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ORIGINAL ARTICLE

Design solution evaluation for metal forming product development

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Abstract In the current metal forming product development paradigm, the simultaneous and optimal design of product, process and forming system is a non-trivial issue as there are many affecting factors which interact and interplay each other. In the up-front design process, the systematic evaluation and verification of design solution is critical as this could shift the product development paradigm from traditionally trial-and-error and heuristic know-how to more scientific calculation, analysis and simulation. To ensure the efficient and accurate assessment and evaluation of design solution generation, state-of-the-art technologies need to be developed. In this paper, a methodology for systematic evaluation and verification of the simultaneous design of metal forming product, process, and forming system is presented. The factors which affect these designs are first articulated and how they interact and interplay are described. The importance of the systematic evaluation of designs is, thus, figured out. In addition, the role that CAE simulation plays in this process is explained. To evaluate the design, detailed evaluation criteria are developed and how the criteria are used through CAE simulation technology to reveal the behaviors and performances of designs is articulated. Through case studies, the developed technology is illustrated and its efficiency is finally verified.

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1 Introduction

In metal forming industries, the CAE simulation is the numerical representation of the forming system by models that imitate the dynamic behaviors of the system in working conditions. The kernel of CAE simulation technology is the numerical method such as finite elementmethod (FEM), which quantitatively represents the action-behavior-property relationship of the design of forming product, process and forming system in such a way that the numerical results generated through CAE simulation correspondingly represent the physical content of the deformation behaviors and the performance of process and forming system in the forming process. Through CAE simulation, the design conceptualization and design solutions can be evaluated and validated from the perspectives of forming product design, process determination and forming system configuration in up-front design process. These activities have shifted the traditional metal forming product development paradigm from traditionally more trial-and-error and heuristic know-how to more scientific calculation, analysis and simulation. Comparing to the traditional metal forming product development paradigm, we find that the simulation-based evaluation and verification of design solutions reduces trial-and-error experiments in workshop, shortens product development lead-time, and improves product quality and productivity.

In traditional metal forming product development, the design conceptualisation and solution generation is generally a trial-and-error process based on experience and know-how. The kinds of experience and know-how are usually acquired through long years of apprenticeship and skilled craftsmanship [1]. Therefore, this kind of conceptualisation paradigm is time-consuming, error-prone and needs a lot of experimental tryout in workshop and many times of design changes, as it is lack of sufficient scientific calculation and robust analysis. In addition, it is difficult to pinpoint the root-causes if the design of product, process and forming system is not satisfied. Since a metal forming system comprises of all the input variables relating the billet, the material, the tooling, the conditions at tool-material interface, the mechanics of plastic deformation, the equipment used, and the process and the characteristics of the final product [2], the final product, process and the entire forming system design are determined by the interplay and interaction of many affecting factors as shown in Fig. 1. These factors include metal forming product design, material selection and property configuration, process determination and parameter configuration, tooling design and fabrication, friction and lubrication conditions in between the workpiece and tooling, and the equipment selection and the entire working process window setting. This further articulates that the optimal conceptualisation of a forming product and system design is a non-trivial issue due to many affecting factors to be considered in decision-making.

To illustrate the interaction and interplay of these affecting factors, Fig. 2 shows an instance for the extra cost induced due to the uncertainty in determination of the maximum deformation load for screw forming processes [3]. The figure presents the interrelationship between the factors affecting the metal forming production. According to the figure, a 30% uncertainty in the determination of the maximum deformation load could lead to extra capital cost for equipment that may be close to 90% and extra direct costs for forged products between 5 and 9%, depending on the cost of materials. In addition, it further confirms that one of the process parameters-deformation load, its determination could significantly affect the equipment selection and product development cost. In traditional forming product development, the 30% uncertainty is the common issue as the deformation load is estimated by empirical formula and thus it is very difficult to give accurate calculation.

The CAE simulation provides an efficient, robust and pragmatic approach for metal forming product, process and system design [4–6]. It has become a standard tool to help design of forming product, process determination, tooling design, product quality control and assurance [2–17]. However, the applications of this technology in metal forming product development are still monolithic and more focused on some specific and individual issues in product design, process and parameter determination, tooling stress analysis and product quality, etc. Using CAE technology for systematic evaluation and verification of design solution considering the combined performance and behaviors from

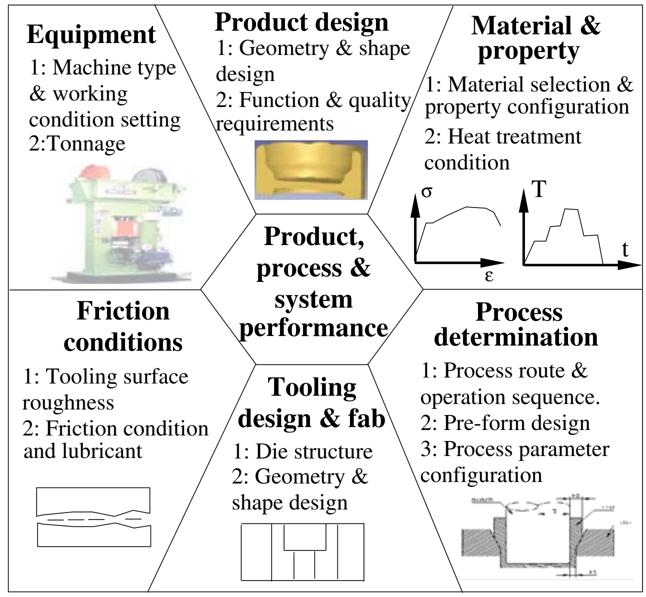


Fig. 1 Factors affecting the performance of product, process and forming system designed

the perspectives of product, process and forming system has not been fully addressed and the publication of the research in this area is also quite limited. Since the design solution generation needs to consider many factors from different perspectives, as shown in Fig. 1, the evaluation needs to take into account the interaction and interplay of these factors based on the defined evaluation criteria. Although there may be no panacea to fully address all the issues and finally come out with a perfect solution, the quantitative analysis of design solutions and comparison of their performances would ensure the best design solutions can be obtained. In tandem with this, this paper presents a methodology to evaluate the product and system design via CAE simulation and finally help generate and identify the best design solution for integrated product, process and forming system design.

2 CAE in integrated metal forming product development

In the integrated design of metal forming product, process and forming system, CAE simulation plays a big role. The simulation-based design solution evaluation and verification systemically investigates all the affecting factors and their effects on the performance of the design solutions. Through this kind of solution evaluation and verification, the best design solution can be obtained and the development lead-time for first article can be shortened. The procedure and the details about CAE simulation in

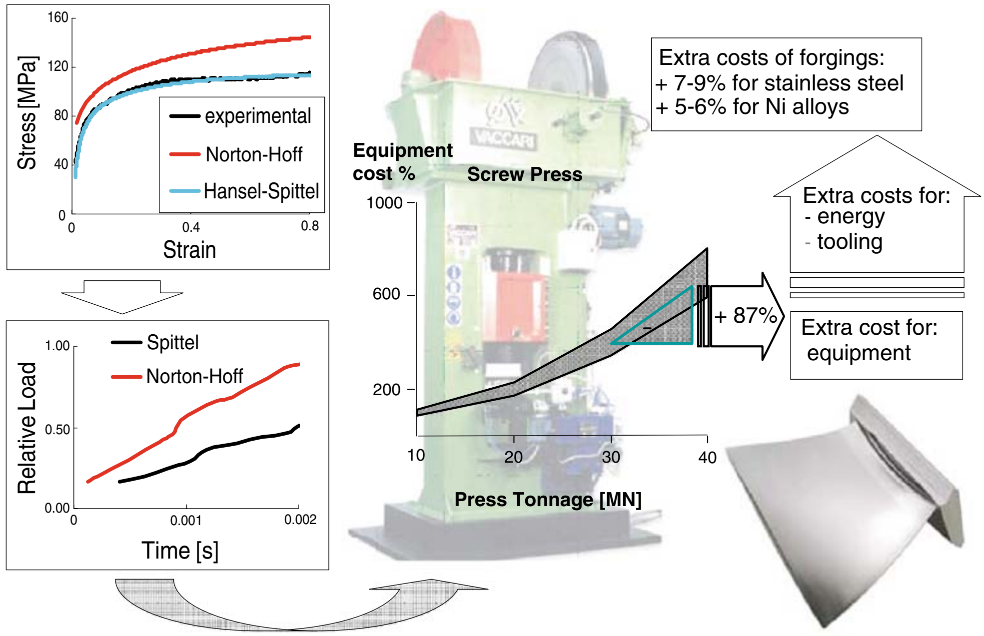


Fig. 2 Extra cost due to uncertainty in evaluating the maximum forging load [3]

integrated design of product, process and forming system are illustrated in Fig. 3.

In Fig. 3, the product design, process determination and tooling and forming system design constitute the whole forming system design. The design of metal forming product needs to consider the voice of the customers (VoC) and the detailed functional requirements and design specifications of the products. Furthermore, the product geometry conceptualisation needs to consider manufacturing process and its formability. Therefore, it is a process- and experience-based conceptualisation. After that, the process and tooling need to be deliberated to construct the preliminary design of the forming system as shown in Fig. 3. In this stage, the CAD representation of the whole design intent from geometry perspective is needed. The whole system performance and the final outcome of the system can then be evaluated and verified through CAE simulation. In this research, the whole system is first modelled through establishing the physical, mathematical and numerical models of the system and then input into the CAE simulation system for simulation. Upon the completion of simulation, the geometric-, physical-, deformation- and property-related data and information are available for verification and evaluation. However, how to evaluate these data and information needs systematic evaluation criteria for quantitative analysis. In this paper, quantitative criteria are developed based on engineering know-how and domain-specific knowledge of metal forming process. The criteria evaluate the system performance from process, tooling, and product quality and product design perspectives and determine which design alternative is optimal.

3 Evaluation parameters

To systematically evaluate the conceptual design of metal forming system, the evaluation parameters should be well defined in terms of the evaluation of system performance. The evaluation parameters are defined in the following:

3.1 Deformation load

The deformation load is one of the key parameters for tooling design and equipment selection. It should be as small as possible as a smaller deformation load requires smaller forming facility plus lower die stress. It would further affect the production cost. The deformation load is the combined representation of the billet design, process determination, metal formed part geometry, tooling structure and geometry and the billet material behaviors. It is, thus, selected as an evaluation parameter in this research. The deformation load is calculated based on the following equation [17]:

$$F = \sum\nolimits_e \int_{Ve} \left(2/3\,\overline{\sigma}/\overline{\varepsilon}\boldsymbol{B}^T\boldsymbol{D}\,\boldsymbol{B}\right) dV + \sum\nolimits_e \int_{Ve} G\,\boldsymbol{B}^T\boldsymbol{C}\,\boldsymbol{C}^T\Big) dV \quad (1)$$

where $\overline{\sigma}$ is the effective stress and equals to the flow stress of the material in the forming process, $\overline{\varepsilon}$ is the effective strain, $\boldsymbol{B}$ is the strain rate-nodal velocity matrix and G is the penalty constant, respectively. $\boldsymbol{D}$ and $\boldsymbol{C}$ are a matrix and a vector of constant components, respectively. The maximum

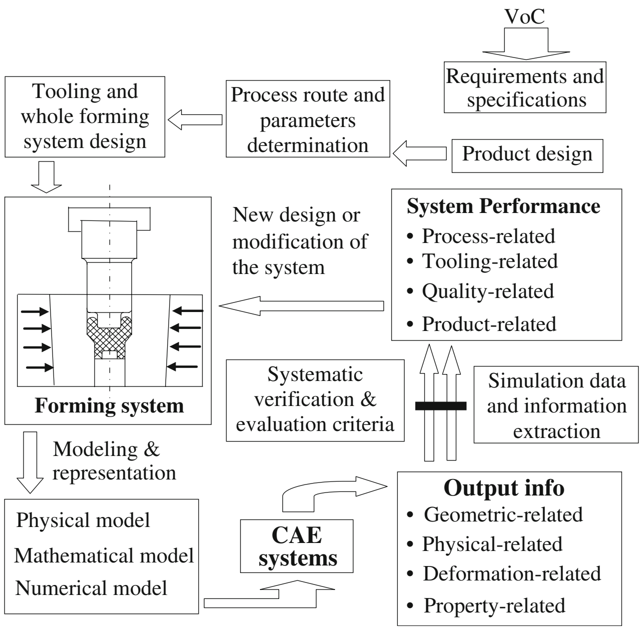


Fig. 3 CAE simulation of design solution of integrated product and system design

deformation load F_{max} in the whole forming process will be considered as an evaluation parameter.

Equation (1) is used to calculate the deformation load by numerical discretization via FEM as it is a non-linear equation from the perspectives of both geometry and material non-linearity and can only be solved by numerical method. Currently, it has been implemented in commercial metal forming simulation tools and the results can be directly provided through simulation.

To verify the accuracy of the deformation load predicted by simulation, Fig. 4 shows a combined extrusion part of aluminum 6061alloy and its deformation loads predicted by simulation and experiment. Two simulation systems, viz., LS-DYNA and DEFORM are used. Figure 4(a) presents the deformed part and (b) shows the deformation loads. The figure illustrates that the experimental and simulation results are in good agreement and the maximum difference is at 8%, which is an acceptable accuracy in deformation load determination in metal forming arena.

3.2 Effective strain

The effective strain represents the accumulated deformation quantity in the strain deformation body. It is defined as

$$\overline{\varepsilon} = (2/3)^{1/2}\left(\varepsilon_{ij}\,\varepsilon_{ij}\right)^{1/2} \tag{2}$$

where ε_{ij} is the detailed strain components. The effective strain is usually used for evaluation of deformation in the forming process. In addition, it also represents the energy needed to deform the billet to a specific geometry. Therefore, the effective strain should be as small as possible and thus the $\overline{\varepsilon}_{max}$ is considered as an evaluation parameter from deformation point of view.

Figure 5 shows a cross-section of the extruded part, as shown in Fig. 4(a). The figure illustrates a clear shear deformation zone in-between the punch and extrusion die. The simulation result of the effective strain, as shown in Fig. 5(b), also reveals this deformation zone and there is a good agreement in-between.

3.3 Damage factor

In metal forming process, the ductile fracture is a common defect. When the deformation exceeds the limit of ductility of the material, ductile fractures may occur. The quality product requires that there is no any micro fracture in the entire product, which would be further decided by the formability of the process and the material in the specific process and material behavior configuration. To model the ductile fracture in forming process, a lot of efforts have been provided to address this issue through establishing different criteria to determine when the ductile fracture occurs in the plastic flow process [19–25]. The criteria are of good research content. From application perspective, however, simple and accuracy criteria may work. In this research, the ductile fracture is modeled by the damage factor defined in the following [26], which articulates the possibility of ductile fracture of the deformation body in the forming process.

$$D_f = \int \sigma * / \sigma \, d\varepsilon \tag{3}$$

where $\sigma*$ is the tensile maximum principal stress and σ is the effective stress in the deforming body. Through simulation, the distribution of damage factor is revealed. But for a given material, its detailed value at which ductile fracture occurs is determined based on experiment. The simulated distribution of damage factor, however, provides a good criterion for evaluation of design solutions and selection of optimal design.

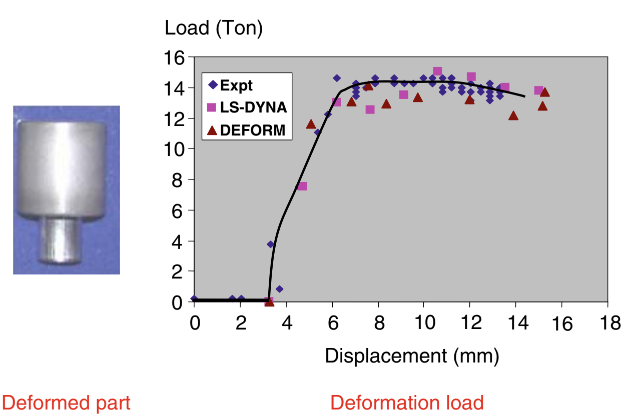


Fig. 4 Comparison of deformation load predicted by simulation

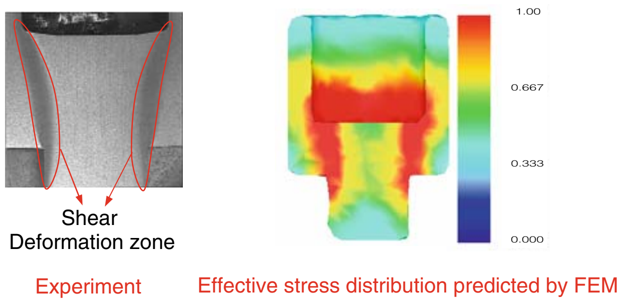


Fig. 5 Effective strain prediction and experimental analysis

3.4 Maximum effective stress

The effective stress is a combined representation of the stress status in the forming process. In a deformation body, the stress tensor is designated as σ_{ij}, which represents the six independent stress variables. The effective stress formulated in the following systematically and uniquely represents the combined stress level and whether they are in the yield status.

$$\overline{\sigma} = (3/2)^{1/2}\left(\sigma'_{ij}\,\sigma'_{ij}\right)^{1/2} \tag{4}$$

where $\sigma'_{ij} = (\sigma_{ij} - \delta_{ij}\,\sigma_m)$. σ'_{ij} is the deviatoric stress tensor, σ_{ij} the stress tensor, δ_{ij} (= 1 for $i = j$ and = 0 for $i \neq j$) the Kronecker delta, and σ_m the hydrostatic component of the stress.

In tooling service life, the tooling life is determined by its cyclic stress. The effective stress of the tooling should be as low as possible in such as a way that the maximum stress does not exceed the yield stress limit and ensure all the tooling service cycles are in elastic range. Therefore, the $\overline{\sigma}_{max}$ will be considered as an evaluation parameter from stress perspective.

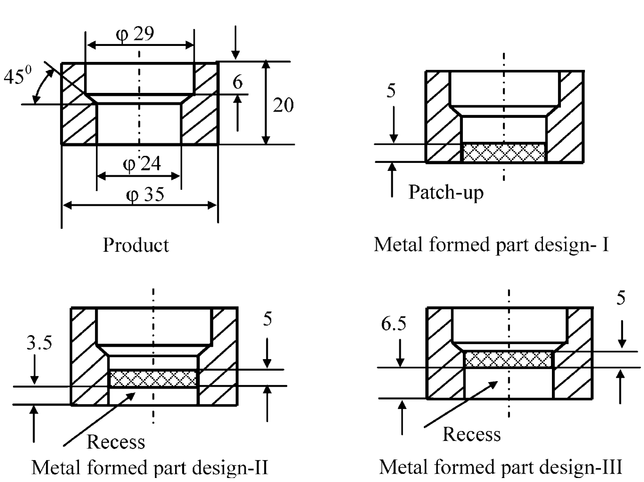


Fig. 6 A product and the related metal formed part design

3.5 Deformation homogeneity

The deformation uniformity articulates the deformation distribution in the deforming body. The process design should ensure the deformation as uniform as possible. It is thus considered as another evaluation parameter in this research for evaluating the forming system design. The deformation homogeneity (DH) is designated as

$$DH = \left(\frac{1}{n}\sum_{i=1}^{n}\bar{\varepsilon}_i^{\,2}\right)^{1/2} \tag{5}$$

Where n is the sampling number in the deformation zone, $\overline{\varepsilon}_i$ is the effective strains extracted at the sampling location. In the real implementation, the maximum and minimum effective strains in the deformation body need to be identified and extracted for the deformation homogeneity calculation. For simplification, only the maximum and minimum effective strains can be used for the calculation.

The above evaluation parameters represent the behaviors of the forming system from different perspectives. Their maximum value is considered in the evaluation of different design alternatives. To quantitatively articulate the performance level, detailed evaluation criteria are defined in the following section.

4 Evaluation criteria

To quantitatively represent the above evaluation parameters, the following criterion is defined to judge the design

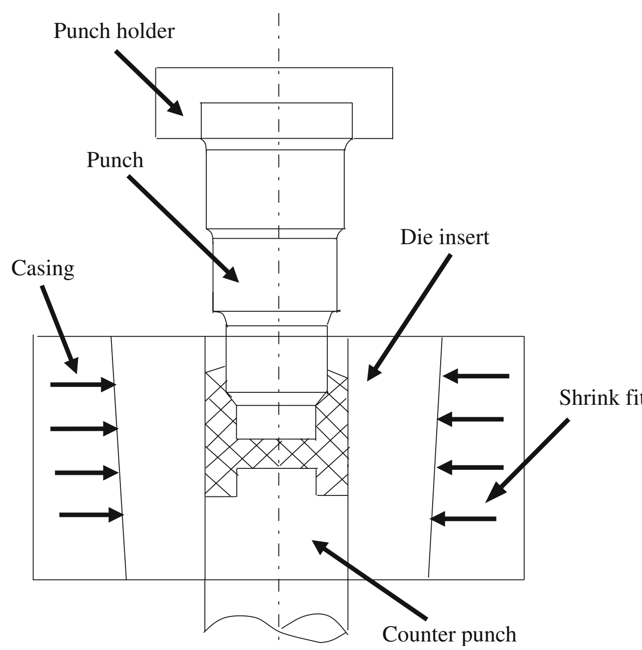


Fig. 7 A forming system based on the specific part design and process configuration

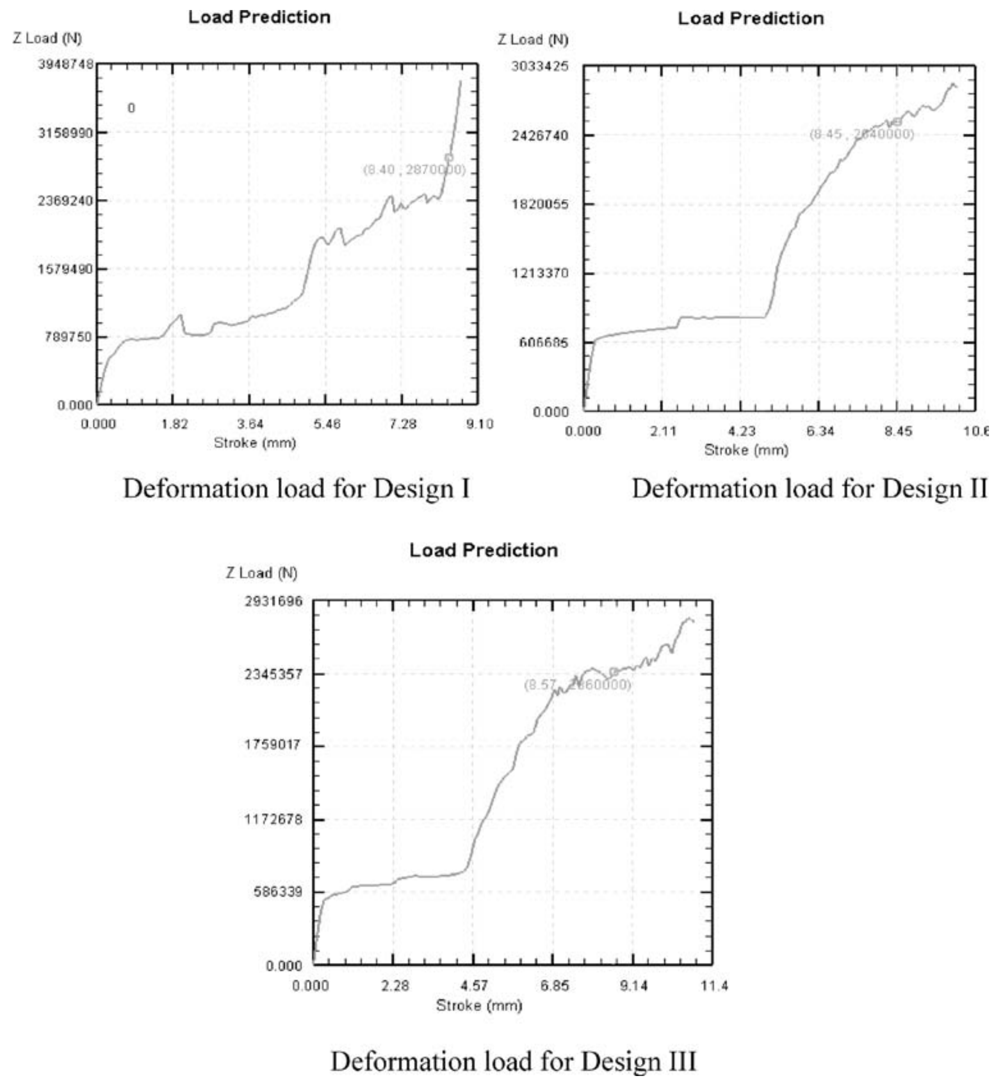


Fig. 8 Deformation loads for design I, II and III

alternative based on the above-defined evaluation parameters. The criterion is called design index and designated as *DI* [4].

$$DI = k(P_i - (P_{\max} + P_{\min})/2)/((P_{\max} - P_{\min})/2) \qquad (6)$$

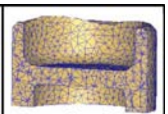
where *DI* is the design index, P_i is the output value of a specific evaluation parameter for design alternative i. The specific evaluation parameters are defined in Sect. 3. P_{max} is the maximum output value of the evaluation parameter in all the design alternatives and P_{min} is the minimum output value of the design parameter. k is a characteristic factor, which is equal to + (plus) when the bigger the output value, the better the designed system; while it is equal to-(minus) if the smaller the output value, the better the design system. Therefore, the characteristic factor is "-" for the deformation load output. Besides, *DI* varies between +1 and −1. For a given evaluation parameter, it is the best design scenario when it has a value of +1 and the worst case when its value is −1.

To systematically evaluating the whole forming system based on the above-defined criteria for the different evaluation parameters, the following system evaluation index is defined and designated as SI.

$$\left.\begin{aligned} SI_{system} &= \sum_{j}^{N} K_j DI_{P_j} \\ \sum_{j}^{N} K_j &= 1 \end{aligned}\right\} \qquad (7)$$

where DI_{system} is the system evaluation index and DI_{pj} is the design index. N is the number of evaluation parameters. In this paper, DI_{pj} is DI_{Fmax}, $DI_{\overline{\varepsilon}\max}$, DI_{DF} , $DI_{\overline{\sigma}\max}$ and DI_{DH} for the evaluation parameters defined. In addition, K_j is the weight number which specifies the important level of the corresponding evaluation parameter and represents how

Table 1 The evaluation parameters

Design alternatives	 Design I	 Design II	 Design III
Deformation (Ton)	287	236	254
DI_{Fmax}	-1.000	1.000	-0.294
Max $\bar{\varepsilon}$	2.56	2.41	2.88
DI $_{\bar{\varepsilon}max}$	0.181	1.000	-1.000
DF	1.52	0.90	1.72
DI_{DF}	-0.5	1.000	-1.000
Max $\bar{\sigma}$	3430	3270	3590
DI $_{\bar{\sigma}max}$	0	1.000	-1.000
DH	(2.56-0.979/2 = 0.791	(2.41-1.03)/2 = 0.690	(2.88-1.01)/2 = 0.935
DI_{DH}	0.18	1.000	-1.000
System Design Index	-0.228	1	-0.859

much the evaluation parameters contribute to the whole system quantitatively. How to determine the value of weight number needs to consider the detailed important level of the individual parameter. For simplicity, the equal weight number value is chosen in this paper, viz., 0.2 for each of the five evaluation parameters. According to the above definition, the system design index has the value between +1 and −1. When the value of SI_{system} is +1, the designed system is the best solution for all the design scenarios and it is the worst case when its value is −1.

5 Case study and results analysis

To demonstrate the application of the above-developed criteria, a case study is shown in Fig. 6. The case is a simple forging part, but the different forged part design can lead to different forming processes and forming systems. As shown in Fig. 6(b), (c) and (d), there are three design alternatives. Each design scenario will have their own forming system and process configuration. In these three design scenarios, the patch-up locations are different. In the design I, the patch-up is located at the bottom of the part. In design II, it is located at the middle of the small hole and in the last case, the patch-up is designed at the top of the small hole feature. Fig. 7 illustrates the forming system for a given metal-formed part design.

In this case study, the FEM simulation approach and DEFORM simulation system are used. The tooling material is M2 and the billet material is structural steel. For the tooling, it is considered as an elastic body and its Young's Modulus E is 250,000 (MPa) and Poisson's ratio γ is 0.3. For the billet material, it is considered as a plastic deformation body and the stress-strain relationship is

$$\sigma = 150_{\varepsilon}^{0.1} + 547 \tag{8}$$

where σ is effective stress and ε is the effective strain.

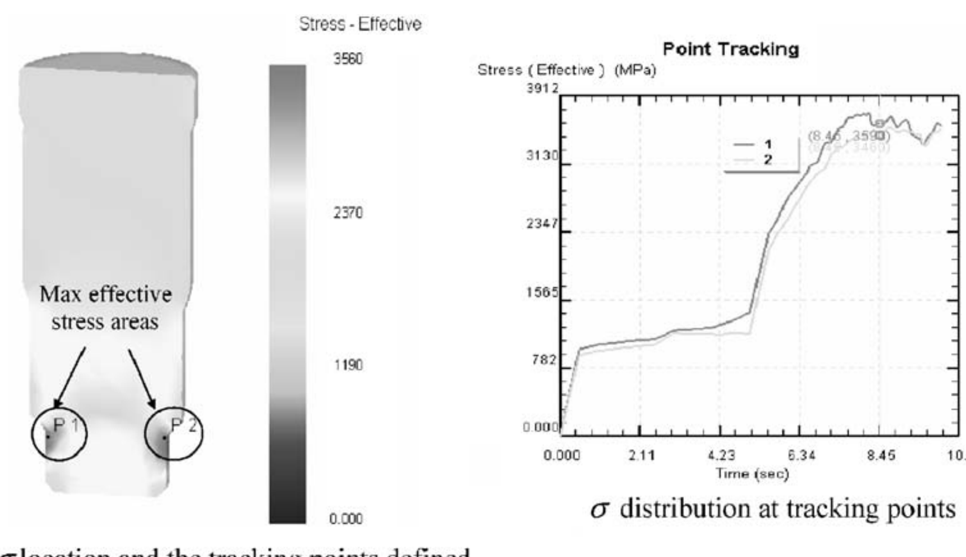


Fig. 9 The maximum effective stress in the punch for design III

For the interfacial relationship between the tooling and billet, the cosntant friction condition is employed. It is represnted as

$$\tau = \mathrm{mk}$$

where m is the friction factor and K is the shear strength of the billet material. m is 0.1 in this research.

For these three scenarios, the CAE simulation is employed to simulate the entire forming process and system. The value of the evaluation parameters defined in the previous section can be extracted and the related *DI* and *SI* can be determined for the evaluation and verification of the design concept. How to retrieve the simulation results for the above evaluation parameters are articulated in the following.

(a) Deformation load: The deformation load in the forming process varies in the forming process, and thus the maximum load should be selected for evaluation and verification of design concept. Generally, the deformation load reaches the maximum when the final design dimensions are satisfied. Therefore, the deformation loads shown in Fig. 8 are extracted from design I, II and III when the final patch-up dimensions are met.

(b) Effective strain: The maximum effective strain needs to be extracted for the evaluation of the design concept. Since it is the accumulated field variable and the maximum should be at the last stage of the deformation when the final part dimensions are met. The effective strain defined in this paper refers to the billet deformation. The detailed values of the maximum effective strain for the above three design scenarios are summarized in Table 1.

(c) Damage factor: The damage factor varies during the forming process. Its maximum value represents the greatest possibility of ductile fracture in the deforming body at the specific deformation stage. The damage factor here refers to the deformation body. The maximum values of the damage factor are extracted for the three design scenarios and the detailed values are also listed in Table 1.

(d) Effective stress: The effective stress defined here represents the stress status of the tooling in the forming system. Since the tooling service life is determined by its stress. The effective stress of the tooling should be as low as possible. In this case study, the maximum effective stress of the punch is selected as the representative as the punch is the most vulnerable part in the entire forming system. Figure 9(a) shows the location of the maximum effective stress for the punch in design III and Fig. 9(b) presents the variation of the maximum effective stress during the forming process. For the other two design scenarios, the maximum effective stresses are summarized in Table 1.

(e) Deformation homogeneity: The value of the deformation homogeneity is extracted and presented in Table 1 for the three design scenarios. Since the DH represents the difference level of the maximum and minimum strains, these values need to be extracted from the simulation results and thus the DH value can be calculated.

For the above extracted five evaluation parameters, their corresponding design indexes are calculated and listed in the table. The design indexes n the system level are then determined and listed. Based on the definition of the system design index, the detailed design index values in the system level are −0.228, 1 and −0.859. Therefore, the design II is the best case and the worst design alternative is design III.

6 Conclusions

The traditional design and development of the metal-formed product, process and system is a trial-and-error process based on heuristic know-how. The solution generation in such a way is lack of scientific calculation and analysis and needs many times of physical tryouts in workshop and design changes. CAE simulation helps evaluation and verification of design solutions in up-front design process and ensures the best design solution can be obtained in such a way to reduce experimental work, shorten time-to-market and cut development cost. The research addressed these issues and developed a methodology for evaluation and verification of design alternatives for the integrated process and product design and development. Through case studies, the efficiency of the developed technology is verified and validated.

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