# Digital twin development for the sensitivity analysis of near solidus forming process

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**Abstract.** Near Solidus Forming (NSF) process, performed at semi-solid material state is gaining popularity due to its good physical properties, low manufacturing cost and material waste. Although the process possesses many advantages over traditional hot forging, the nature of the process itself is very complex and due to this the researcher struggles to identify the material behavior at NSF conditions. Especially the material model in this condition has not been stated clearly before and therefore it is important to develop a reliable digital twin (DT) strategy which can validate the material model efficiently. Therefore, the objective of this work is to investigate the influence of all DT parameters like billet material and dimensions, billet and dies temperature, heat transfer coefficient, emissivity, ambient temperature, and friction coefficient, in two industrial components such as H spindle and R spindle. The Taguchi Design of Experiments (DOE) approach combined with numerical simulation in FORGE NxT® is employed to develop the sensitivity analysis of the process. The impact of all parameters in the DT are evaluated in terms of die filling and forming forces, and its importance in the material model is studied. Results show that the newly developed approach proposed a novel optimum NSF-DT calibration strategy for material-model validation. Which can be used to develop an accurate model of the NSF process at the laboratory and industrial scale

## Introduction

Forging is a widely used technology in the field of automotive, aerospace, and other engineering sectors around the world. The process is important due to its cost efficient and reliable spectrum of manufacturing for planes, cars, and ships components. Furthermore, the processed components possess superior mechanical properties which are best suited for critical applications. The process is done either at room or high temperature based on the material and the desired properties of the components. In particular, Near solidus Forming (NSF) process is referred to the one developed critically close to the solid temperature and it is gaining popularity due to its good physical properties, low manufacturing cost and material waste compared to traditional hot forging process [1,2]. Although gaining popularity, the process is not still fully developed, and it is not clear how the physics behind the NSF develops [1]. This is due to the complex behavior of the material at such a high temperature. Previous NSF-DT studies have shown an important gap on the prediction of forces and filling [2]. Researchers suggested that material is the key factor influencing the process and developing a correct model can be a key object to understanding how this process works [3]. Others investigated that the boundary conditions play a significant role in the process and by controlling certain parameters the processes could be developed accurately [2].

Talking about the history of the process the main development was gained in the semi-solid forming processes initially from the investigation of low melting point alloys [4], even some trials were carried out with stainless steels [5]. However, the high costs associated with the production of globular aluminum alloys, compared with the die casting ones, made this process infeasible for industrial production. Despite this drawback, some electronic consumer goods and automotive parts were manufactured by taking advantage of this technology [6].

Nevertheless, in 1992 the first investigations about semi-solid forming of steels at high solid content were performed by P. Kapranos et al. [7]. Since then, many researchers have tried to manufacture sound components by gaining the advantage of this near-net-shape technique to bring it closer to industry without fortune[8, 9]. Gourlay et al. studied material behavior at a high solid fraction, typical in NSF processes [10]. For instance, at values from 0.9 to 1, granular behavior was reported. Another important aspect is the process temperature as maximum load and ductility were shown to decrease when the temperature is increased [11].

To learn the process deeply, the investigation of certain factors is necessary such as the values of the heat transfer coefficient (HTC) and friction factor during the process. This knowledge is necessary to achieve realistic simulations and generate reliable, and useful results about the process.. As friction is a universal phenomenon influencing the metal forming process and it is inevitable for friction to exist between dies and workpieces. In addition, friction gives rise to redundant energy usage by increasing the process load requirement. The forming load, the die wear and the surface finish of the product are significantly influenced by the friction. For this reason, an appropriate evaluation of this parameter is very essential in metal forming. To obtain precise friction characterization during the forming process, several experimental methods were presented. There are several friction tests, some of which has advantages over another and also shortcomings. Noticeable among them are the ones employed in metal forming: the ring test, double-cup extrusion test and the spike test [12,13]. Specifically for the case of NSF, a T-Shape spike test which is developed by Zhang et al. can be used to avoid the difference of friction conditions on the cylinder surface and end surface of a round billet [13,14]. Deformations, including both extrusion and compression, are involved in this test and only the cylindrical surface of the billet is in contact with the punch and die.

Furthermore, Dadras and Burte et al. investigated the interface HTC [15]. Later, Burte and Stone extended the work of Dadras and predicted HTC values and simulated forging operations [16]. To understand the heat transfer under lubricated condition, Azushima et al. conducted the compression and compression-sliding tests of aluminum-coated 22MnB5 under dry and lubricated conditions using the hot fat drawing test simulator [17]. Similarly, Y. Chang et al. also investigate factors that influencing the HTC and an actual hot-formed automotive B-pillar was obtained in experiment to validate its formability under various contact pressures [18, 19].

Bai et al. introduced an efficient closed-form technique for the determination of HTC at different forming and contact conditions based on finite element (FE) heat transfer analysis using FE software DEFORM [20]. Similarly, Chang and Bramley used FE tools to determine the HTC at the work-piece/die interface for forging process by conducting an upsetting test where the surface temperature of the die was recorded [19]. Then the measured and predicted temperatures were combined using an inverse algorithm to determine the HTC.

The nature of the NSF process is that the real-time experiments are time-consuming and costly [21]. To overcome this, the Finite Element Method (FEM) tools are widely used to model and simulate forming processes and results such as temperature changes, stress, strain, deformation and load history in the die, and in the workpiece can be studied [22]. However, advances in the numerical analysis of complex forming processes require the better understand of interface characteristics for heat transfer and friction. For example, Petersen et al. proposed the FEM in conjunction with metal experiments to verify the general feasibility of the proposed test geometry and pointed out that the practical ring-compression test was more commonly used for the quantitative evaluation of the tribological conditions at the die/work-piece interface in metal forming [23].

Nevertheless, many authors compared the DT material models to their experiments and concluded that the material model plays a vital role in the forming processes and the actual models are not capable of correctly representing the NSF phenomenon[24]. However, NSF-DT are strongly depended on the process parameters noise and BC uncertainty, e.g., HTC, friction coefficient, billet tolerances. Therefore, without having all these dependencies under control one can does not assure that the differences shown between experimental, and NSF-DT are coming from the material model. This work has a double objective. On the one hand, by means of a DOE approach, the sensitivity to the main outputs (force and filling) to the material model and other influencing parameters is studied. In this way, the impact of each factor can be evaluated. On the other hand, once the influencing parameters and their impact are established, the optimum NSF-DT strategy is developed in order to be able to rely on the DT for material model validation purposes.

## Material and Methods

The material used in this process is 42CrMo4 steel and its chemical composition is shown in the Table 1. The material is suited for high-temperature forming due to its fatigue strength and ductility properties. The industrial process used as a reference in this study consists of three major steps, shown in Fig.1. Initially, the billet is heated homogeneously in the furnace to the desired temperature by maintaining a uniform temperature throughout the furnace. Next, the billet is transferred from the furnace to a worktable through a mechanical arm as quickly as possible to minimize heat loss. The deformation die-set consists of top and bottom dies while a punch which deforms the billet. Finally, in the last step, the punch moves from the top dead center to the bottom dead center and the deformation takes place, this way the desired shape is achieved.

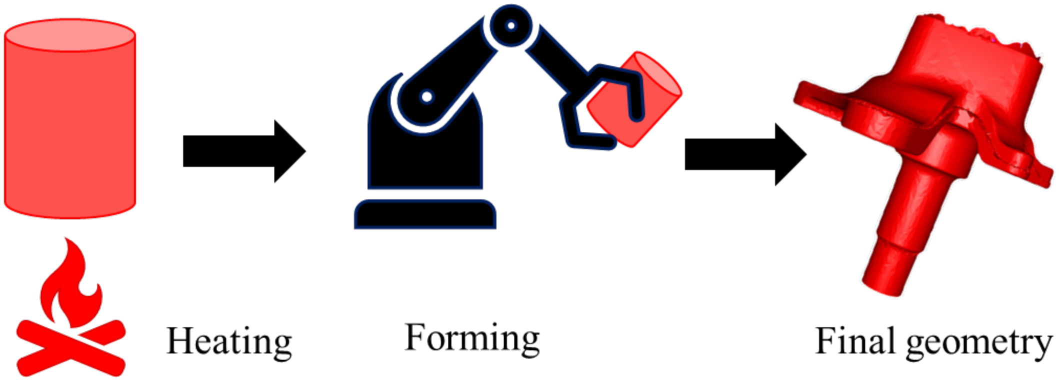


*Fig. 1. NSF process flow detail.*

The two industrial components used in this study which were recently manufactured at Mondragon University are shown in Fig. 2. The weight of H spindle workpiece is a ~2.3 kg and the R Spindle a ~3 kg.

*Table 1. Chemical composition of 42CrMo4 steel %wt.*

| Cr | Mn | C | Mo | Si | P | S |
|---|---|---|---|---|---|---|
| 1.05 | 0.75 | 0.41 | 0.22 | 0.20 | 0.02 | 0.02 |

The numerical tool FORGE NxT® is used to reproduce the entire NSF process in order to analyze the effect of all parameters during forming. The simulation procedure includes all the steps such as heating of the billet in the furnace, transfer of the billet and lastly the deformation phase. A servomechanical press with a capacity of 400 tons was used and its specification of forces, ram speed and ram position during deformation can be seen in work from Lozares et al. [2].

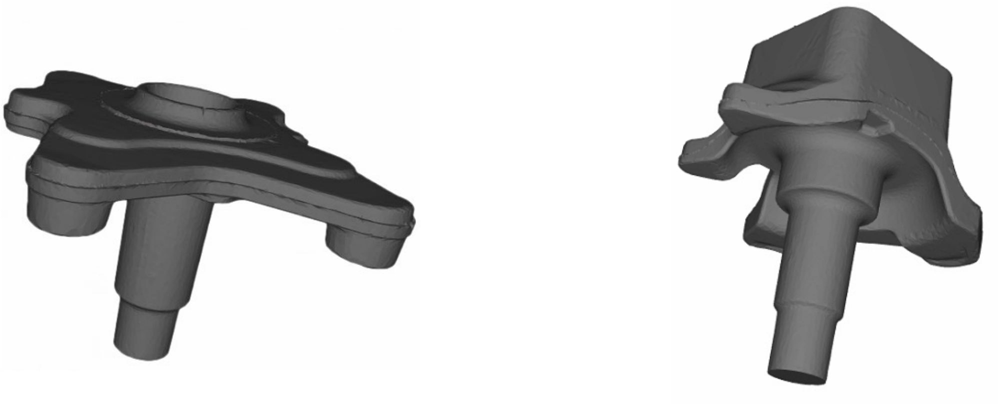

(a) (b)

*Fig. 2. NSF industrial components (a) H spindle and (b) R spindle.*

In the study, the effect of 10 parameters such as material, billet dimensions and temperature, (HTC), friction coefficient (FC), ambient temperature and emissivity are investigated. To study the effect of material on the process the strength of the material is reduced by changing the constitutive parameters. The level of each individual parameter is presented with symbol letters from V1 to V10, shown in the table 2. Since a list of parameters are considered in this study and to fully investigate the effect of individual parameter a design of experiment Taguchi DOE approach is used where the effect on input parameters is studied in relation to the forming force and fillings. However, based on the available data, the L16 orthogonal array is selected. The experimental design table is generated by employing data into Minitab software. Overall, total of 32 simulation were run, 16 of which for the H spindle and 16 for the R spindle and their result has been presented in the results section.

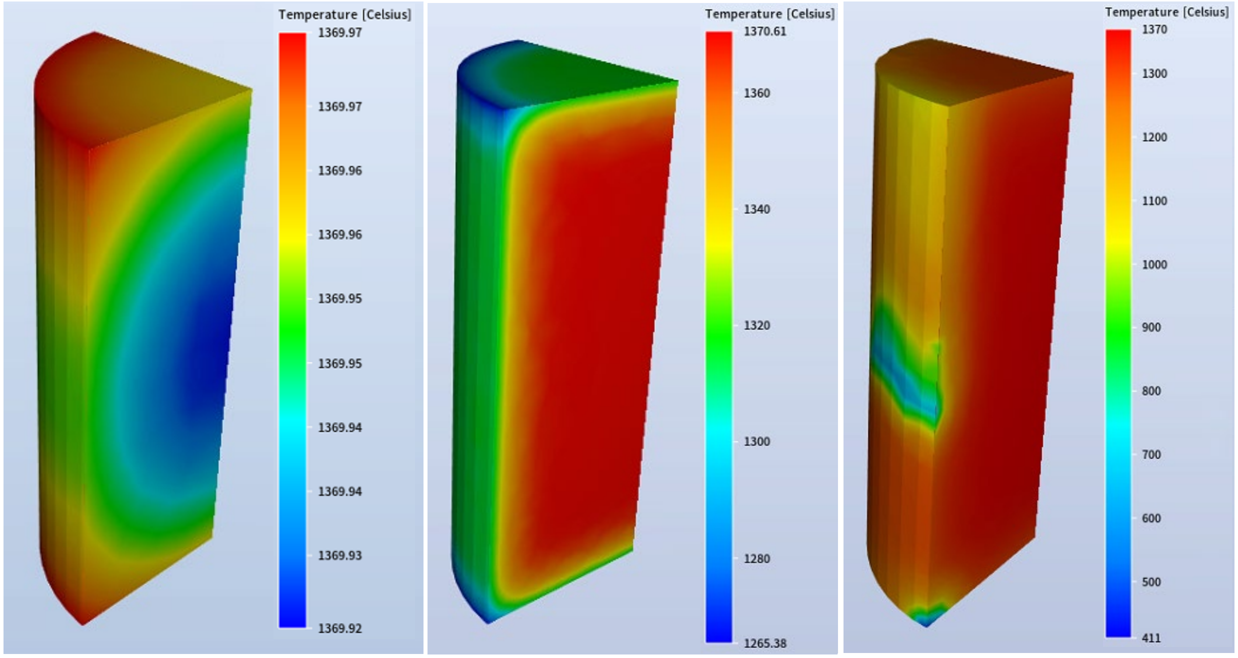
*Table 2. Parameters detail and its Levels in Taguchi Method.*

| **Component** | **Symbol** | **H-Spindle** Level 1 | **H-Spindle** Level 2 | **R-Spindle** Level 1 | **R-Spindle** Level 2 |
|---|---|---|---|---|---|
| Billet Location (four points) | V1 | 1,2 | 3,4 | 1,2 | 3,4 |
| Billet Diameter (mm) | V2 | 64.7 | 65.3 | 68.7 | 69.3 |
| Billet Length (mm) | V3 | 89.5 | 90.5 | 92.5 | 93.5 |
| Material Strength % | V4 | 50% | 100% | 50% | 100% |
| Billet Temperature (°C) | V5 | 1360 | 1370 | 1360 | 1370 |
| Dies Temperature (°C) | V6 | 200 | 270 | 200 | 270 |
| Heat Transfer Coefficient (kW/m$^2$.K) | V7 | 2000 | 20000 | 2000 | 20000 |
| Emissivity | V8 | 0.35 | 1 | 0.35 | 1 |
| Ambient Temperature (°C) | V9 | 50 | 70 | 50 | 70 |
| Friction Coefficient | V10 | 0.25 | 0.45 | 0.25 | 0.45 |

For filling calculation, horizontal and vertical filling has been selected and based on the components shapes five points have been selected for the R and H spindle. The filling has been calculated from these reference points at three different punch strokes in each case. Similarly, the forces were also calculated at three different strokes.

## Results and Discussion

NSF process strongly depends on the temperature and a small variation can make a big difference in the output. Therefore, knowledge of the process cycle during heating and also in the transfer phase is mandatory. A typical example of the billet heating phases from heating to the deformation stage is shown in Fig. 3. Fig. 3(a) represents the temperature field of the billet inside the furnace when heated up to 1370°C. The temperature distribution seen in Fig. 3 (a) shows clearly that the outer surface of the billet has the highest temperature reading as it is directly in contact with the heat source. Overall, it can be seen that uniform temperature distribution is achieved at the end of the heating phase. Fig. 3(b) represents the temperature plots after the transfer phase, which indicates that the surface of the billet cold fairly fast even for the transfer time of ~3 seconds. The temperature field after the stand-by time of workpiece for ~2 seconds on the compression tool is given in Fig. 3(c), where the temperature range is between 411°C and 1370°C. This? shows how quickly the heat can be transferred from the billet to the contacting surfaces especially the ones with lower temperatures. That's why it is always preferred to deform the billet as soon as it is placed inside the forming tool.



(a) (b) (c)

*Fig. 3. Temperature distribution (a) After heating the billet up to 1370 °C (b) temperature field at 1370 °C after transport to compression table (c) temperature field after waiting time.*

The deformation phases of R spindle during simulation from start to end is shown in Fig. 4. The equivalent strain representation shows that the higher values of stresses are develop in the contacting area of the billet and the punch at the initial stages of the process. Once the process crosses through a certain threshold, the stress concentration shifts to the lower side of the billet where the deformation is intense as can be seen in the Fig. 4 right side geometries. Similar behavior is noticed in H spindle as well.

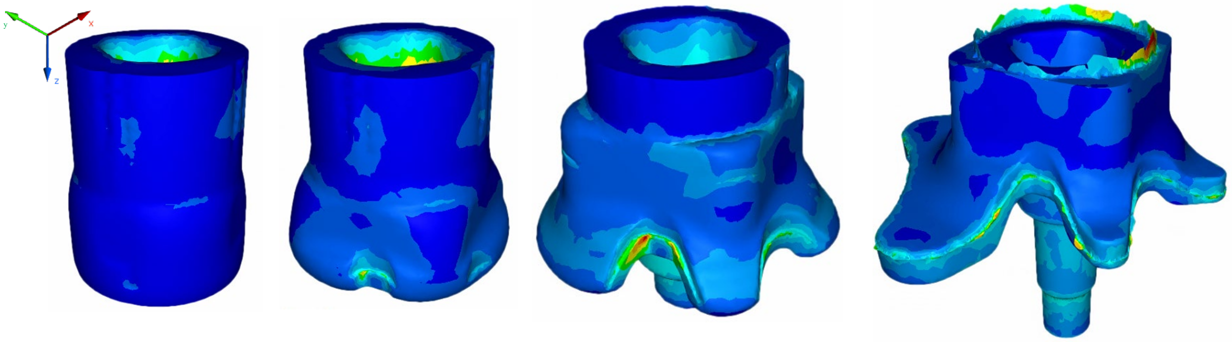


*Fig. 4. Deformation phases of the R spindle from the start to the end of the process.*

The results of the die filling and forces are indicated in Fig. 5. The x-axis of the plots shows the ten parameters while the y-axis represents the nominal value percentage of filling and forces values. As mentioned before that we have two types of filling, Fig. 5(e) represents the filling calculation in the punch direction which will be in the z-axis according to the Fig. 4, while Fig. 5(a-d) indicates the filling in the horizontal axis horizontal to the z plan. The forces are indicated in Fig. 5(f). The plots are calculated at three different strokes in each benchmark in order to have an overall view of the parameters effect by taking the average of the outputs values.

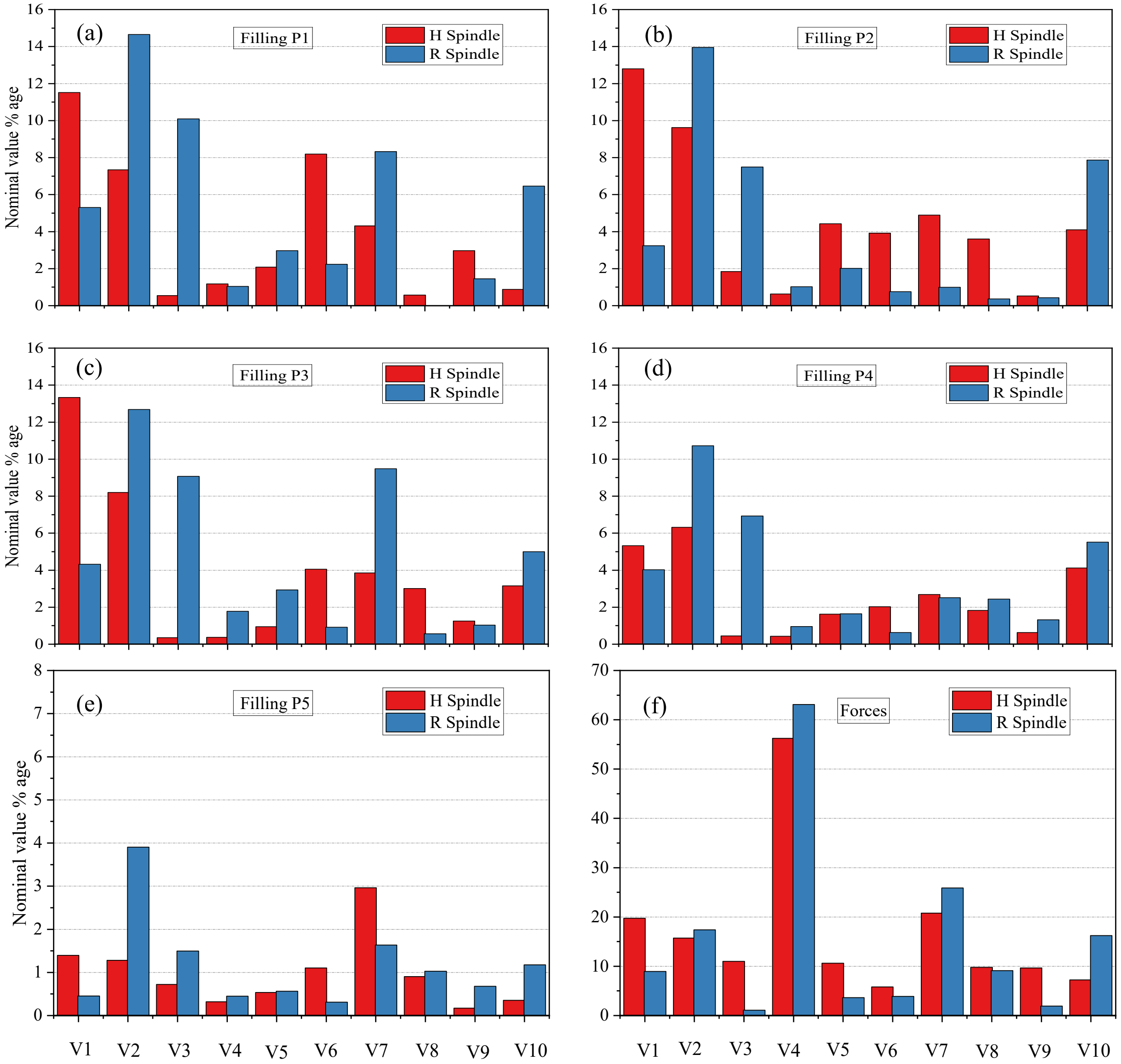


*Fig. 5. Nominal value percentage of H and R spindle (a-e) die filling (f) punch forces.*

Nevertheless, it is clear that the filling in the horizontal axis strongly depends on the location of the billet placement as shown in Fig. 5(a-d). Where in terms of forces the location plays a minor role in this process, see Fig. 5(f). The billet location can be optimized by trial and error, and it can be always different for every single component. Next when it comes to the dimension of the billet, its effect is always found to be high seen in Fig 5(a-e). For example, filling in any axis is strongly dependent on the diameter and length of the billet meaning the billet with a bigger size can achieve better and complete fillings whereas a smaller billet can cause pores or unfinished surfaces in the part.

In the boundary conditions parameters, which can be of the most interest for the NSF process. The major influencing factors are the heat transfer coefficient, friction coefficient (FC) and material strength which is having a nominal value percentage effect of up to 9 % on the process as shown in Fig. 5. The result suggested that by increasing the FC from 0.25 to 0.45 the material flow in the process was reduced and similar behavior was noticed for HTC and material strength. Other boundary condition parameters such as ambient temperature, billet and dies temperature are negligible as they have on average of 2-3 % effect and changes in its values had a minor effect on the process.

Next, the punch forces are found to be strongly dependent on the material of the component as shown in Fig. 5(f), with a whopping value of 55-65 %. It is obvious, a material with high strength will require more force to deform compared to ductile material. The most interesting thing to notice here besides material is the effect of HTC and FC on the forces. The effect of HTC is found to be 24 % and FC at 15 %. From the calculation, the forces are found to be rising by making an increase in the values of these two individual factors. And the remaining parameters are found to be least influencing factors with the individual effect below 9 %.

Overall, we can conclude from the DT of the NSF process, to optimize the filling it is important to focus on the location, billet dimensions, HTC and FC. While to reduce the punch forces it is important to study and optimize the material properties, HTC and FC. And by characterizing these parameters and optimizing their values at the NSF condition, one can create a material model with good accuracy.

## Summary

The effect of process parameters and boundary conditions in the NSF process is numerically investigated for 42CrMo4 steel. Taguchi design methodology combined with Minitab is employed and the data were simulated in the FORGE NxT®. The outcome of the process is stated in terms of forces and material filling in the dies. The following conclusions are drawn from the present work:

- Among all ten factors, the most significant factor which affects the filling is the location and dimensions of the billet, which are subjective factors and can be optimized by trial and error.
- The important parameters which can be of scientific interest for the development of the NSF process model are the material strength, HTC and FC, and their impact is also high on the filling.
- For the forces, the major influencing factor is the material, and this factor contributes 55-65 % of the total force values. Other factors such as HTC and FC are found to be up to 30 %.
- The remaining factors such as billet and dies temperature, emissivity and ambient temperature can be neglected and always remember that these parameters can have a different effect on the process if their ranges are different to the assumed ones. But since NSF is performed at high temperatures these ranges are considered based on the temperature requirements of the process.
- With all this knowledge in hand, it is concluded that to develop an accurate model of the process it is important to characterize first the most influencing factor both in filling and also for forces. These factors can be characterized by using experiment tests such as spike test for FC and compression test for HTC and so on.

Overall, the developed DT strategy provides useful information regarding NSF process at the industrial level and using this result one can develop an accurate material model by focusing on the major influencing factors in the process.

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