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Parameters Optimization of Metal Forming Process

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In metal forming process, the initial shape of the billet is usually simple. Even for some complicated parts, the cylinder is always be used. But defining the dimension of the initial cylinder billet is the most important step for product quality control. Reasonable initial billet dimension can not only reduce raw material cost but also improving mechanical properties of the part.

In this paper, a metal forming parameters optimization system was developed. It arrives at the optimum values by using finite element analysis numerical simulation and response surface method (RSM). To develop this optimization system, several numerical tools are required: geometric modelling (CATIA V5™), FE analysis (ABAQUS®), and optimization computation (ModeFRONTIER®).

A two-step axisymmetric forging project was studied as an example by using proposed method.

Keywords: Metal Forming Process; Numerical Simulation; Optimization; The Initial Billet Dimension; Response Surface Method (RSM)

Introduction

Nowadays, in metal forming process the numerical simulation is used to avoid long and expensive experiments and many research works have been made in this aspect [1-2]. In this paper, the main objective is to simulate metal forming process coupled with an optimization procedure in order to obtain the optimal parameters. In the Mechanical System and Concurrent Engineering Laboratory (ICD-LASMIS), an extensive work has been developed since ten years. A finite element package has been developed to solve thermo-visco-elasto-plastic problems with ductile damage in large deformation. This package allows realizing automatically numerical simulation of metal forming processes. In order to avoid large mesh distortions and achieve properly the convergence of calculation, meshing and re-meshing procedure are also included [3-5].

The whole model of metal forming process optimization system is shown in **Figure 1**. In order to connect all these operations together automatically in ModeFRONTIER®, the different macro commands are used to realize it. First, the CATIA™ macro command is used to create the geometry of the tools and define the parameters that we want to optimizer. Then, the ABAQUS® macro command is used to input the shape and processing parameters into a software package based on ABAQUS® to simulate the metal forming process. Finally, the advanced optimization algorithm is performed to reach the optimum variable values on the response surface established.

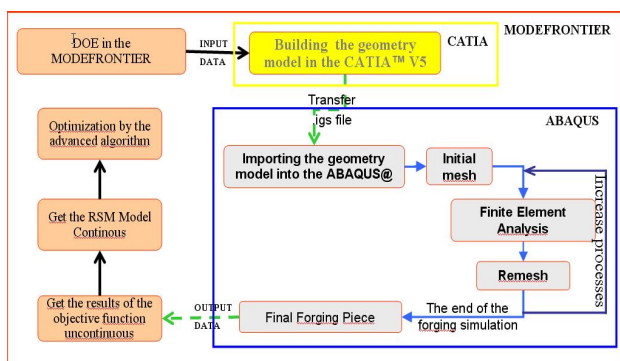


Figure 1. The metal forming process optimization system.

1 Numerical Simulation of Metal Forming Process

The numerical simulations of metal forming processes by using the finite element package developed in our laboratory are presented in this paragraph.

1.1 THERMO-VISCO-ELASTO-PLASTIC BEHAVIOUR MODEL

A thermo-elato-viscoplastic behaviour model is used for the simulation of forging operation imposed different multi-physic coupling (temperature, plastic strain, and plastic strain rate). This advanced constitutive equations proposed a non linear isotropic and kinematic hardenings strongly coupled with ductile isotropic damage. The coupling between the ductile damage and the elasto-viscoplastic constitutive equations is formulated in the framework of the thermodynamics of irreversible processes together with the Continuum Damage Mechanics (CDM) theory [4-6].

1.2 NUMERICAL ASPECT

The fully coupled thermomechanical constitutive equations presented above have been implemented into Abaqus/Explicit FE code using the Vumat user subroutine. The dynamic explicit resolution procedure has been used in order to solve the thermomechanical problem based on both weak forms relative to the equilibrium and thermal equations. In the case of an updated Lagrangian formulation, the high non-linearity and the large plastic deformation can distort the element of the mesh. To avoid this numerical problem and modulate the fracture propagation, a new numerical methodology based on different tools (DIAMESH2D: 2D triangular and quadrangular mesher, error estimates, transfer fields, automatic sequence load or re-meshing) has been developed in ICD/LASMIS in collaboration with UTC/Roberval [3-4].

2 Optimization Problems

2.1 VARIABLES

There are so many factors associated with the metal forming process. In this paper, we deal with the example of an

aluminum forged part which is obtained by two different operations (plating and forging).

The plating operation (**Figure 2**) is realized with a mechanical press, and the upper tool is translated with a constant velocity $V_{tool}=50\text{ mm/s}$. The forging operation (**Figure 3**) is realized with a hammer, two blows are needed to completely deform the part. The kinematic energy imposed to the upper tool is the same for blow 1 and blow 2, which is equal to 30KJ. We defined that the initial dimension of the cylinder billet $R_{initial}$ and $H_{initial}$ and the final height of the billet after plating process H_{final} are the variables to be optimized which are shown in **Figure 2** and the final shape of the part after forging operation is shown in **Figure 3**.

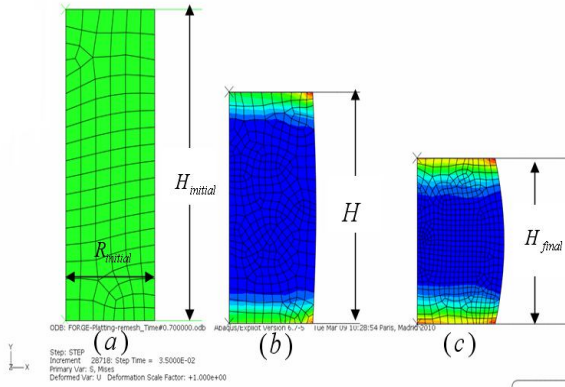


Figure 2. Plating operation.
(a: $H=H_{initial}=110\text{mm}$ b: $H=90\text{mm}$ c: $H=H_{final}=70\text{mm}$)

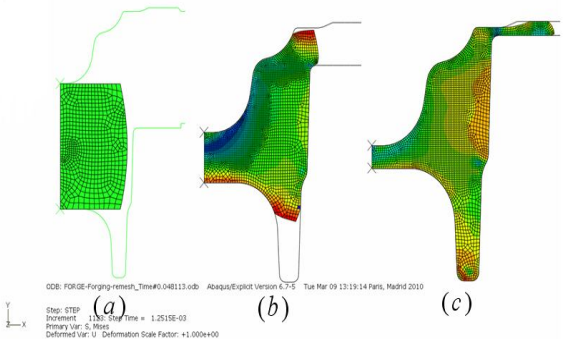


Figure 3. Forging operation.
(a: Initial shape b: Shape after one blow c: Shape after two blows)

2.2 OPTIMIZATION OBJECTIVE FUNCTIONS

The forging energy is strongly related to the over heating. From an economic point of view, it is important to minimize forging energy [7]. Another criterion that should be taken into account during the optimization is the metallurgic quality of forged parts. It's related directly to the uniformity of distribution of plastic deformation [8].

So in our work, the objective functions are defined as the minimization of forging energy, improving metallurgic quality of forged parts and reducing the maximum forging force during the operations. And it can be summarized as the following functions (1-3):

$$F_{obj}^I = \min \left(\int_0^{t_1} \int_{V_{plating}} (\underline{\sigma} : \underline{\dot{\epsilon}}_1) dV dt_1 + \int_0^{t_2} \int_{V_{forging}} (\underline{\sigma} : \underline{\dot{\epsilon}}_2) dV dt_2 \right) \quad (1)$$

$$F_{obj}^{II} = \min \sum_{i=1}^{Nb_{ele}} \frac{V_i}{V_T} (\bar{\epsilon}_i^p - \bar{\epsilon}_{avg}^p) \text{ with } \bar{\epsilon}_{avg}^p = \sum_{i=1}^{Nb_{ele}} \frac{V_i}{V_T} \bar{\epsilon}_i^p \quad (2)$$

$$F_{obj}^{III} = \min F_{max} \quad (3)$$

Where $\underline{\sigma}$ is the Cauchy stress matrix; $\underline{\dot{\epsilon}}$ is the (elastic and plastic) strain rate; Nb_{ele} is the total number of the elements; V_i is the volume of element i ; V_T is the total volume; $\bar{\epsilon}_i^p$ is the equivalent plastic strain computed at the unique Gauss point of the element i ; $\bar{\epsilon}_{avg}^p$ is the average equivalent plastic strain; F_{max} is maximum force value during the plating operation.

2.3 OPTIMIZATION CONSTRAINTS

Several constraints should be considered, including damage, wrinkle and achieving the right configuration at the end. And it can be summarized as the following functions (4-6):

$$S.T. D(i) \leq D_{max} \quad (4)$$

$$\theta(i) = \arccos(\vec{n}_i \cdot \vec{n}_{i+1}) \geq \theta_{min} \quad (5)$$

$$S = \sum gap(i) \leq S_{max} \quad (6)$$

In function (4), $D(i)$ is the damage value of the element i inside the machining part of the piece which is shown in **Figure 4** and the maximum value of the damage D_{max} is set to 0.1. If the damage value outside this part is larger than D_{max} , we also think that the forged part is available for the following operations.

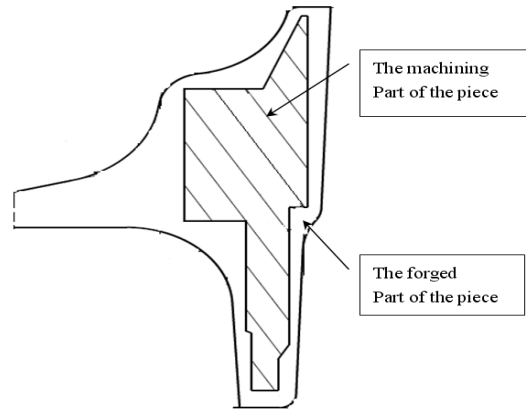


Figure 4. The constraint of Damage condition.

In function (5), θ is the angle value of the nearby two contour elements as shown in **Figure 5** and the minimum value of the angle θ_{min} is set to $\pi/3$. If $\theta(i)$ is larger than θ_{min} , we can get the conclusion that there is no wrinkle in the forged part.

In function (6), S is the total value of the gap distance between the contour element nodes of the achieved part and the required part and the maximum value of the total distance S_{max} is set to 6mm. This value is to verify whether the part fills well or not in the tools. As shown in **Figure 6**, in order to make the value more precise, we

make a box at the end of the flash part, because when calculating the gap, this part is useless to our results, so we just accumulate the gap value outside this box.

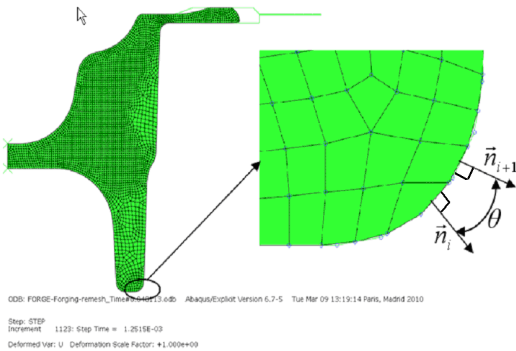


Figure 5. The constraint of Wrinkle condition.

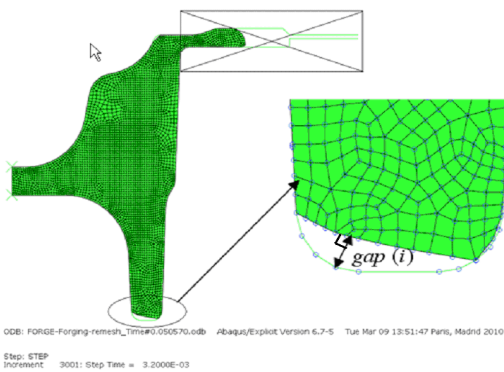


Figure 6. The constraint of Filling condition.

3 Optimization System Model

There are several steps for this metal forming optimization system, including input part, output part and the simulation running part. The workflow in the ModeFRONTIER software is shown in Figure 7.

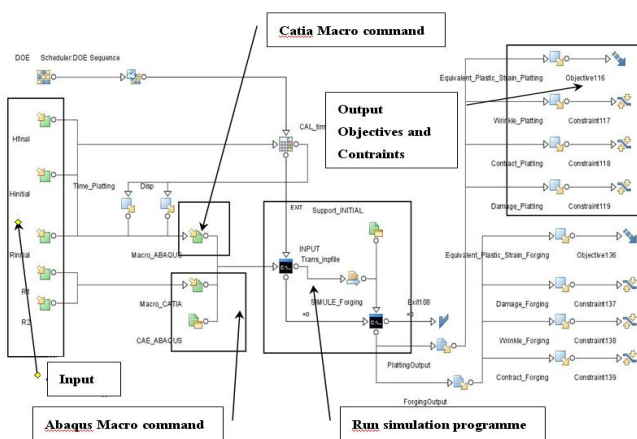


Figure 7. The optimization system workflow in ModeFRONTIER.

4 Response Surface Method

A simulation of the forging process requires a large amount of calculation. In this situation, a meta-model based on the responses surfaces can be built with few simulation processes. A meta-model can be defined as a

collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes [9]. So to rapidly get the optimum design values, an appropriate optimizer algorithm is used and all evaluations on the objective and constraint functions are evaluated with a specific meta-model.

5 Applications

To illustrate the methodology described above, an initial billet dimension optimization system based on response surface method is proposed. In our application, it is assumed that the starting shape is cylinder, and we set the value of variable $H_{initial}$ are 110, 115, 121, 128 and 135mm. The volume of the initial billet ($V_{initial}$) is fixed which is equal to 552640 mm^3 , so $R_{initial}$ can be calculated. Another variable H_{final} are defined as 70, 75, 80 and 85mm. There are 20 simulations have been down and the Simulation parameters are as follows: material: 2017A, forging temperature: 360° .

F_{obj}^I	70	75	80	85
110	1,584E+07	1,602E+07	1,869E+07	1,917E+07
115	1,985E+07	1,578E+07	1,441E+07	2,162E+07
121	1,485E+07	1,664E+07	1,655E+07	1,454E+07
128	1,539E+07	1,509E+07	2,212E+07	1,430E+07
135	1,902E+07	1,416E+07	1,649E+07	1,563E+07

Table 1 The simulation results of F_{obj}^I (Mille Joules)

F_{obj}^{II}	70	75	80	85
110	4,338E-01	4,707E-01	4,758E-01	4,499E-01
115	4,239E-01	4,357E-01	4,422E-01	4,391E-01
121	4,205E-01	4,314E-01	4,394E-01	4,463E-01
128	4,149E-01	4,255E-01	4,291E-01	4,401E-01
135	4,132E-01	4,355E-01	4,342E-01	4,387E-01

Table 2 The simulation results of F_{obj}^{II}

F_{obj}^{III}	70	75	80	85
110	9,639E+05	9,180E+05	8,782E+05	8,378E+05
115	9,396E+05	8,987E+05	8,621E+05	8,266E+05
121	9,121E+05	8,802E+05	8,467E+05	8,154E+05
128	8,890E+05	8,550E+05	8,281E+05	8,013E+05
135	8,609E+05	8,249E+05	8,074E+05	7,850E+05

Table 3 The simulation results of F_{obj}^{III} (Newton)

After finishing all the simulations, we can get the interesting values that we need, including the objective functions results and the constraints results. The Tables (1-3) show the three objective functions results.

Based on all these results, the surface response model are generated which are shown in **Figures (8-10)**. For each figure, the left 3D picture is the response surface model. It represents the relationship between the two variables and the objective functions values. We get it by using classical two degree polynomial model which is easy to implement in solving our problem. The right one shows the contours plots of the variables values and the objective function results.

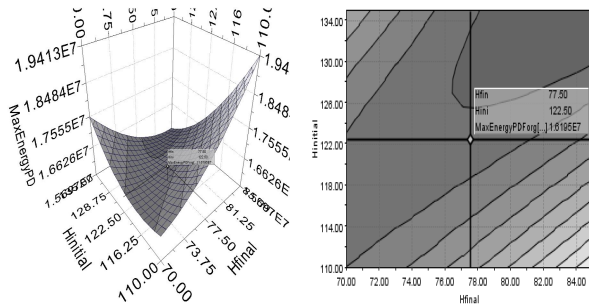


Figure 8. The response surface representing the relationships between the objective function F_{obj}^I and the variables.

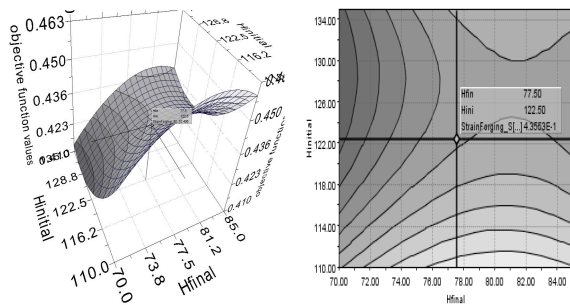


Figure 9. The response surface representing the relationships between the objective function F_{obj}^{II} and the variables.

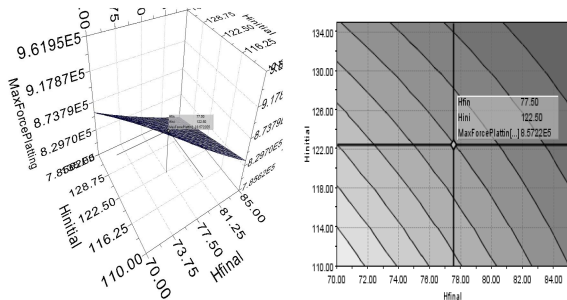


Figure 10. The response surface representing the relationships between the objective function F_{obj}^{III} and the variables.

Figure 8 shows that the distribution of the forging energy is nonlinear. The objective function F_{obj}^I reaches the maximum value when H_{final} is equal to 85mm. So during the forging process, the larger of the value of H_{final} , the more energy is needed. From **Figure 9** it can be learned that F_{obj}^{II} is more influenced by the value of H_{final} and decreasing H_{final} leads to increase the deformation uniformity. When the value of H_{final} is small, the equivalent plastic strain propagates uniformly in all part which may benefit the forging part. But for a large value of H_{final} , the

equivalent plastic strain locates in the middle of the billet which is the typical phenomenon of forging core. Seen from **Figure 10**, we can find that the surface generated is almost a plane. So it can conclude that the objective function F_{obj}^{III} is linear and when increasing the value of $H_{initial}$ or H_{final} , it will decrease linearly.

For a point on the response surface showing on these figures, when $H_{initial}$ is equal to 122.5mm and H_{final} is equal to 77.5mm, the objective function value F_{obj}^I is equal to 1.6519E7MJ, F_{obj}^{II} is equal to 4.3553E-1 and F_{obj}^{III} is equal to 8.5722E5N.

Conclusions

In this paper, the advanced simulation technique is applied to a two-operation metal forming process. The optimization module uses response surface method to search the optimal parameters by changing the variables within the specified limits.

In the future, it is desired that we should incorporate more global optimization algorithms with the surface repose method. Because the response surface approach is a method of the Meta-model, it does not have the function of improving the response surface. It will be better that meta-modelling combined to an evolutionary strategy, or to a genetic algorithm, as in the hybrid approach.

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