke, **b** hook filling at 68%, 83%, 93% of total stroke, **c** filling of R spindle at 72%, 86%, and 97% of stroke

Overall, for vertical filling P_1, the NVV trend at each stroke decreases towards the end of the forging stage while the opposite behaviour is noticed in the case of horizontal filling. This suggests that material flows more in the vertical direction at the start of the forging step and decreases towards the end while less material flow is noticed in the horizontal direction at the start and more at the end of the process. The process parameter location has a minor effect when it comes to the vertical filling at P_1, but a significant effect is noticed when the location is studied for the horizontal filling (see Figs. 5 and 6). Also due to the higher clearance value between billet and dies surface in the H spindle, the NVV is found to be much higher in Figs. 6a, c, e, g compared to Figs. 6b, d, f, h, in R spindle.

From the force sensitivity analysis (see Fig. 7), the major outcome is the fact that the HTC and the material model are the main influencing factors and that these ones have an impact above the 20% on the NVV for all three industrial benchmarks. Due to the particular shape of the Hook benchmark, the friction coefficient also has a remarkable impact at intermediate filling with a minimum impact on the final stroke force as the filling is complete at that stage.

Aimed at developing the optimum NSF-DT calibration strategy for material-model validation/development, the following steps can be developed.

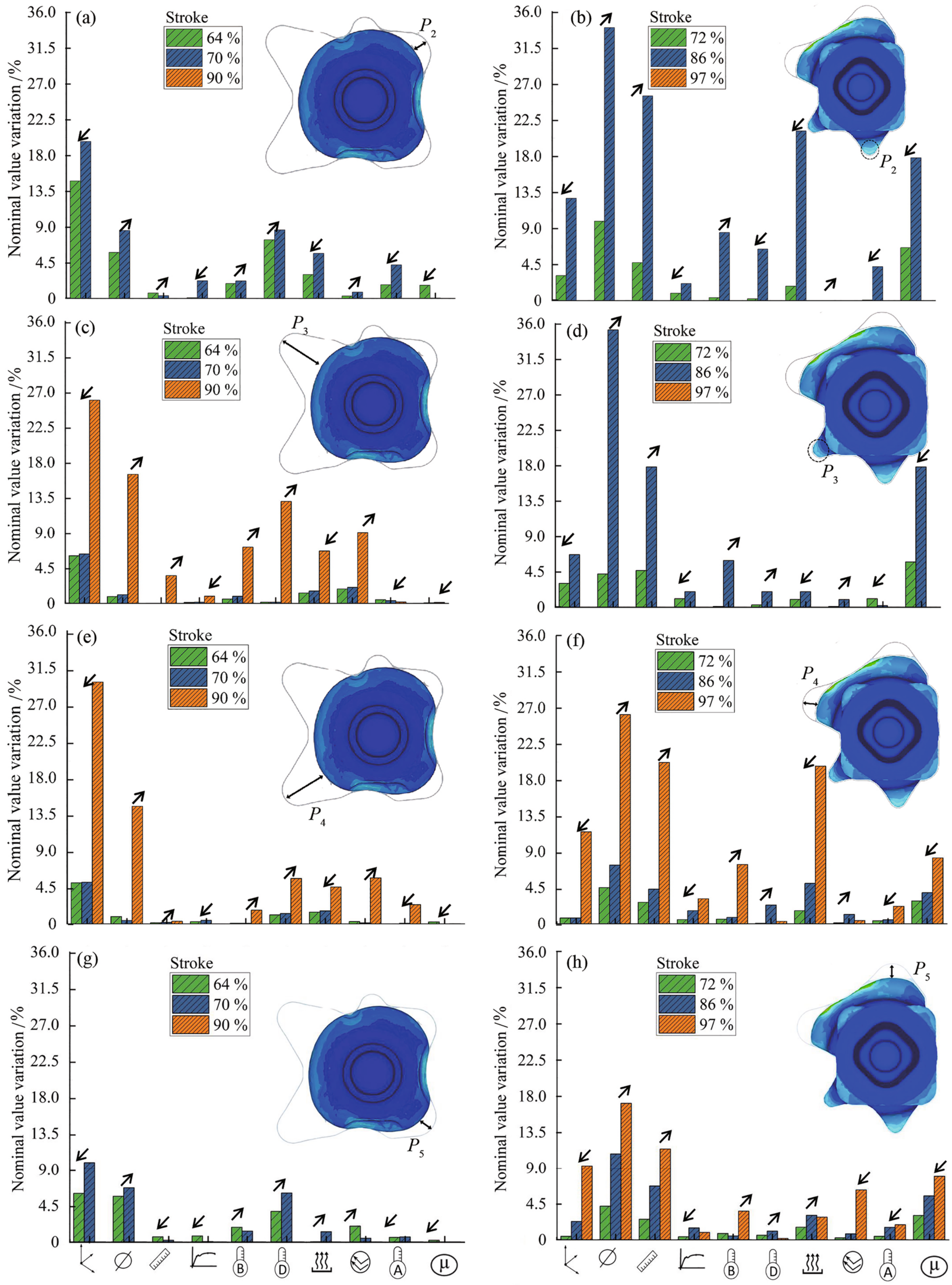

Fig. 6 Percentage effect of all input parameters **a**, **c**, **e**, **g** horizontal filling of (P_2-P_5), **b**, **d**, **f**, **h** horizontal filling of R spindle (P_2-P_5)

(i) First, it is critical to follow a unitary billet measurement (and therefore unitary inverse NSF-DT simulation for the validation) to take-under control the impact of the billet length and diameter.

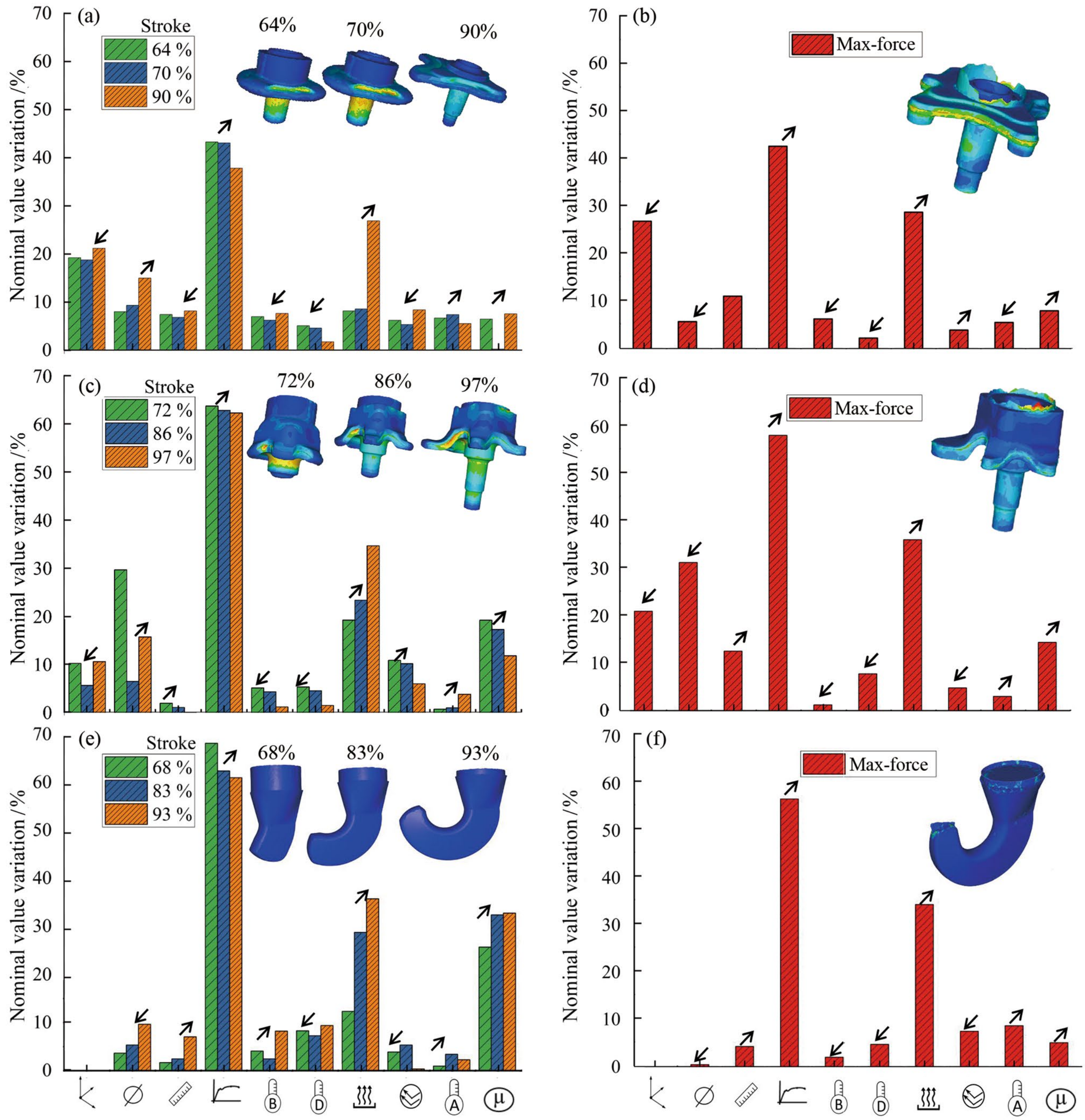

Fig. 7 Percentage effect of all input parameters on forming force **a**, **c**, **e** forces at three different strokes in all geometries **b**, **d**, **f** the maximum forces in all three geometries

(ii) To conduct HTC experimental characterization at NSF forging temperatures to have the correct HTC value. This could be performed using the columnar testing procedure presented by Ref. [40] for hot stamping applications.

(iii) Once the HTC is characterized, friction characterizations can be performed by spike test as proposed by Ref. [21] on their work on friction characterization of hot Ti forging.

(iv) Then, the thermocouple-based die temperature measurement, together with the inverse fitting methodology, using the vertical and horizontal filling measurements, could lead to the correct calibration of the emissivity, die temperature and ambient temperature. Even if they are not critical for the forging forces, the higher the accuracy of each parameter, the higher the precision of the NSF-DT.

(v) Finally, the force measurement of the three benchmarks cases at different strokes could be used to develop/validate new NSF material models with the believe of the right influence result ratio.

4 Conclusions

Aimed at developing the optimum NSF-DT validation for the NSF material model development a Taguchi's DOE technique was used on three industrial benchmark cases, i.e., H and R spindles and a Hook. In this sensitivity study, the major process parameter noise and BC parameter uncertainty impact on die filling and forming forces have been studied. These process parameters are proposed of location, diameter and length of the billet, material, billet and dies temperature, HTC, emissivity, ambient temperature, and friction coefficient. The process parameters were examined using the Taguchi design technique. Overall total of 44 experiments were performed on three industrial components made of 42CrMo4 steel sheets and the following findings were made based on DT analysis.

(i) Results showed that material flow was faster in the vertical direction at the initial stage of the process which decreased towards the end of the forming stage while the opposite behaviour was noticed for horizontal filling (P_2–P_5).

(ii) Taguchi results revealed that the NVV of filling for P_1 was majorly affected by the diameter and length of the billet, HTC and friction coefficient which was range between 2% and 9%. While the location, material and temperature of the billet, die temperature, emissivity and the ambient temperature had a negligible effect on the filling.

(iii) Similarly, the location, diameter, length of the billet, HTC and friction coefficient had a significant effect on the horizontal filling from P_2–P_5 whereas other parameters such as material, billet and dies temperature, emissivity, and the ambient temperature had a minor effect.

(iv) Moreover horizontal (P_2–P_5) and vertical filling (P_1) is directly proportional to the diameter, length of the billet, temperature of the billet and dies while inversely proportional to the material properties, HTC, ambient temperature emissivity and friction coefficient in the process.

(v) The principal factors for the press forces are found to be the material of the billet, HTC, and friction coefficient with the NVV range from 30%–64%, while the next significant parameter is the billet diameter, where as the remaining parameters have a small effect on the process forces.

(vi) The press forces increase by increasing the material properties, billet length, HTC, ambient temperature, and friction coefficient and decrease with the increase in diameter, emissivity, billet and dies temperature.

Overall, to develop an accurate DT strategy of the NSF, where the forces is the major factor to consider, it is important to focus on the material properties, HTC and friction coefficient. Similarly for the material flow inside the dies, these parameters are diameter, length of the billet, HTC and friction coefficient.

With all these conclusions in hand, the authors proposed novel optimum NSF-DT calibration strategy for material-model validation/development. The authors believe that the conducted sensitivity study and the proposed calibration strategy will be a key information for future NSF-DT developments and their industrialization.

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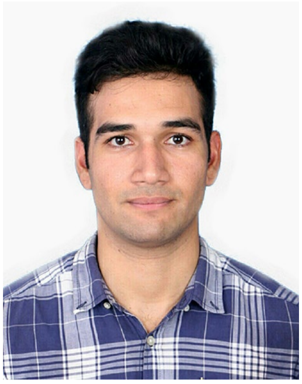

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