OPTIMUM FLASH-LESS COLD FORGING PROCESS FOR AUV PROPELLER FABRICATION WITH FEM

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OPTIMUM FLASH-LESS COLD FORGING PROCESS FOR AUV PROPELLER FABRICATION WITH FEM

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NOMENCLATURE

Symbol	Description	Page
L_1	Length of initial work-piece	75
r_1	Radius of initial work-piece	76
V_{wp}	Volume of initial work-piece	75
V_f	Volume of final product	75
V_i	Initial volume from which final product volume is to be subtracted	76
V_C	Volumes to be subtracted from initial volume	77
A_{wp}	Area of work-piece	105
t_{wp}	Thickness of work-piece	106
$\sigma_{ij,j}$	Stress velocity component	66
$\dot{\varepsilon}_{ij}$	Strain velocity component	67
$u_{ij}\, u_{ji}$	Velocity components	67
u_{ii}	Velocity components	67
$\dot{\varepsilon}_v$	Volumetric Strain rate	68
σ'_{ij}	Stress velocity component	67
$\bar{\sigma}$	Effective stress	68
$\dot{\boldsymbol{\varepsilon}}$	Effective strain	68
$\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{ij}}.$	Strain velocity	67
$\dot{\bar{\varepsilon}}$	Effective strain rate	68

σ_{ij}	Stress velocity component	67
F_j	Force on the boundary surface	67
S_F	Boundary surface	68
u_i	Deformation velocity	67
U_i	Deformation velocity on the boundary surface	67
S_U	Boundary surface	67
dV	Volume dependent variable	68
t_i	Traction specified on the boundary S_F	68
v_i	The velocity component	68
dS	Surface dependent variable	68
$\delta\Pi$	Functional variation	68
$\delta\dot{\bar{\varepsilon}}$	Variations in strain rate	68
δv_i	Arbitrary variation	68
σ_{11}, σ_{22} $\sigma_{33}, \sigma_{13},$ $\sigma_{23}\sigma_{12}$	Stress components	125
K	Penalty constant	68
A_2	Area of bigger circle of chamfered work-piece	75
A_3	Area of smaller circle of chamfered work-piece	75
r_2	Radius of smaller circle of work-piece	75
h	height of triangle which would be subtracted from initial work-piece	75
r_1	Radius of bigger circle of work-piece	76

ABBREVIATION

FEM	Finite Element Method
AUV	Autonomous Under Water Vehicle
EDM	Electrical Discharge Machining
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAE	Computer Aided Engineering
SDM	Surface Deposition Machining
IFM	Infinite Focus Machine
CV	Constant Velocity
FVM	Finite Volume Method
BEM	Boundary Element Method
3D	Three dimensional
mm	Millimeter
nm	Nanometer
N	Newton
mm^3	milimetercubic

PROSES TEMPAAN SEJUK KURANG-SISA OPTIMA UNTUK FABRIKASI PENDORONG AUV DENGAN FEM

ABSTRAK

Dalam pemilihan proses pembuatan, rekabentuk dai tempaan sejuk kurang-sisa dan pengoptimuman benda-kerja adalah merupakan isu-isu utama untuk mengurangkan kos keseluruhan pendorong. Banyak penyiasatan telah dijalankan dalam bidang ini, oleh banyak penyelidik menggunakan pelbagai perkakasan dan teknik. Walaubagaimanapun, tempaan sejuk geometri yang rumit seperti hab dan bilah pendorong masih lagi kurang. Selain itu, analisis isipadu dan pengoptimuman benda-kerja belum lagi dilaporkan setakat ini untuk geometri yang rumit. Dalam disertasi ini, proses tempaan sejuk telah digunakan untuk menghasilkan hab dan bilah pendorong. Analisis tiga-dimensi unsur terhingga (FE) dan ujihaji tempaan sejuk hab dan bilah pendorong AUV aluminum dibentangkan. Benda-kerja yang digunakan adalah daripada AISI AL6061 dan bahan dai pula ialah besi dai (AISI D2). Berdasarkan keputusan simulasi, operasi tempaan sejuk kurang-sisa telah berjaya dilakukan oleh mesin 100 ton jenis-C. Dikalangan lima kes benda-kerja yang dikaji, benda-kerja yang optima telah didapati dengan tidak ada isian-bawah dan sisa yang minima bagi kedua-dua hab dan bilah. Beban yang diperlukan untuk tempaan dan tegasan berkesan pada dai adalah berkurangan untuk menghasilkan hab dan bilah. Peratusan tanpa isian-bawah untuk simulasi adalah 13.72% dan untuk ujihaji sebanyak 4.54% telah didapati. Pendorong telah diuji dengan ujian bengkokan dan kesimpulan yang diperolehi menunjukkan pendorong yang dihasilkan sesuai untuk aplikasi AUV. Dalam kajian ini, hab dan bilah pendorong AUV yang telah

dimodularkan telah dihasilkan dengan jayanya menggunakan proses tempaan sejuk. Tempaan sejuk kurang-sisa untuk profil rumit, analisis isipadu yang terperinci, pengoptimuman benda-kerja dan pengendalian geometri yang nipis dan rumit adalah merupakan sumbangan utama kajian ini.

OPTIMUM FLASH-LESS COLD FORGING PROCESS FOR AUV PROPELLER FABRICATION WITH FEM

ABSTRACT

The selection of the manufacturing process, flash-less cold forging die design and optimization of work-piece are the major issues to reduce the overall cost of the propeller. Substantial investigations have been carried out on this area, by many researchers using various tools and techniques. However, cold forging of complex geometries such as propeller hub and blade is still lacking. Moreover, volumetric analysis and optimization of work-piece have not been reported so far for complex geometries. In this thesis, the cold forging process has been adopted to produce the propeller hub and blade. Three-dimensional finite element (FE) analysis and experimental flash-less cold forging of aluminum hubs and blade of AUV propeller was presented. The work-piece used was of AISI AL6061 and the die material was die steel (AISI D2). Based on the simulation results, the flash-less cold forging was successfully done on a 100 ton C-type machine. Among the five cases of work-pieces studied, optimum work-pieces were obtained for no under filling and minimum flash for the hubs and blade. The load required for forging and effective stresses in the die were significantly reduced for hubs and blade. With no under filling, the percentage of 13.72% was obtained for simulation and 4.54% was obtained for experiment. The propeller was tested for bending and concluded that the produced propeller was suitable for AUV. In the present study, the modularized AUV propeller hubs and the blade were produced successfully by cold forging process. Flash-less cold forging for complex

profile, detailed volumetric analysis, work-piece optimization and handling of complex and thin geometries were the remarkable contributions in this work.

CHAPTER ONE

INTRODUCTION

1.1 Background

Autonomous underwater vehicle (AUV) is an unmanned, tether-free vehicle which is powered by battery or fuel cell (Zhao, 2004). The direction of AUV is controlled by preprogrammed computers utilizing various navigation sensors such as inertial measurement unit, sonar sensor, laser ranger, pressure sensor etc. The research on AUV is becoming very important and interesting as well, among the marine researchers since the last two decades. The demand in the current market is tremendous for AUV; hence researchers are working to fulfill the requirement.

Yuh (2000) reported that in 1990s, 30 AUVs were developed by researchers around the world. Because of its ability to do the task independently, researchers have used it for various applications such as ecology survey and sea bed mapping. It has been reported by many researchers like Yuh (2000), that AUV could be used successfully in hazardous conditions like deep ocean. The AUV system is an integration of some essential subsystems. Propulsion system is one of the subsystems. In practice, the propulsion system of AUV contains propeller and electric motor (Marsh, 2004).

1.2 Motivation

In practice, the propellers are manufactured using die casting where the molten metal is injected in to the die cavity; because of the high temperature the system is costly and a cooling system is required. The dies undergo high thermal stresses which reduce the die life (Pantani et al., 2005). Hence, proper material which withstands the high thermal stresses should be selected, and stress relieving has to be done to remove the residual stresses which are increasing because of high temperature (Krug et al., 2000).

In cast products the flaws, thermal problems have to be solved, preheating system required to heat work-pirce and grain structure cannot be controlled (Kalpajian and Schmid, 2005). The strength is also less compared to cold forging and the production time is significantly higher. In hot forging, the preheating system required to heat the work-piece. The thermal and residual stress problem has to be taken care of; altogether will lead to an increase in the total cost of the product. In addition, machining of complicated profiles like propeller is difficult and time consuming. The collision between tool and work-piece is more, material wastage is more and tool vibration is high (Young et al., 2004) compared to forging process, since for complicated profiles, the number of operations involved to manufacture are more. The grain structure also cannot be controlled in machining. The hardness of final cold forged product is higher compared to machining processes.

In smaller scale of AUVs, critical components are not usually commercially available. The cost of non-standard parts is relatively high in the development of AUV propeller blade. Cheng et al. (2008) have adopted the shape deposition manufacturing (SDM) due to the 3D profile and resolution requirements. To produce the marine propellers of moderate size, Geoffrey and Vickers (1977) have presented a unique computer-based method. The surfaces of the propeller were calculated from a table of offsets as an array of rectangular coordinate points and displayed on a graphics terminal where they can be examined and, if required, interactively modified. Lastly, it required little finishing which is obtained using a numerically controlled milling operation. The flash-less forging leads to reduction in load required to forge, wastage of material, time and number of operations for the complex component like AUV propeller.

1.2.1 Design of AUV propeller to be forged

The propeller of AUV was designed by Universiti Sains Malaysia's Under Water Robotics Research Group to generate the thrust to drive the AUV. The hydrodynamic design of propeller blade is very complex as shown in Figure 1.1; its design has been optimized to achieve the maximum thrust. The fabrication of propellers by cold forging is a tedious task; especially designing the dies and partning line to forge the propeller as single piece is very difficult. Further, to achieve flash less forging is nearly impossible. Because of its complexity, it is very difficult to achieve the dimensional accuracy and exact shape of the propeller if it is forged as single piece. Hence, the propeller is modularized to cold forge easily. The propeller is split in to three major components; one is front hub and second is back hub lastly the blade as shown in Figure 1.2. All three components are designed in such a way that, after forging the components can be assembled easily. The assembly of components of propeller after forging is done as shown in Figure 1.3.

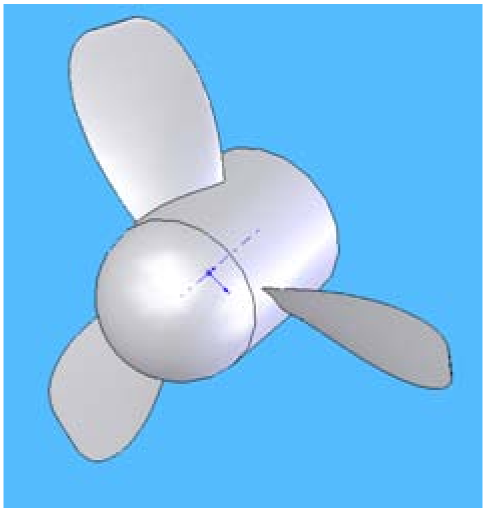
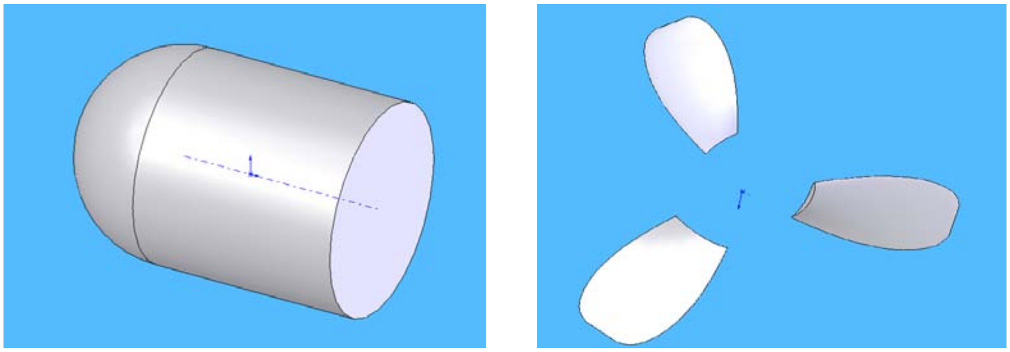


Figure 1.1 The design of AUVs propeller to be forged



(a) (b)

Figure 1.2 Modularization of propeller for forging

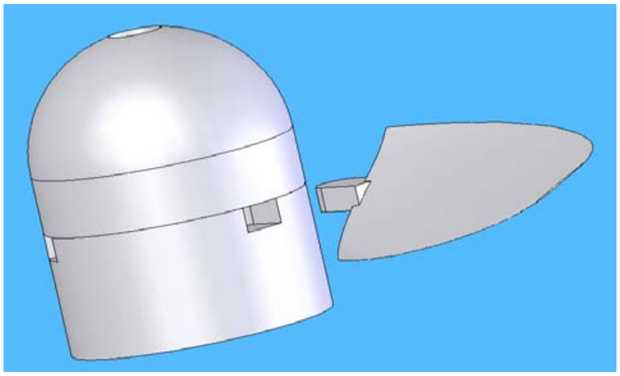


Figure 1.3 Assembly of designed components of AUV propeller to be forged

1.2.2 Complexity of blade

The thruster of AUVs is used to develop the thrust to propel the AUV. The thrust generation that capable to utilize minimum power, depends on the design of the blade. The blade of the propeller is very complex in the sense that it is made hydrodynamic and twisted, to increase the thrust. The hydrodynamic blade is varying in height; the middle is 3mm and tip is 0.3mm as shown in Figure 1.4. The cross sectional view of the blade is as shown in Figure 1.5. The twist angle of the blade is 40^0 as shown in Figure 1.6.

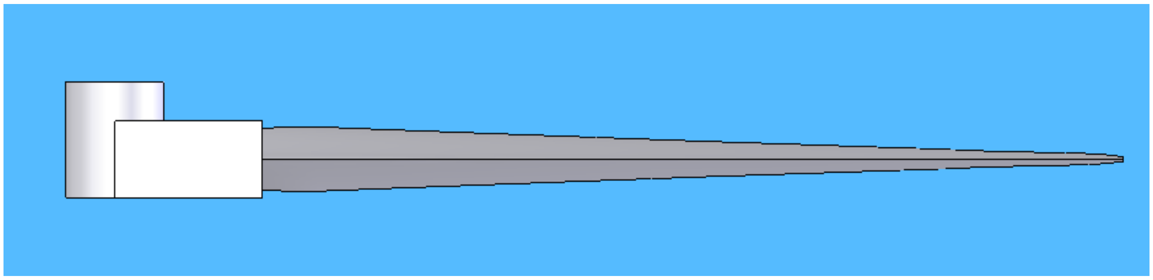


Figure 1.4 Designed of AUVs propeller untwisted hydrodynamic shape blade to be forged

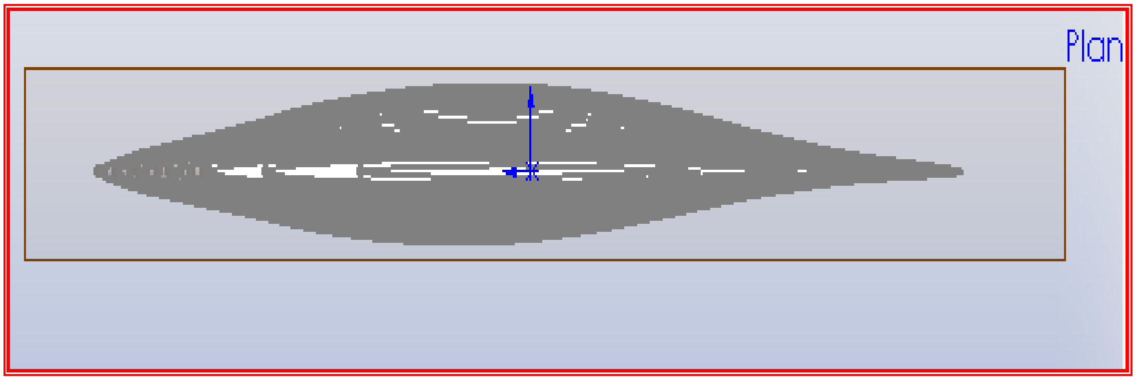


Figure 1.5 Front view of the hydrodynamic untwisted blade

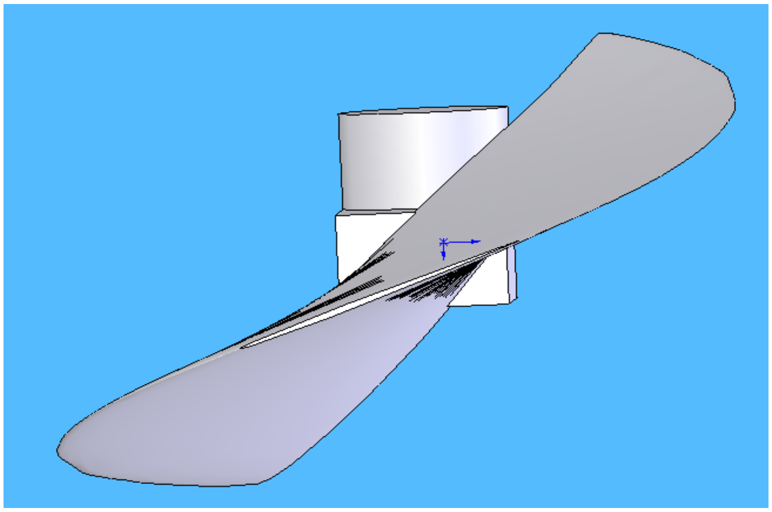


Figure 1.6 Design of AUVs propeller twisted hydrodynamic shape blade to be forged

1.3 Application of CAD/CAE in forging process

Cold forging has various advantages such as improved strength, geometrical precision, high production rate and less porosity with little loss of material. Forging industries are developing and keeping pace with the other metal forming industries, with the implementation of modern technologies like CAD, CAM, and CAE to design and manufacture forging dies as well as to optimize the die design. In the conventional methods, there is lot of material wastage of 20-40% (Vazquez and Altan 2000) and time consumed. Also they are laborious and require skilled persons for design and fabrication. Nowadays, forging industries are using CAD/CAE /CAM with which design engineer can simulate his designed die in the computer.

It is very easy to perform the changes to get the optimum design without wastage of material and time, and ultimately production cost will be reduced. Designer can visualize the product before production takes place; by visualizing the 3 dimensional views, the designer can change the product specifications aesthetically as well ergonomically without breaking any component and wasting time. To achieve the optimized product aesthetically as well as ergonomically by altering various parameters, designers are using CAD/CAE/CAM with which parametric study requires very little time with no damage to material. Typical examples for near-net-shape forging parts that have a great degree of similarity to machined parts are bevel and cylindrical gears forged with tooth development (Tomov and Gagov, 1999).

Recently, computer aided design (CAD), computer aided manufacturing (CAM) and computer aided engineering (CAE) are increasingly implemented in all fields of design and manufacturing. These techniques are used to simulate the forging process to optimize the work-piece, deformation and to find the stresses in the die during forging process. Substantial efforts have been made by many researches on cold forging. The use of DEFORM and DEFORM-3D FEM systems for cold-forging study has been reported by Kim et al. (1994). They have also presented a new tool design for cross groove inner race for a constant velocity joint, flash-less forging of an aluminum connecting rod, design of cold forgings and forming sequences, die wear in warm forging extrusion, and examples of DEFORM-3D simulations of a connecting rod and blade coining.

Kim and Alfan (1996) have given several examples of cold forged parts collected from literature and cold forging industry. They have verified forming sequences generated by FORMEX with finite element (FE) simulation program such as DEFORM. Petersen and

Frederiksen (1994) have presented the results of two-dimensional FE analysis with special emphasis on the effects of plasticity.

1.4 Problem Statement

The manufacturing processes which exist as discussed in Section 1.2 to produce AUV propeller are having certain disadvantages and considering the advantages of cold forging as discussed in Section 1.3, hence, the cold forging process is chosen. It is very difficult to achieve the flash less and net shaped cold forged propeller. In order to minimize the wastage and load required to form the product, it is essential to optimize the work-piece. At the same time, the under filling and folding also should be avoided. Many researchers have attempted to optimize the work-piece without under filling and folding. Kim et al. (1997) have optimized the parameters of work-piece to fill the die cavity using FEM and neural networks, but they have not discussed the flash. Similarly, Dean (2001), and Tomov and Gagov (1999) presented the net shape forging, but did not report the flash minimization. For propeller blades, achieving net shape without flash is difficult. The hot forging of aerofoil blades was performed by Hu et al. (1999). They measured aerofoil blades flash at several regions and found the flash ranging from 40%-90% at various regions, and thus caused more wastage of material. The flash-less cold forging is defined as the one in which the amount of flash is minimal i.e. 5% (Vazquez and Altan 2000). Cho and Kang (2000), and Vazquez and Altan (2000) also worked on no under filling and flash-less forging. No under filling in the die cavity leads to net shape forging. Flash is wastage of material and requires extra operation to remove or trim it to get the desired shape and it requires more load for forging operation which reduces the die life (Vazquez and Altan, 2000). Attempts have been made by Cheng et al. (2008) to simulate the forging process of a gas turbine compressor blade from a cylindrical billet to a complicated product, using 3D rigid-viscoplastic FEM.

Even though, many researchers have focused on various manufacturing processes to produce the AUV propeller, like machining, casting, injection molding and hot forging, attempt for cold forging of complex geometries such as AUV propeller hubs and blades has not been reported so far. Optimization of work-piece to achieve flash-less forging for complex profile and stress analysis of induced effective stresses are to be studied thoroughly. Moreover, research is required to be done in die design especially cold forging die because the die will undergo high loads; hence it has to undergo stress analysis. The work-piece has to be optimized for forging of hubs and blade of propeller for flash-less forging with no under filling to reduce the induced stresses in the dies, to reduce the number of operations and to obtain dimensional accuracy. Predominant complexity in the propeller blade is hydrodynamic profile and twist because of which it is very troublesome to achieve the flash-less forging, especially in cold forging.

The predominant issues in manufacturing of AUV propeller by cold forging are:

- The process parameters involved have to be studied to produce the flash-less forging.
- Cold forging tooling and process need to be designed to achieve flash-less cold forging.
- FEM analysis for flash-less cold forging and experimental validation.
- The work-piece has to be optimized to reduce the flash with no under filling.

- The load required to be reduced for forging to increase die life.

1.5 Objectives

The main goal of this research is to produce an AUV propeller using cold forging process in order to fulfill the design geometric specifications given in the AUV design. To achieve this goal, the following objectives have to be carried out.

1. To design and analyze cold forging tooling using CAD (SOLIDWORKS) and FEM (DEFORM)
2. To determine the optimum tool parameters in producing flash-less AUV propeller.
3. To perform the comparative study of the dimensional errors of FEM, designed and experimental models of the AUV hubs and blade.

1.6 Scope

In this research work, cold forging process and die design were done as per existing techniques like CAD and FEM. Forging component and its material were selected on the basis of machine capacity to forge which was 100 ton for the experimental work and corrosion resistance in water since the propeller is going to be used under water. SOLID WORK 2007 SP4.0 was used for modeling and DEFORM F3 V6.1 was used for the FEA simulation. It was considered that the pre-form and dies satisfy the equilibrium and continuum equations. The process dies, and pre-form have been designed according to standard.

1.7 Approaches

The study was carried out to analyze the process, and to design the cold forging die as per the dimension of the designed geometry, by using FEM technique and experimental analysis; SOLID WORKS and DEFORM-F3 software are used for design and for analysis respectively. The optimization of pre-form for propeller hubs and blade was done by varying the design parameter. Experimental method has also been used to validate simulation results.

1.8 Thesis organization

The thesis is organized in such a way that it provides information to the reader in continuous and smooth fashion, regarding flash-less cold forging, its process design and stress analysis of the dies using FEM. This thesis contains five chapters which are sub divided into suitable sections that are again sub divided wherever required.

Chapter 1 presents the introduction of the work carried out, and gives a brief background and the importance of the flash-less cold forging of AUV propeller hubs and blade. It highlights the problem statement and objectives of the present study.

Chapter 2 states the literature survey relevant to the cold forging, highlights briefly the different aspects of the forging and specifically flash-less cold forging being addressed by the other researchers.

Chapter 3 gives the methodology adopted to achieve the design of tooling and process for flash-less forging of AUV propeller hubs and blade. All aspects to achieve the optimum work-piece using FEM and experimentations are discussed in this chapter.

Chapter 4 explains in detail the investigation of the optimum work-piece for flash-less and with no under filling. The load and dimensional analysis have been discussed. Further, the stress analysis has been discussed in this chapter.

Chapter 5 gives the concluding remarks and suggests future works required to improve the research.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

As mentioned in the previous chapter, the research on forging has a history of many years, and most of the works on this area were well documented. Prior to arriving at the actual geometry to be selected and technique to be employed in the current study, a thorough review of related previous works has been made and presented systematically in this chapter.

2.2 Manufacturing of propeller

Manufacturing of propeller is a very complex process since the profile is very complex. Researchers who worked on this, like Cheng et al (2008) have used rapid prototyping (shape deposition manufacturing) process for manufacturing the propellers with smooth surfaces. Few researchers have reported about the manufacturing of AUV propeller. The manufacturing of propeller using other techniques like Verton long glass fibre reinforced polyamide thermoplastic has been reported by Marsh (2004), and Geoffrey and Vickers (1977) have presented a unique computer-based method which was explained in Section 1.1. The machining of the marine propeller blade surface was done using NC programming by Kuo H-C Dz and W-Y (2002). Whereas, Cheng et al. (2008) and Hu et al**.** (1999) have adopted the hot forging process to manufacture gas turbine compressor blade and Titanium alloy blade.

Furthermore, Brooks et al. (1998) have also used the hot forging to manufacture titanium aluminide gas turbine blade. Na et al. (2003) stated that the grain size can be controlled by the thermo-mechanical process, including heating, forging and cooling sequence and they also used hot forging. No literature is available on manufacturing of propellers using cold forging. From literature, it has been observed that the propeller manufacturing by hot forging, machining and injection molding was reported, but, the manufacturing of propellers using cold forging has not been reported so far, especially on AUV propellers.

2.3 Propeller modularization

In practice, modularization is a process of making product in a module for practical production objectives. It was first mentioned in the literature in the 60s (Jose and Tollenaere, 2005). The modularity refers to the use of common units to create product variants. To increase the production rate of large variety in industry, the modularity has to be introduced to enhance the productivity, since currently it has not been implemented (Huang and Kusiak, 1998). They have developed the models and solution approaches to the modularity problem for mechanical, electrical, and mixed process products**.** On the other hand, Guan et al (2007) have used modularization to develop the robot. The modularization is the strategy to implement mass customization. The problem in the modularization should be solved, some researcher try to solve these problem like Olivares et al (2008) by selecting a common platform for a modular product. Seliger G and Zettl M (2008) have worked modularization and they concluded that the modularization increases the productivity of resources.

This Section gives the literature survey for modularization. From the previous researches, it is evident that the modularization was done for various applications but was not used to manufacture AUV propeller by cold forging. The modularization reduced the complexity of product to be manufactured. In the present work, the modularization is used to manufacture AUV propeller by cold forging.

2.4 Cold forging analysis

Monaghan (1993) performed experimental and theoretical analyses of the metal deformation arising during the cold forging. He derived the expression for the punch work-piece interface and the mean forging pressure using the slab-analysis method. The predicted results were found to be match with experimental results. Nagahama and Enomae (1992) focused on the hardware aspects of forging technology, specially related to the automotive industry. They studied the aspects like market trends in forming methods and press capacity. They also worked on requirements for cold and warm forging presses. Further, they focused on the process and main features of warm forging, including die life and die lubrication.

Pale et al. (1992) have reviewed the recent developments in cold forming tooling, machines and processing. They primarily focused on forming complex parts which often required a combination of forward, backward and radial extrusion, using novel multi-action tooling and forming equipment. Sevenler et al. (1987) developed a prototype expert system for forging sequence design in cold and warm forging for axisymmetric parts. The different design parameters for a rod and cup component were discussed. Sutradhar et al. (1995) investigated the various aspects of cold forging of iron powder pre-forms. An upper bound solution was built to determine the die pressures developed during the cold forging of iron powder under axisymmetric and plane-strain conditions. Robinson et al. (1978) selected gear to study the surface cracking. They focused on workability analysis that could predict the surface cracking during cold forging. The workability analysis was applied to both stages to determine the effect of process variables on the likelihood of surface cracking. A criterion to predict wall instability during upsetting of a ring was also presented.

Arentoft et al. (2005) worked on reversed straining in axisymmetric compression test. Because of reversed straining, plastic deformation of the work-piece would affect the resulting diameter of the work-piece. In order to simulate these conditions, a reversed axisymmetrical material tester was designed and constructed. They tested three different materials, aluminum alloy AA6082, technically pure copper (99.5%) and cold forging steel, at different temperatures. Krusic et al. (2009) have worked on stochastic nature of typical cold forging processes. They applied FE computations to backward extrusion, free upsetting, closed-die forging and forward rod extrusion in order to study the effect of input parameters on the dimensional accuracy of products and on the tool service life. Ohashi and Motomura (2000) reported a study on detecting the risk of forging defects and their causes in cold processes. The system involved risk analysis for a computer aided process planning system. They developed risk analysis tree networks to evaluate the risk potential and described the risk potential by fuzzy language. The risk analysis tree networks were developed for each kind of typical defect and the location on the forging part at which they occurred. On the basis of the experimental details of cold forging process planning, the disadvantages of a rule-based solution were discussed by Lei et al. (2001) and they proposed case based and reasoning based cold forging process planning system model. Various shortcomings in the process were analyzed; to solve the problems like case representation and case retrieval, they introduced a feature-based part representation scheme and a two-level retrieval mechanism.

Li and Wu (2007) have studied the high strength and low yield ratio of cold forging steel using thermo-mechanical simulator, a laboratory hot rolling mill and a multistage cold former. The results have shown that multiphase microstructure contains polygonal ferrite, dispersed pearlite, granular bainite and retained austenite obtained by thermomechanical processing (TMP). The cold forging of steel could be directly used to fabricate bolts from hot rolled bar due to its low yield ratio; by applying TMP the mechanical properties of the finished bolts could achieve the standard of class 8.8 bolts without heat treatment. This was because the hot rolled bars after TMP possess multiphase microstructure, which contributes to an increase in mechanical properties, strength and ductility of the bolt.

The process plan is one of the most important stages of cold forging design. Web-based and knowledge-integrated engineering design has now flourished and is widely used in engineering fields. Zhang et al. (2004) proposed a web-based intelligent cold forging process plan and conducted research on related key technologies which led to the development of a prototype system. Through the use of web and intelligent approach, the cold forging knowledge could be effectively incorporated into the process generation system and a web-based cold forging process generation system could be implemented. A hot extrusion system with controlled cooling was investigated by Yanagimoto et al. (2009). The formability of the ultrafine-grain steel manufactured using the proposed system was examined by a cold-forging experiment.

The effect of nitrogen on the cold forging properties of a low carbon steel as a function of temperature, this was studied by Douthit and Tyne (2005). A new surface processing technique for cold forging of steels was developed by Dubar et al. (1998). To reduce pollution and for easy implementation, they adopted coatings, designed to replace phosphatation. A new approach based on industrial tool life data was introduced for estimation of fatigue properties of the tool material by Saroosh et al. (2007). In their study, high cycle fatigue life prediction based on material property of the work-piece has been made. The effect of the strength coefficient K and strain hardening exponent n of four different work-piece materials was considered in the local stress and strain approach.

By considering all these parameters, they have derived a simple relationship between the high cycle fatigue life and material property of the work-piece. A FE technique was used to analyze forging process having a floating die by Ryu and Joun (2001). Its numerical characteristics were investigated in detail. They used rigid-plastic FEM together with a search scheme of obtaining the proper floating die velocity that makes the floating die load to be less than the user-specified tolerance. In addition, they have given an application example of an axisymmetric three-stage cold forging process having a floating die.

In order to clarify the forming limit of magnesium alloy in cold forging, the workability of magnesium alloy AZ31B (Mg-3%Al-1%Zn) was examined by upsetting and backward extrusion by Matsumoto et al. (2007). In the upsettability test, at the temperatures lower than 170 °C, the shear type fracture occurred at a small equivalent strain of about 0.15. To explain the experimental results, the mechanism of fracturing was discussed on the basis of strain localization, and a fracture criterion of magnesium alloy in cold forging was suggested. The proposed criterion provided much better results than the existing criteria.

Baskaran and Narayanasamy (2008) have worked on experiments to generate data on cold upset forging of commercially pure aluminium solid of irregular shaped billets. For example, the elliptical billets with white grease as a lubricant applied on both sides in order to evaluate the barreling. Bay (1997) worked on the ongoing development of cold forging technology which was manifested lately by the increasing application of components in cold forged aluminium alloys. By applying precipitation hardened alloys, components with great strength to weight ratio could be produced with strength compared to unalloyed steel.

The different alternatives to improve the life of a tungsten carbide insert used in a cold forming operation were suggested by Vazquez et al. (2000). These alternatives were as follows: (1) double tapered insert, (2) split insert design, and (3) change of insert material. Although, the techniques were applied to a specific case, they might be applicable to other cold forging tooling as well. They performed metal flow and stress analysis to improve the life of the insert, using DEFORM. In the current study cold forging process was adopted to produce AUV propeller to achieve the net shape forging with reduction in wastage of material. The grain structure can be control, no extra cost required for heating the work-piece before forging. The temperature was low compare to other manufacturing process which affects the die property. From this literature survey, it was observed that the producing propeller and specially AUV not reported so far.

The Section gives enough literature in cold forging analysis. Even though the cold forging process has lot of advantages over other manufacturing processes, the manufacturing of complex profiles like blade using cold forging process has not been reported so far. In the present research, the cold forging process is used to manufacture the AUV propeller.

2.5 Forging process and tooling design using CAD/CAE

CAD and FEM have been adopted by many researchers for process optimization of tooling and work-piece to achieve flash-less forging thus increasing die life and reducing process time, and reducing the cost of the product. These tools have been used to perform design and analysis of process and tooling of forging, and to get the accurate results without damaging the physical structure. The physical structure can be easily modeled in CAD package and then can be transferred to FEM package where the various analyses can be done. To optimize the product, one can easily change the geometry in CAD model to get the optimized geometry. Similarly, the material properties can also be changed to carry out the optimization. Researchers have excellently used these tools for the simulation.

Many researchers made attempts to give the solutions using the FEM, like Castro et al. (2004) who made an attempt to obtain an optimal design in forging. They formulated design problem as an inverse problem incorporating a FE thermal analysis model. They adopted an evolutionary strategy in the optimization process. They adopted rigid viscoplastic flow-type formulation which was valid for both hot and cold processes. They developed numerical algorithm based on a genetic search supported by an elitist strategy and selected work-piece pre-form shape and work-piece temperature as design variables. They developed a new evolutionary search model for optimal design of hot metal-forming processes. DEFORM and DEFORM-3D FEM systems have been used for analysis by Kim et al. (1994). They proposed a new tool design for cross groove inner race for a constant velocity joint and they also studied the flash-less forging of an aluminum connecting rod. Kim and Alfan (1996) surveyed the literature and cold forging industry; from this survey they gave several examples of cold forged parts. For the example, parts forming process sequences, including the dimensions of the work-piece at each forming station were given. For programming and to verify forming sequences they used FORMEX with FE simulation program such as DEFORM. Petersen and Frederiksen (1994) presented the results of two-dimensional FE analysis, and they emphasized on the effects of plasticity. They mainly studied stress concentration and plastic zone propagation in the sharp corners of a bolt-head die.

Song and Im (2007) and Hu et al. (2007) have used FEM to simulate the cold forging process of the spur gear and to study the process design for closed-die forging. Similarly, rigid–plastic FE simulation was used by Kim et al. (2003) to analyze the deformation characteristics of the whole impeller hub forming processes and to optimize the process. Ishikawa et al. (2000) investigated analytically the dimensional changes in punch die and work-piece due to stresses and heat generated during forging process. They used numerical technique, using thermo-elastic-plastic FEM code to investigate change in outer and inner diameter of backward extruded cup. They compared the calculated results and found good agreement with the experimental results.

Ohashi et al. (2003) developed a CAD system to design forging sequences and die profiles, and proposed a system which could design one forging process and pre-form. It could also do the internal profiles of dies and export them as point line into general purpose CAD systems. CAMP*form* was used as CAD simulation tool by Hussain et al. (2002) to investigate the usefulness and effectiveness of employing numerical simulations in the design process of metal forming parts like inner gear component, clutch-hub. They studied aluminum alloys, Al1100-O, Al2024-T3, Al6061-T4 and Al7075-T4 with respect to their defect factors of work hypothesis. They found that only Al6061-T4 could be considered as a substitute material of steel for cold forging of the clutch-hub. Im et al. (1999) and Lee et al. (1999) have used computer aided process design technique and computer-aided die design system using Auto-Lisp in cold forging. Im et al. (1999) worked on cold forging of ball joints. They used computer aided process design technique based on a forging simulator and commercial CAD software together with its related design system. The forging simulation technique was used to verify the process design. It was shown that engineering and design productivity was much improved by the presented approach from the practical standpoint of process design engineers.

Lee et al. (1999) developed a computer-aided die design system using Auto-Lisp. The design characteristics of the die elements and the die assembly were expressed in parametric programmed form. They finalized three modules of cold forging die design in the proposed system, namely, forward extrusion, upsetting and combined extrusion. With the aid of the proposed system, the functions of die-element design, die-assembly design, automatic graphics and dimensions generation, redesign, dimension constraint correlations and bill of materials will provide efficiency and convenience of die design. Falk et al. (1998) assessed the applicability of different failure concepts for a closed cold forging die. The critical process dependent load was quantified and localized by using FEM. Based on the resulting stress and strain distributions, the damage parameters were calculated, yielding different estimates of tool life that were compared with practically experienced data. Kim et al. (1997) adopted neural network technique to determine the initial billet geometry for the forged products using a function approximation. They used simulated data to determine the aspect ratios that fill the die cavity. Hence, the number of simulations was reduced. By using the neural network, they predicted the unfilled volume for some aspect ratios of the billet that fills the die cavity. They reduced the number of FEM simulations in process planning.

Xu et al. (1997) carried out an analysis of isothermal axisymmetric spike-forging using an integrated FEM code. Simulations were conducted to investigate the influence of different geometric parameters, processing variables and interfacial conditions on the instantaneous spike height. The simulations results were discussed along with comparisons with available experimental results. Hsu and Lee (1997) proposed a cold forging process design method based on the induction of analytical knowledge. They used analysis engine, which is a FE based program, to analyze various multi-stage cold forging processes based on predefined process condition parameters and tooling geometry. Their method was useful for the shop floor to decide the cold forging process parameters for producing a sound product within the required minimum quantity of the die set.

Computer aided engineering (CAE) techniques have been increasingly applied with great success in metal-forming research as well as in the cold and hot forging industry. Altan and Knoerr (1992) adapted CAE for cold forging applications and summarized relevant industrial research results obtained with DEFORM. Further, they reported the investigation of a suck-in type extrusion defect, forging of bevel gears. The design of a net-shape cold forging operation for pipe fittings and development of a new test to evaluate lubrication in cold forging have been reported by them. Oh et al. (1992) worked on features required to simulate cold forging operations. Example solutions were also presented to demonstrate the capabilities of the DEFORM system. It was also shown that the automatic mesh generation and re-meshing capability was an essential feature for industrial applications.

Meidert et al. (1992) worked on two modeling techniques, FE based numerical modeling and physical modeling with plasticine, that were presented as process design tools in cold forging. They developed a strategy to allow successful 2D FE modeling of bevel gear forging. They used the results from the process simulation as a load input data for punch stress analysis. Thus, it was possible to modify the punch geometry in order to reduce the punch stresses. They applied physical modeling to verify the simulation results.

Friction control is one of the essential process parameters to achieve better results of flow of material and to reduce the load required to forge the work-piece into the desired shape especially in complex profiles. Buschhausen et al. (1992) worked on a friction test based on a double backward-extrusion process to obtain information on lubrication quality. They used the program DEFORM for FEM analysis which was conducted for different area reduction ratios and billet heights. Their simulation results were very close to the experimental results.

The elastic deformation in the dies and the work-piece lead to the dimensional inaccuracy in final product of forging, hence analysis of the dies and forged component is predominant (Natsume et al., 1989). They have studied systematically, to understand the dimensional difference between forging tools and forged components by both experimental and FEM analysis. It has been found that the difference was mainly influenced by the elastic deflections of the die and the elastic recovery of the forged part.

The FEM analysis results from the consideration of the die as a deformable body agreed with the experimental results and in their study shrink-fitting factor has been considered. Similarly, the elastic behavior of the tool material is studied by Lee et al. (2002a) using FEM.

Heat transfer at the region of die and work-piece is a noticeable aspect for the die life and the residual stress build in the forged component. Qin et al. (2000) worked to combine coupled thermo-mechanical FE plastic simulation and heat transfer across die and work-piece interfaces. The functions were then used for initiating heat transfer analysis on the die with the repeated heat-loading for the given cycles. Since only heat transfer analysis was required for the die for the multi-cycle analysis, high-efficiency of the computation was achieved.

Jun et al. (2007) used FEM to study the experimental approach for systematically estimating the geometric dimensions of cold forgings. The rigid-thermoplastic FEM was adopted for the simulation which assumes the dies and tools as rigid. The spring-back analyses were carried out using the information obtained from the forging simulation for die structural and work-piece. The approach was applied to test cold forging process. A comparison between predictions and measurements demonstrated that the proposed approach was acceptable for this application. Hua and Han (2009) and Han and Lin (2009) worked on reasonable 3D elastic–plastic dynamic explicit FE model of cold rotary forging of a cylinder work-piece. Modeling and analysis were executed using the ABAQUS software environment.