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Cold Forging Die Design: Recent Advanced and Future Trends

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Abstract: Die design in the forging process become crucial as the production cost and accuracy of the forged part being tighten. The study present a review of the current advanced of die design used in forging process and the system associated with in order to enhance the design process and performance of the die. At the end of this study future challenges of the die design area and the approach taken to develop a support system that can fulfilled the customer demand is also outlined.

Key words: Forging, die design, support system, performance, die life

INTRODUCTION

Cold forging can be described as a process in which a piece of metal is shaped to the desired form by plastic deformation of a simple starting form such as bar, billet, bloom or ingot at room temperature. Initially forging operation has various advantages compared to other metal manufacturing including little loss of material, improved strength, geometrical precision of components and high production rates (www.forging.org). There are variety of processes that can be classified as forging such as open die, impression die, ring rolling, warm forging and cold forging. Currently in practice forging process design (mainly die) repeatedly carries out trial and error based skill experience of designer who is familiar with the forging problem. Currently most of the companies still rely on formulas, standards and experience to aid their die design. In forging process, performance of the die is measure based on quality of the forged parts and reliability of the die itself. Due to demands for complex part, long life die and accurate tooling recently becomes crucial. The success of cold forging process depends on two main criteria i.e., the selected tool material and dies design (Vasquez and Altan, 2000a). Since the process involves huge pressure, selection of material which exhibit the both criteria i.e., high strength and toughness is very crucial (Destefani, 1994). Commonly material that own these criteria is expensive. Compared with the tooling material, the design of die is claimed has bigger influences. This is because choosing in different material may not extend the die life until the die is properly design. In practice the die design process begins upon requirement and specifications from customer and then followed by the tooling design and forging process stage. The process ends upon customer satisfaction in terms of die performance and auxiliary tools required, the general die design process as practice by the industry is as shown in Fig. 1.

Researchers take the advantages of computer advancement to integrate CAD/CAM in design of optimal tooling (Jolgaf *et al*., 2003), FE capabilities (Walter *et al*., 2000; William *et al*., 2002) and some of the others integrate with Rapid Prototyping (RP) in demonstrating and evaluating the forging process (Yang *et al*., 2002). In metal forming, the research can be divided into three main areas;

- **Die design:** Several tools and approach have been used such as CAD/CAM, expert system and mostly FEA methods to obtain the best and efficient design. Improvements of die life and decision support system are the main area being studied.
- **Process planning:** The research is focus on the development of the most efficient and economic process sequence and planning and it is commonly used knowledge-based or expert system and CAD/CAM as the medium.
- **Product performance:** In this field the quality and reliability of the final product such as un-filling phenomenon, accuracy and fatigue behavior of the forged part are the area of focus. The approach usually taken is either physical modeling or real experiment.

Due to demand, forging technique has been enhanced by time. This is to fulfill high precision and complexity of recent product as required by the customer (Voelkner, 2000). For example flash-less forging concept, which has been proposed few years ago and performed

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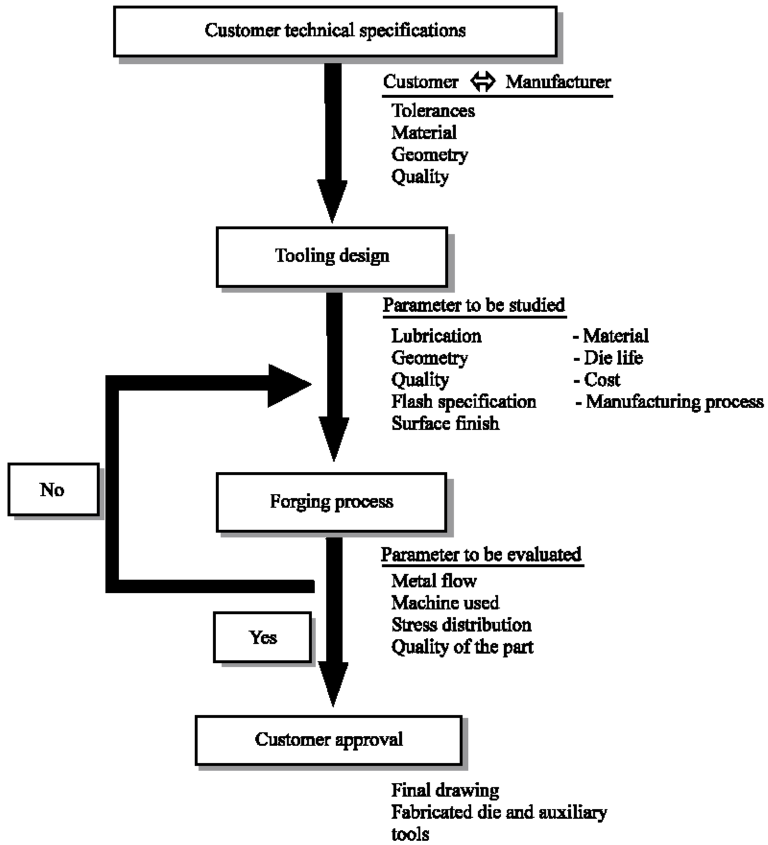

Fig. 1: General forging dies design process (Mynors *et al*., 1997)

several advantages (Vasquez and Altan, 2000a, b; Takemasu *et al*., 1996, O'Connell *et al*., 1996; Lee *et al*., 1997).

This study intent to review the cold forging die design, by focusing on the researches being done in improving the die design process and also performance of the die at the design stage. The study starts with introduction and the forging parameter, which described the most crucial parameters that could affect the die performance. Then followed by the factors that influenced the die life and related research. The study also presents the approaches taken by the researchers. The main contribution of the study is the discussion on optimization and system that have been developed to aid in every aspect of die design especially the preform, die geometry and etc. which can be used as a guide in the die design in the future. At the end paper, the authors conclude with several questions and challenges for future research.

DIE SERVICE LIFE

Die life is defined as the number of parts produced by the die before it fails. Fatigue and wear are the major causes of die failure. Fatigue is due to cyclic loading of the tool and can be described by two factors; i) when the stress exceeds the yield strength of the die material, a localized plastics zone generally forms during first load cycle and undergoes plastic cycling during subsequent unloading and reloading, thus microscopic cracks initiate and ii) tensile principal stresses cause the microscopic cracks to grow and lead to the subsequent propagation of the cracks. Wear caused by the combination of high contact stress and cumulating sliding strength. To measure die service life, two approaches are usually used either S-N approach or strain based approach. In dealing with die life, the working pressure becomes the most critical value and in forging it consists of three components (Tong *et al*., 2003);

- Resistance for ideal deformation
- Frictional resistance
- Resistance for redundant work (in-homogeneous material flow)

There are several methods used to predict performance of the die such as (Altan *et al*., 1983; Rao *et al*., 2003; Mungi *et al*., 2003; Rusinoff, 1964):

Table 1: Approaches taken to extend die life

Authors	Methods	Effect
	Surface Finish/Treatment	
i) Farrahi and Ghadbeigi (2006)	a) Shot peening	a) Die life increased by 14%
ii) Jeong *et al.* (2001)	b) Single Stage Nitriding	b) Die life decreased by 50%
iii) Wagner *et al.* (2006)	c) Single Stage Nitriding	c) Die life decreased by 8%
	d) Nitrocarburizing	d) Die life decreased by 29%
	e) Hard roller burnishing	e) Die life increase by 100-160%
	f) Laser beam treating	f) In progress
	g) Surface texturing	g) Die life increased by 84-122%
	Pre-stressing element	
i) Koç and Arslan (2003)	a) Stress pin	a) Increase die rigidity
ii) Vasquez *et al.* (2000) and Garat *et al.* (2004)	b) ariable shrink-fit interference	b) i) Cost reduction
iii) Vasquez *et al.* (2000)	c) Split insert design	ii) Simplify the die design
		iii) Stress level decreased
	Process optimization	
i) Xia *et al.* (2001) Tong *et al.* (2001)	a) Forging steps/sequence	a) i) Reduce forming pressure up to 30%
ii) Lapovok (1998)	b) Preform	b) Reduce stress level
iii) McCormack and Monaghan (2001a)	c) Lubrication	c) Reduces the stress level and prolong the die life
	Geometry	
i) McCormack and Monaghan (2001b) and Garat *et al.* (2004)	a) Corner radii	a) Stress level reduced by 30% and increase die life up to 150% with increased of radius (0.05-0.5 mm).
	b) Fillet	b) Increasing the fillet also increases the stress level
	c) Size/Shape	c) Increasing the size will increases the stress level due to contact area increment.
	Tool material	
i) Lee and Chan (2001) and Vasquez *et al.* (2000)	a) Hardness	a) Die life increase as the hardness increases.
	Machining	
i) Sasahara (2005)	a) Surface roughness	a) Increase fatigue life by avoiding initiation of crack.

- The slab method-assumes homogeneous deformation
- Uniform-deformation energy method-calculates average forming stress from the work of plastic deformation
- Slip-line field theory-permits point-by-point calculation of stress for plane-strain conditions only
- Upper- and lower-bound solutions-based on the theory of limit analysis, uses reasonable stress and velocity fields to calculate the bounds within which the actual forming load must lie
- Finite Element Method, a numerical method most widely used in recent years to solve any mechanical and physical problem. Much more complicated factors, such as friction, temperature, pressure and stress can be easily determined.

There are several approaches being used in extending the die service life as summarized in the Table 1.

STRECON ® technology is one of the world-wide manufacturer who dealing with forging die and their recent design is claimed to be extended up to 10 times of the common design of die and at the same time die deflection can be reduced by 30-50% (Groenbaek and Birker, 2000). In terms of cost, Vasquez *et al.* (2000) claimed that by improving die life up to 25%, overall cost saving is about 12.5%. Choi and Dean (1984) proposed a system that provide cost of the die and preform design based on built-in design rules. The system also provide information regarding to the amount of flash, flash geometry, mass distribution curve, forging energy and load, hammer size, minimum preform operations and bar size.

APPROACHES

Several methods have been used in studying the forming process either analytical, numerical or experimental methods. Usually experimental will be used to verify analytical and numerical results. But this approach requires higher cost and material. Alternatively physical modeling is used to replace the experimental but has limitation in terms of material similarity.

The use of physical modeling can reduce load and energy, reduce the size of forming machine, simple experimental procedure, easy observation of the flow pattern and cheap and easy methods for preparation of test specimen. Plasticine is the most widely used model material because of low price, easily found and non-toxic, other material such as lead and wax cam also be used. For die material, wood and aluminum are the most often used. The physical modeling is carried out based on extended similarity law (Powelski, 1992). Pertence and Cetlin (2000) simulate the cracking behavior by focusing on ductility of the material. Yuli *et al.* (2000) used the physical modeling to perform the forging of grade 2 stator blade. Zhan *et al.* (2001) extend the study by using plasticine as a billet material and equip by platform with damper to produce the same shape. Sofuoglu (2006) and Sofouglu and Rasty (2000) study flow behavior of the plasticine by taking into consideration color of the plasticine, lubrication and deformation speed. He found that they had a significant effect to the flow behavior of the material. Fereshten and Moghaddam (2004) focus on friction modeling of bulk metal forming process. In their research thirteen lubricants conditions were employed of varied result shows that physical modeling can effectively model almost all of the friction condition. Fereshten and Hossein (2006) study the effect of flash allowance and bar size on forming load and metal flow and indicate that the greater flash allowance the larger the forming load. They study the effect of axisymmetry of part and found out that part with horizontal axis much sensitive to forming load compared to vertical. Moon and Tyne (2000) used the physical modeling as a validation tools to investigate the cracking criteria resulting from upper bound technique. The upper bound analysis used to provide the geometric and processing condition that can be used to avoid the development of un-acceptable side-surface cracks.

Numerical analysis becomes popular due its flexibility that allows quick changes in the tooling design. In modeling of forging process, several available packages have been employed such as Ansys, I-DEAS, DEFORM, FORGE and CAM*form* (Hussain *et al*., 2002; Vazquez *et al*., 1996; Button and Roque, 2000). CAE help in evaluation of part performance and it is possible to detect, understand and improve problems early in the manufacturing process through process simulation. For example in die stress analysis which could save a lot of money; for example 5-15% of the sales cost is on die itself. If performance of the die can be evaluated based on fatigue behavior, stress distribution and life prediction numerically, the perfect die design can be achieved at lower cost. In order to predict the life of the dies, numbers of research have been conducted (Garat *et al*., 2004; McCormack and Monaghan, 2001b; Lapovok, 1998; Ohashi and Motomura, 1996; Vazquez *et al*., 2000). The results are then verified by the experimentation and suggestion for design improvement is proposed. In cold forging process, there several operating environment that should taken into consideration in manufacturing process such as quantity of the forged parts, quality and pressure applied. There are researchers who studied the flashless and precision forging, metal flow pattern and preform effect to the product quality using FEA. The result indicate that metal flow depends on the cavity, flash opening and billet geometry, percentage of flash and heat transfer of the billet and tooling.

Development of an integrated system to be used in assisting the forging designer has great potential in die design. To date there are several systems that have been developed. Jolgaf *et al*. (2003), developed a system that can simulate and optimize the die design and based on the result, a machining code is produced using available CAM software and then fabricate using CNC machine. The integration between CAD and CAM tools can be utilized in the manufacturing process for economic production. Yang *et al*. (2002) and Srinivasan *et al*. (2002) constructed a larger scope system where they also integrate the rapid prototyping (RP) technology to demonstrate the physical model of the process at different stages. The technology can also consider the process characteristics such as geometrical complexity, effects of the process parameters, flow pattern of work piece, deformation induced defect and etc. In this research, the deformed shape at different processing stages is physically presented by converting CAE data into file format that can be read by RP system (i.e., stl format).

In other research, factor such as preform shape is also taking into consideration in order to improve dimensional accuracy of the forged parts and at the same time to forming load (Koc and Arslan, 2003). Choi *et al.* (2006) study the effect of process parameter of round shape product focusing on feed rate and rotation angle for optimal forging pass design. Other area is the machining condition of the die where the effect of depth of cut, type of machining tools and surface roughness of the die being studied (Sasahara, 2005). Desai *et al*. (2005) study the design parameters of gear forging using FEM and Design for Experiments (DoE) and found that several parameters such as shear friction factor, punch velocity, aspect ratio and temperature on die will affect the quality of the forged gear.

DESIGN OPTIMIZATION

There are numbers of research have been done in the area of design optimization, one of them is Santos *et al*. (2001) which optimize the die design by taking into consideration shape and size of the initial billet and predict the forces needed as well as the defect occurrences. Lapovok (1998) study the extension die life of hot forging by minimizing the damage accumulation and development of optimal preform design. This is done by investigating the tool fracture and lower-bound ductility of the tool steels. Chen *et al*. (2004) study the method to minimize errors occur during forging process and indicates that there are several factors which contribute to the error such as die-elasticity, secondary yielding, springback and temperature involve. In other research, factor of preform shape is also taking into consideration to improve dimensional accuracy of the forged parts (Kim and Chitkara, 2001). They use a crown gear as a case study by utilizing upper bound analysis and experimental method. Choi *et al.* (2006) study the effect of process parameter of round shape product focusing on feed rate and rotation angle for optimal forging pass design. They proposed an optimal process condition based on FEM result. Several other tools are used in determining optimal design and process parameter such as genetic algorithm (Castro *et al.*, 2004), sensitivity analysis (Zhao *et al.*, 2004), neural network (Li and Mori, 2005), inverse methods (Sousa *et al.*, 2002) and statistical tools such Taguchi Methods and ANOVA (Liou and Jang, 1997) and design of experiment (Sofouglu, 2006).

Lee *et al.* (2002) study the elastic characteristic of the forging die for dimensional accuracy of forged parts using FEM and experimental method. Jolgaf *et al.* (2003) developed a system that can simulate and optimize the die design and based on result, the die is produced using CNC machine. The integration between CAD and CAM tools are utilized in the system for economic production. Studies also focus on optimization of design and process planning (Yang and Osaka, 1990), preform shape (Lapovok, 1998) and also lubrication effect (McCormack and Monaghan, 2001a) and most of them are using FEA. Rapid prototyping technology is also utilized to demonstrate the process and to study the performance of the forged parts. Yang *et al.* (2002) study the effect of preform to predict material behavior and the CAE result is verify by conducting an experiment using models (e.g., plasticine). Most of the effort was focused on aspect of tool path generations and preform design and optimization of die design using FEA.

DIE DESIGN SUPPORT SYSTEM

Currently even though the CAD and CAM can be found easily, but most of the activities and costs related to the planning of forging route are heavily dependent on human expertise, creativity and intuition. Various tools and approaches have been applied such as fuzzy logic, Finite Volume Method (FVM), features eliminations and parametric study (Im *et al.*, 1999; Ohashi *et al.*, 2003; Lee *et al.*, 1999; Fereshteh and Moghaddam, 2004; Sakamoto *et al.*, 2001; Zhao *et al.*, 1996; Lee *et al.*, 2002). In the most of CAD systems, the die geometry design parameters such as corner and fillet radii, draft angle and etc. and product performance is the main concern. Proper blocker design for example is important in order to ensure defect free metal flow, complete filling and minimal loss of flash gutter. Conventionally the blocker is design based on experience and design guideline. There are several guidelines that have been proposed but still cannot be used for all types of forging process. For example guideline for cold forging is not suitable for hot forging due to part complexity. In the area of blocker design, to achieve a perfect design of blocker is very difficult. For that reason, Choi *et al.* (1995) developed a computer aided design for blocker design. Ohashi *et al.* (1996) proposed a 2D CAD system that is capable of outlining the process sequences and die profiles. The sequences are based industrial experience. There are die design guidelines developed uses in computer aided die design (Kim and Im, 1995; Kim *et al.*, 2002). Kong and Nahavandi (2002) developed an on-line monitoring system to observe die condition using ANN.

Computer-Aided Manufacturing can be defined as the process of using specialized computers to control, monitor and adjust tools and machinery in manufacturing. After decision has been made by referring the result from CAE packages, product or die is constructed. There are several methods being used, such as CNC machine or rapid prototyping techniques. The same approach also being used by Jirathearanat *et al.* (2000).

An expert system is a tool that has a proven database which was constructed using case base experienced by the experts in the industry (Fujikawa and Ishihara, 1997). An expert system is developed to help less experienced designer in making decision. In forging process, recommendation from an expert system can help in ensuring that productions are at the most optimal quality and economic values. There are many researchers that tried to solve the problem occurs and suggest the best alternatives for forging condition. Kim and Park (2000) developed a system that almost covers all basic things in the forging process. The system is constructed by focusing on hot forging process and capable to design the geometries of the finisher, blocker, buster, billet and corresponding dies. The system is automated to do calculation of the required forging load, the volume and the strokes from the geometry of the machine part. Ohashi and Motomura (2000) developed an expert system which can automatically identify the defect cause on product for further improvement.

In developing an expert system, there are two types of approach used, knowledge-base and rule-base (Kulon *et al.*, 2006). For example Kim and Im (1995) and Yang and Osaka (1990) used a finite element analysis result in verifying the decision made by the expert system. Other than that Kim and Im (1999) employ the depth-first search method to reinforce the engine of an expert system. There are other knowledge-base methods such as neural network, fuzzy logic, AI and redesign algorithm

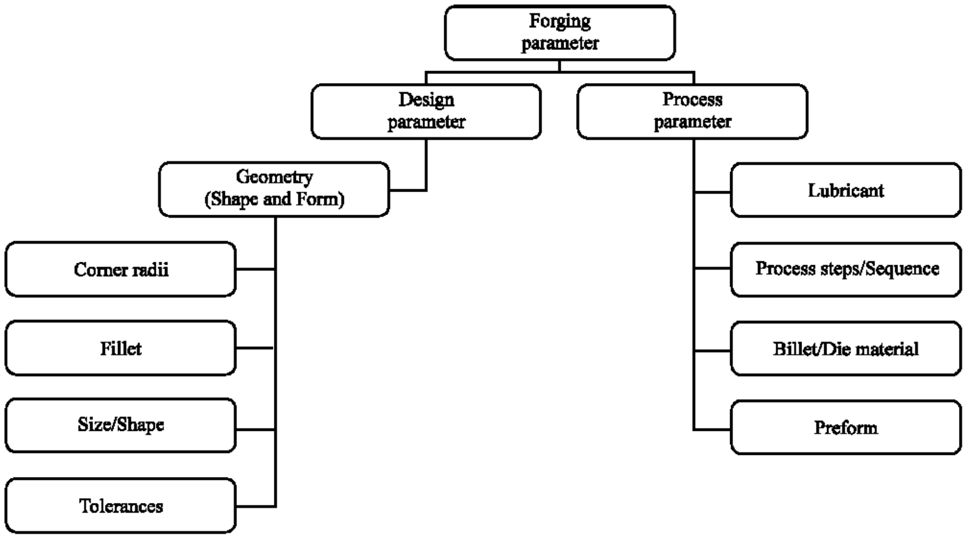

Fig. 2: Forging parameters

It covers the area of die design, diagnosing the defects, forging sequence and monitoring control (Fujikawa and Ishihara, 1997; Glynn *et al*., 1995; Ohashi *et al*., 2003; Kong and Nahavandi, 2002). Song and Im (1999) developed a modular expert system which contain of an expert system itself, database system and a computer aided design (CAD). Katayama *et al*. (2004) used the fuzzy pattern matching to developed fuzzy rules based on Genetic Algorithm (GA). Caporalli *et al*. (1998), developed an expert system named Automated Design of Hot Forging Dies (ADHFS), which can be used in assisting process planning and beside that the FEA result also can be obtained from the system. Similar to that, Lengyel and Awan (1988) proposed a knowledge based system called COFEX (Cold Forging Expert). To date the system is going to be improved to cope with the complexity of the product shape, application and material used.

FORGING PARAMETER

From the above discussed, there are several parameters that affect the die performance or forging parameter can be divide into two, design parameter and process parameter. The former play roles during the die design process i.e., modeling stage and the latter during it use. Design parameter represents the geometrical aspect of the die such as corner radii and fillet. Process parameter is a variable related to the forging process condition such as process stages, load applied, shape of the die, preform and lubrication. Machining process of the die can also be considered as process parameter. The effect of some of the parameters have been studied numerical and experimentally. Figure 2 listed the forging parameters that influence the die performance.

FUTURE TREND

The cold forging field currently shifted from less form mass production to more form less production, which means that amount of part or process cycle is reducing and die life need to be designed to meet specific production demand of the customer. This is because to extend die life, requires special process and tight procedure either at design or manufacturing stage and it costly. The introduction of smart tooling in forming process will give advantages to the production. Qin (2006a) proposed a new forming tool concept namely a smart tool by focusing on reducing pressure, extending the life of the tools, improving the part quality and enhancing the flexibility of the tooling system. Even though the idea still at the conceptual stage, the preliminary result shows great potential of the concept. Vollertsen *et al*. (2006) and Qin (2006b) discussed the technology on micro-forming and present the initial problem encounter in performing the technologies. The recent issue is developement of precision forming die system to fulfill the current demand of part of higher complexity and precision.

CONCLUSIONS

The study presents the approaches taken in the die design process and outlines the recent advanced and future trends of the die design. In the literature there are several aspects that being focused;

- Extending the die service life by introducing several methods mechanically or chemically and the performance of the die is evaluated analytically, numerically or experimentally.
- Decision support system that capable to assist designer to produced a good die. This approach can be divided into two; expert system and computer aided system. These systems developed either to recommended the best design process planning or suggest the support information in order to ensure the process can be proceed effectively

Based on the conclusion and discussion in the paper, there are two raised issues; i) up to what extend the die need to be prolong and ii) what are the minimum information needed for effective decision support system.

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