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Concurrent design and process optimization of forging

Murat Ozturk, Sinem Kocaoglan, Fazil O. Sonmez *

Department of Mechanical Engineering, Bogazici University, Istanbul 34342, Turkey

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ABSTRACT

In this study, a concurrent design optimization methodology is proposed to minimize the cost of a cold-forged part using both product and process design parameters as optimization variables. The objective function combines the material, manufacturing, and post manufacturing costs of the product. The part to be optimized is a simply supported I-beam under a centric load. Various constraints are imposed related to the performance of the product in use and the effectiveness of manufacturing. Nelder–Mead is used as search algorithm and analyses are conducted using commercial finite element software, ANSYS. Results show considerable improvement in the cost.

1. Introduction

Various manufacturing methods can be used to produce mechanical parts. A suitable method is chosen based on the geometry of the part, the required quality, the quantity to be produced, and the manufacturing cost. In this study, forging is considered, which is one of the widely used manufacturing methods for metals. If the forming process occurs below the recrystallization temperature of the metal, the process is called ‘cold forging.’ This has certain advantages such as high dimensional accuracy, superior mechanical properties and microstructure, better surface finish, and no oxidation. Furthermore, forging to net or near-net shape dimensions reduces material as well as post processing cost. However, because of relatively high tooling and equipment costs, the process is feasible only if the part is to be produced in large quantities [1].

In the traditional approach, manufacturing procedure is decided based on experience. In most cases, values for processing parameters selected based on experience and intuition do not give satisfactory results. Hence, they are modified via a trial-and-error-correction method. For manufacturing processes requiring high tooling costs, these trial-and-error efforts drastically decrease the efficiency of the product development phase. Besides, the resulting processing conditions would be less than the optimum. The traditional approach has become obsolete with the developments in the computational technology. Numerical methods like FEM allow prediction of the effects of process parameters on the end product by simulating the manufacturing process. This reduces trial-and-error efforts dramatically. On the other hand, FEM as an analysis tool only provides outputs for a given process; it cannot appraise these outputs and suggest a better processing scheme. Integration of simulation models with optimization algorithms helps to determine the optimum processing conditions. The forging process has a number of parameters that are under the control of the process designer, which can be used to optimize the process. By optimizing the controllable processing parameters, one can improve the product quality and manufacturing efficiency, and decrease costs considerably. In a process optimization study, according to the desired optimization aim, a suitable objective function is constructed. Choosing appropriate objective and constraint functions, optimization variables, and search algorithm has utmost importance on the effectiveness of the optimization. In the literature, different approaches were adopted in this respect.

In the previous studies of forging process optimization, the researchers considered forging of blocks by upsetting [2–15], H-shaped axisymmetric parts [5,6,16–25], I-beams [26,27], aerofoil blades [3,28–32], hollow cylinders [15], axisymmetric parts like disks or cups [2,8,13,25,27,32–43,44], other 2D parts [43,45], steering links [46], wheels [31,45], hubs [47,48], spindles [49], gears [49], and other 3D parts [10,50]. In some of these studies, forging process was simulated as hot [2,4–6,13,16,17,21–23,25–30,32,34,35,37,39,43,44–46,48–50], in others [11,14,17,20,27,32,33,36,38,40–42,47] as cold.

In an optimization procedure, depending on the quality and cost requirements on the part, a suitable objective function is chosen. In

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* Corresponding author. Tel.: +90 212 359 7196; fax: +90 212 287 2456.
E-mail address: sonmezfa@boun.edu.tr (F.O. Sonmez).

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the previous studies, the goal was to minimize the deformation energy [19,20,49], the difference between the desired shape and the final realized forged shape [2,3,7–11,13,23,25,26,28–30,32], cost [52], excess material or flash, which is the portion of the workpiece bulging out of the die, in order to obtain net shape [35,47], unfilled area of die [27], damage index of the workpiece [38,40], variation in hardness distribution [33], variation in grain size [21], variation in the temperature [34], variation in effective strain [22,24,41–43,46,48], maximum strain rate to avoid folding defect [45,49], die wear [18]. In another study [36], die fatigue life was maximized. Besides, multi-objective optimization problems were considered where the objective was to minimize the forging energy and the difference between the realized and prescribed final forged shape [4–6,12,14–16,44], unfilled area of die and forging energy [42], unfilled area of die and flash area [17,31], unfilled area of die, forging energy, and strain variation [39] total strain energy, strain variation, and forging force [37], material use, total strain energy, and strain variation [43]. In some cold forging operations, deformation becomes so extensive that forging operations are conducted in sub-steps followed by annealing. In order to obtain the desired shape or avoid forging defects, more than one forging operation may be needed even in hot forging. Hence, in some studies [4–6,7,8,17,18,23–26,34,38,40,44,49], forming stages were optimized.

In forging process optimization studies, optimization variables are chosen among the processing parameters that have an effect on the objective function. Parameters defining preform-die shape or final-die shape [2–6,7,8,16–18,20,23–26,28–32,36,38–40,43–45,49], fillet radii of the die [20,33,37], preform shape [5,6,9,11–15,31,35,41,43,50,46,48], preform dimensions [17,19,21,27,33,37–40,47,49] number of forming operations [40], thickness of the flash [20], initial temperature [4,14,16,22,34,30], ram velocity [12,21,22,34,39], pressure or force applied by the tools [42,50], stroke [17,22,30], were selected as optimization variables in the process optimization problems considered in the previous studies.

In a process optimization procedure, while improving the objective function by modifying the optimization variables, constraints are imposed on these variables to avoid underfilling of the die cavity [5,8,16,19,21,22,35,37,41,42,46–48], folding or wrinkling [2,15,23,35,37,50], the difference between the produced shape and the target shape [3,8–10], shape errors [10], excessive flash [21]. Constraints are also applied to limit the maximum strain [40], the variation in strain [19], effective strain rate [34], maximum temperature [4,14,16], maximum pressure on the die [40], and forging load [22].

Effectiveness of an optimization procedure depends on the search algorithm. Some researchers used stochastic global search algorithms like genetic algorithms [2,4,12,14–17,38,40]. Some other researchers used gradient [5,6,7–11,13,18,21,23–26,28,44,45] or non-gradient [29,31,33,34] based local search algorithms. In many of the previous studies, a meta (or surrogate) model is constructed representing the objective and constraint functions using response surface method [3,19,22,30,32,41,42,46,48,49], artificial neural networks [27,39], multivariate polynomial interpolation [37], or Kriging [37,49], then optimization is conducted using the model via a local search method. If few parameters are used as optimization variables, a parametric study [20,35,36,43,47,50] may be conducted to improve the forging process.

In most applications, the manufacturing efficiency, manufacturability, cost, and quality of the resulting product depend on both processing and design parameters. For this reason, integrating product design and manufacturing design phases, which is called concurrent design approach, enables consideration of interacting effects of these parameters. Accordingly, designing forged products includes not only the optimization of the part geometry and material but also the selection of appropriate manufacturing process conditions so that desired properties can be obtained (strength, tolerances, residual stresses, grain structure, surface properties, etc.) with minimum cost. Through the use of a concurrent design procedure with an optimization algorithm, both manufacturing process and part performance can be optimized. A concurrent design optimization scheme includes both design and processing parameters as optimization variables and also design and manufacturing constraints. Some concurrent design optimization procedures were previously developed by several researchers [51–54] for some manufacturing processes. Chang and Bryant [53] minimized the cost of aircraft torque tubes, piston and cylinder components and the tube weight by using the part thicknesses as optimization variables. The design and the processing were optimized concurrently to minimize the volume while maintaining its strength. Al-Ansary and Deiab [54] minimized the total machining cost of mechanical assemblies including the cost of all individual machining operations by taking product design dimensional tolerances and machining tolerances as optimization variables. They considered two mechanical systems, piston-cylinder assembly and rotor assembly, and optimized the tolerances of their individual parts. Janakiraman and Saravanan [52] minimized the total manufacturing cost and the deviation from the targeted performance. Three cost components, operation cost, tool cost, and tool replacement cost, were included in the objective function. Number of rough turning passes, cutting speed, feed and depth of cut in each step were taken as optimization variables; upper and lower limits were set on machining parameters, cutting force, power, and surface roughness. Chen and Simon [55] optimized product performance and welding process. Height of the beam, its thickness, depth and length of the weld were selected as optimization variables. Constraints were imposed on these parameters to avoid large deflection and static and buckling failure. There is only one study on forging process optimization using a concurrent approach [51]; however it is rather on the development of a support software module aimed at assisting manufacturing design decisions. This system combined theoretical and empirical knowledge about a variety of aspects of product design and manufacturing, and thus, it provided guidance for engineers to decide on some factors like material type, lubricant, and machine type. In that respect, the present study can be considered to be the first study on the concurrent optimization of forging processes. Besides, in comparison to the forging optimization studies that considered a part with a similar geometry like reference [20], a larger number of parameters are considered as optimization variables and also a larger number of constraints. Therefore, the present study is more comprehensive in regard to processing optimization.

2. Problem statement

The aim of this study is to develop a concurrent design optimization methodology for the combined optimization of product design and processing design phases of a forged part. The methodology is applied to a simply-supported beam with an I-cross section subjected to a centric load as the worst loading condition during its use as shown in Fig. 1. I-beams are generally used in the industry due to their good load carrying capacity under bending.

Manufacturing of an I-beam can be achieved by forging, extrusion, or roll forming. The choice between these methods is made based on the feasibility, the manufacturing cost, the target mechanical properties, and the dimensions of the beam. The part considered in this study is a short beam with dimensions $400 \times 45 \times 35$ mm with large web and flange thickness (about 10 mm); forging can then be considered to be a suitable processing method. Accordingly, the manufacturing method is chosen to be