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Full Length Research Paper

Effects of die shape modifications on the geometrical and dimensional accuracies of cold forged AUV propeller blade

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Geometrical and dimensional accuracies are two major concerns in precision forging and they become more critical with increasing part complexity. In this study, the geometrical error of an autonomous underwater vehicle (AUV) propeller blade is quantified by comparing the blade and punch profiles. The nominal geometry of the blade is compared to the blade profile measured using the optical technique *Infinite Focus Alicona* system to determine profile deviation. The current study aims to investigate the contributions of die shape modifications on the error formation of the two most critical geometries, namely, blade thickness and twist angle. The results show that die modification has a significant effect on geometrical and dimensional errors.

Key words: Geometrical and dimensional accuracies, die shape modifications, cold forging.

INTRODUCTION

Cold forging has become one of the major manufacturing methods because of its high strength and good dimensional accuracy. Cold forging is governed by many factors that could affect the dimensional and geometrical accuracies of the produced part. Lange (1985) found that either the shape or dimensional error can influence part accuracy. Shape or geometrical error can be described as the deviation of the geometrical form of a part, whereas dimensional error is defined as the deviation of the actual dimension from the desired value. In evaluating component error, two most common terminologies are usually referred to ‘as manufactured’ and ‘as targeted’ to represent the component produced at the end of the forging process and the desired shape that is supposed to be produced, respectively.

Most cases on component error are related to die designs and their behavior to date. Kuzman (2001) found that the huge load required for the cold forging process plays a significant role on the accuracy of the tools because of die deflection. Finite-element methods (FEMs) have become the main tools for investigation of the component error because of their flexibility. Wanheim and Balendra (1997) utilized FEM to investigate the effect of the in-process compensation of errors in the form of the extruded part. Their results show that error compensation can be achieved by rotating the die about its bearing surface. Lee et al. (2004) investigated the effect of punch elasticity under certain process conditions on the formation of errors by employing both experimental and numerical methods to simulate the closed-die upsetting of ferrous metal at three different stages, including loading, unloading, and ejecting. They concluded that die deflection during the loading and unloading stages is more important than the elastic recovery of a work piece during the ejecting stage. Behrouzi et al. (2010) recently proposed a die shape compensation method to obtain the optimal die profile. They employed an algorithm for inverse springback

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modeling using bending theory and FEM modeling. Shi et al. (2007) improved part quality by introducing a new die design technology. They used a three-dimensional FEM to simulate the forming process of the impeller. Moreover, they improved the forgeability of the impeller blades based on the new die design and avoided certain defects, such as underfill and flash. Similarly, Lee et al. (2008) adopted a specially designed split die to produce an impeller used in a fuel cell system. They successfully controlled part errors caused by burr and under-filling. Abdullah et al. (2007) reviewed the die design process and optimization and found that die shape compensation is one of the recent approaches used for minimizing errors. Yang and Ruan (2011) considered two important aspects, namely, compensation magnitude and compensation direction, to compensate for the spring back problem, resulting in higher precision, especially for a complex panel with advanced high strength. Rosochowski (2001) proposed a procedure based on a hybrid physical modeling/finite-element approach. He considered two major sources of error, namely, die deflection and component springback. Ou et al. (2012) developed a two-step optimization approach, which is composed of a direct compensation method for die shape modification and a control variable method for the reduction of random variations, to minimize systematic errors. Lu et al. (2009) proposed a new direct compensation method by employing variable weighting factors in die shape optimization for the net-shape forging of 3D aerofoil blades for aeroengine applications to minimize the total forging tolerances in forging optimization computations. Ou and Balendra (1998) initiated the concept of a weighting factor, which is used for correlating quantified forging tolerances and the required die shape modifications. Makem et al. (2012) proposed a virtual inspection system for virtual forging error assessment in a robust framework. Lu et al. (2011) developed an efficient and easy method to implement optimization algorithms in metal forming simulations that often involve complex tool and workpiece interaction and coupled thermal and mechanical analyses. They used three direct search algorithms, including a modified simplex, random direction search, and enhanced Powell's methods, together with a new localized response surface method to solve die shape optimization problems and achieve net-shape accuracy in metal forming processes. Zhang et al. (2007) investigated the performance of a multi-pin die with pins in a circular array and an adjustable blank holder. They found the die shape optimization design method to be useful in reducing shape error in the formed work piece using inverse displacement compensation.

Most studies conduct the die compensation or die shape optimization and predict the errors prior to die fabrication. However, none of these studies measured the error encountered after the dies were fabricated. In practice, even though the die shape had been optimized, errors still occur and obtaining the desired shape in the first trial is difficult mainly because of the behavior of the die material during the process. Thus, the dies should be modified until the desired part is produced, and the modification is usually done via trial and error.

The current study aims to investigate the effect of die shape modification on the component accuracy of a cold forged AUV propeller blade. The geometrical error is determined by comparing the resulting profiles obtained from the surface measurement system, namely the *Infinite Focus Alicona* system. Three different profiles of the forged blade, including the nominal model, the punch, and the forged blade were considered to represent the targeted, modified tooling, and manufactured profiles, respectively. The amount of error caused by the modification can be found by comparing these stages. A coordinate measurement machine (CMM) was used for validation. This study starts with an introduction and a brief explanation of the cold forging process of the blade, followed by the derivation of the formula used to evaluate the contribution of die modification to the total error. Then, the methodology is presented and the results are discussed. The paper ends with a conclusion.

Cold forging process an AUV Blade

Khaleed et al. (2010) introduced the cold forging process, which is a new method for manufacturing AUV propeller blades. A modular AUV propeller generally consists of three components, including the front hub, the rear hub, and the blade (Abu-Bakar et al., 2008). The blade is formed in five steps using the cold forging process, as shown in Figure 1. An Aluminum AA6061 sheet with thickness of 3 mm was blanked into a preformed shape. The preformed shape is then forged to a blade with hydrodynamic profile. In the third stage, the excessive material or flash was trimmed using a shearing operation. Next, the pin is created and the forged blade with complex profile is twisted in the final stage, which is also the most critical stage. Figure 2 shows the geometries of the blade.

Die shape modification

In obtaining the optimal part, the punch and die are usually modified based on the experience of the designer. In practice, producing the profile of the forged blade as intended in the first trial is difficult. Therefore, modifications are made via trial and error until the targeted profile is achieved. Measuring the amount of grinded surface at each modification on site is difficult. The amount of modification can only be determined after achieving the forged blade with an acceptable allowance by comparing the CAD model and final shape of the die. The current study investigates a punch/die for the final

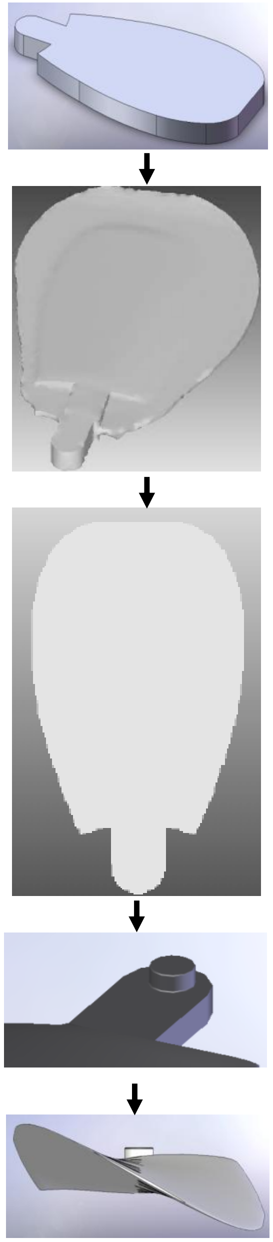


Figure 1. Cold forging process steps of the AUV blade manufacturing.

stage of twisting. Figure 3 shows the fabricated punch and die.

The geometrical error is measured based on the deviation between the targeted and manufactured profiles, that is, the deviation from the profile of the blade that is forged at the end of the process to the profile created in the CAD model. The total error can be represented as follows:

Error total = Profile targeted – Profile manufactured (1)

or

= Profile blade, CAD – Profile forged blade (1a)

The modified die and punch profiles, which contribute to the total error, can be determined by calculating the difference between the nominal profile obtained from CAD model and the profile on the die and punch measured using CMM. The modified profiles can be expressed follows:

Error modification = Profile blade, CAD – Profile die-punch (2)

or

Profile blade, CAD = Error modification + Profile die-punch (3)

Similarly, the error measured on the forged part from the difference between the measured die and punch profiles using CMM can be determined as follows:

Error post-forging = Profile die-punch – Profile forged blade (4)

or

Profile forged blade = Profile die-punch – Error post-forging (5)

Therefore, the total error is the difference between the blade measured using CMM and the nominal profile in the CAD model.

Error total = (Error modification + Profile die-punch) – (Profile die-punch – Error post-forging)

= Error modification + Error post-forging (6)

Methodology

In this study, the blade and punch profiles are obtained using optical techniques, and the nominal geometry from the CAD model is considered as the targeted part. Solid works, which is commercial CAD software, was utilized to model the blade. The data are then exported to the CAD environment in 3D form (Abu-Bakar et al., 2008). The die and punch were consequently fabricated. Khaleed et al. (2010) optimized and fabricated the die and punch designs. A 100-ton C-type mechanical press machine was used for forging the process of the blade.

Image scanning

For image scanning, the blade and punch were placed on the table of the *infinite Alicona* system, as shown in Figure 4(a). It should be noted that a very thick layer of white acrylic was sprayed on the

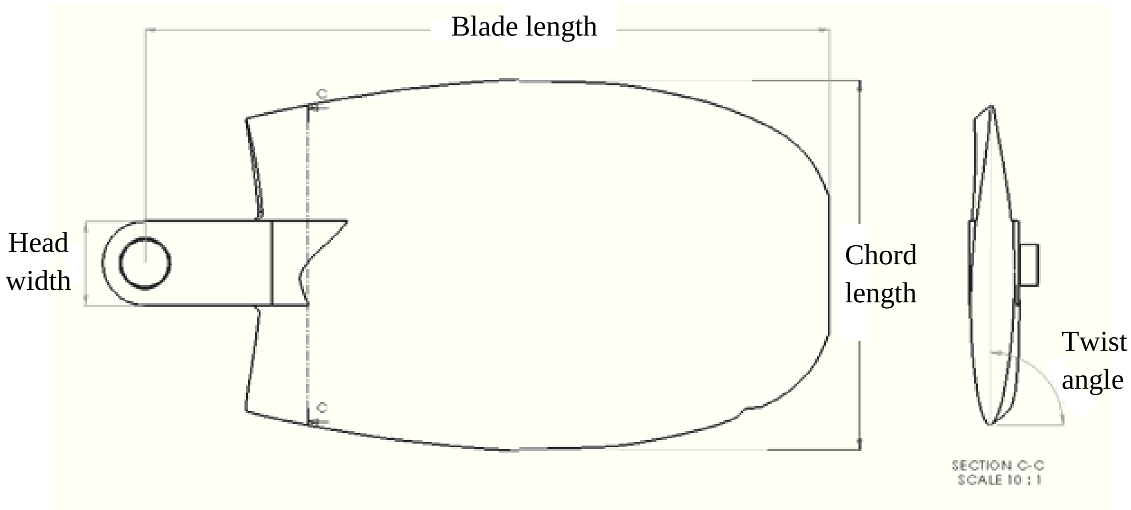


Figure 2. The geometries of the blade.

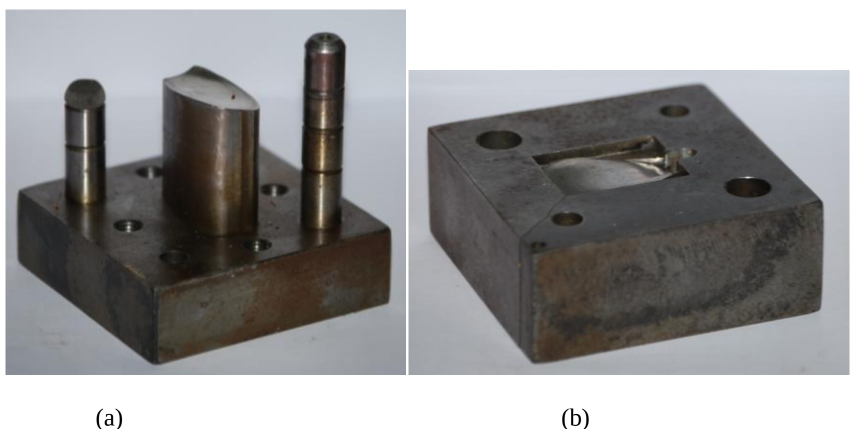


Figure 3. The (a) punch and die (b) for the twisting stage.

blade and the punch surface prior to scanning to obtain a good image, as shown in Figure 4(b). A 2.5x resolution lens with vertical resolution of 2,300 nm was used in the scanning process. For validation, a DCC coordinate CMM with measurement accuracy of 0.1 micron (0.001 mm) was used. The blade was divided into five sections, as shown in Figure 5(a), and the profile was scanned on the same section line to measure the deviations. The x and z axes of the machine then translated as the profile of the blade, which were obtained in the form of length, *l*, and z coordinates, as shown in Figures 6(a) and 6(b), respectively.

Profile mapping

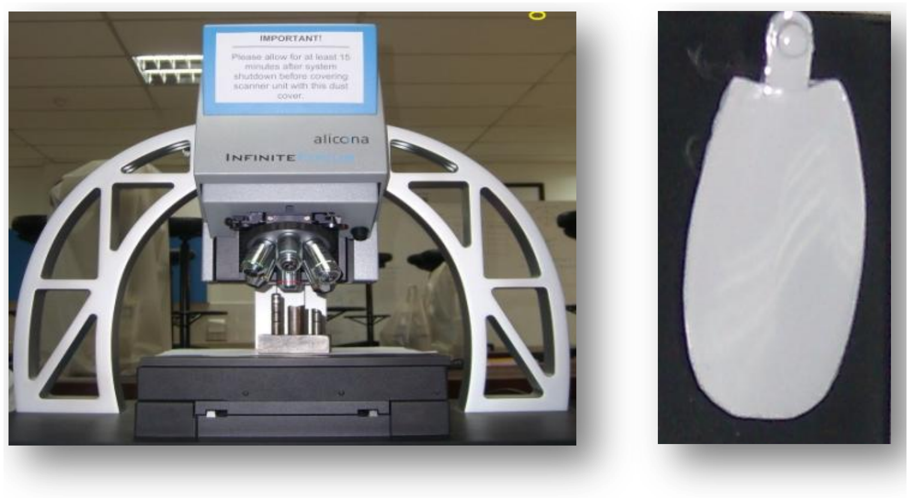
The results were exported to an Excel sheet to map the die and punch profiles. In the current study, the deviations of the profiles were easily measured using the developed approach, which will be discussed in the next section.

Measurement of the profile deviation

A mirror line was defined because the die and blade profiles were not similar in terms of direction, as shown in the work of Abdullah et al. (2011). The mirror line was defined because the *Alicona* system creates the profile based on the scanned surface, and thus, the die produces a concave profile and the blade produces a convex profile. The mirror line was constructed as the reference line to measure the difference between the blade profile and the punch shape. Error, δ, is defined as the difference between the distances of the mirror line to the blade, Δ_b, and die, Δ_d, profiles.

RESULTS AND DISCUSSION

In the comparison of the profiles, a point should be determined as a reference point at each section and the right end of each section is selected as datum. Hence, the error is quantified based on the difference between the constructed profiles. In this case, only one of the surfaces is investigated since the punch and die profiles are similar. The punch profile is selected to determine the deviation between the designed and fabricated profiles, and then a comparison between the profiles obtained



(a) (b)

Figure 4. (a) The punch placed on the table for scanning facing the lens and (b) the forged blade with a very thick spray paint for ease of image capturing.

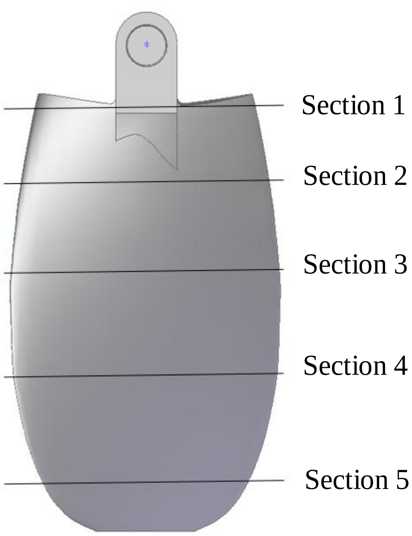
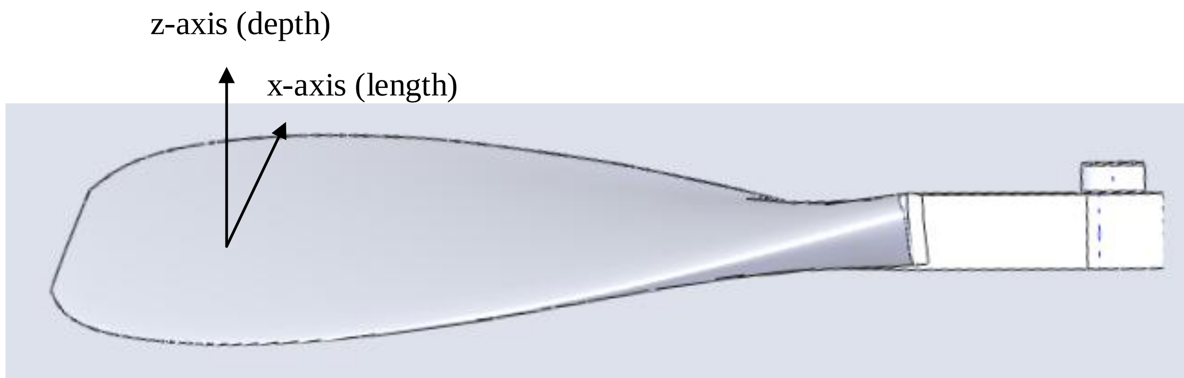


Figure 5. The blade divided into five section views.

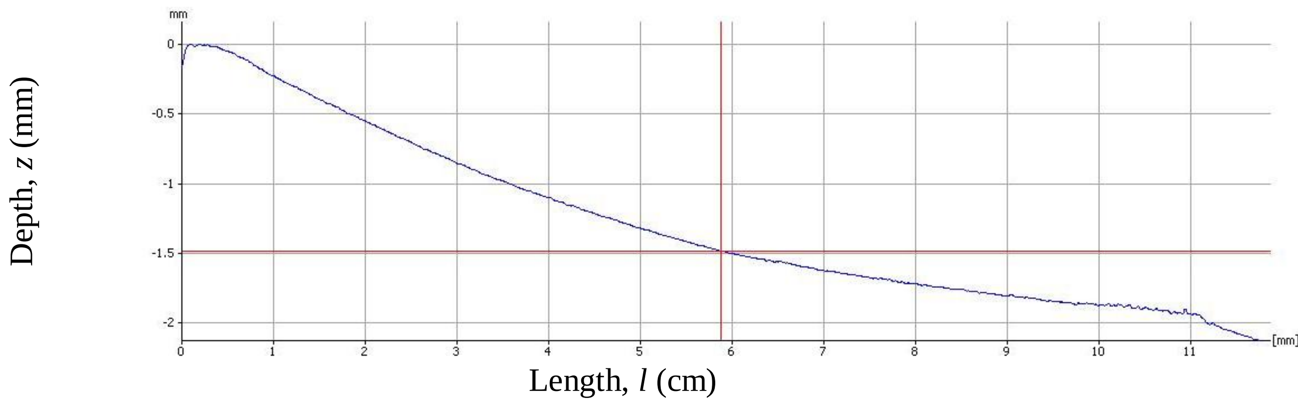
from the *Alicona* system is made. Figure 7 shows the thickness pattern of each section along the chord. As can be seen in Figure 7, sections 1 and 2 had the highest maximum thicknesses, and thus, they formed larger deformation ratios. In this study, deformation refers to the difference in thickness before and after forging. Therefore, the deformation ratio is the ratio of maximum and minimum thicknesses along the chord. For comparison, the forged blades were cut using abrasive cutting at the same sectioning line, as shown in Figure 8, where the profile differences were obvious. It should be noted that the CAD model had a sharp edge, and thus, obtaining the profile was impossible, and the gap between the punch and die was approximately 0.7 mm in this case.

The deviations of the profiles were also measured. The percentages of deviations are summarized in Table 1. The deviations were measured by manually comparing the profiles obtained from the *Alicona* system and then mapping them in the worksheet. Figures 9(a) and 9(b) show the profile deviations for sections 1 and 3, respectively. The deviation was determined by taking the mirror-line as a reference point, and the difference between the upper and lower profiles were calculated. The highest and lowest deviations were observed in sections 3 and 1, respectively. The results show that the average punch profile deviation caused by the die shape modification was approximately 1.7 mm or 54% from the desired shape modeled in the CAD environment. Thus, the exact amount of deviation of the blade can be determined further.

For this approach, a mirror-line should be constructed to allow deviation measurement. In the current study, two edge points were determined from the mapped profile by referring to the chord length obtained in the previous step. The results show that the first two sections depicted a larger amount of error compared to the rest of the section. Moreover, the maximum amount of error was 0.46 mm because the location was at the middle and minimal deformation was involved in the CAD model for section 1, that is, the location was initially preformed at 3.0 mm to the final dimension at 2.84 mm, or approximately 5.33% deformation. Section 2 involved 23.33% deformation. Measurements on the punch and forged blade profiles were conducted to obtain the contribution of the die shape modification to the total error. As can be seen in Table 2, the modification and forging processes contributed to 70 and 30% of the total



(a)



(b)

Figure 6. (a) The blade scanning axis (c) the resulted profile.

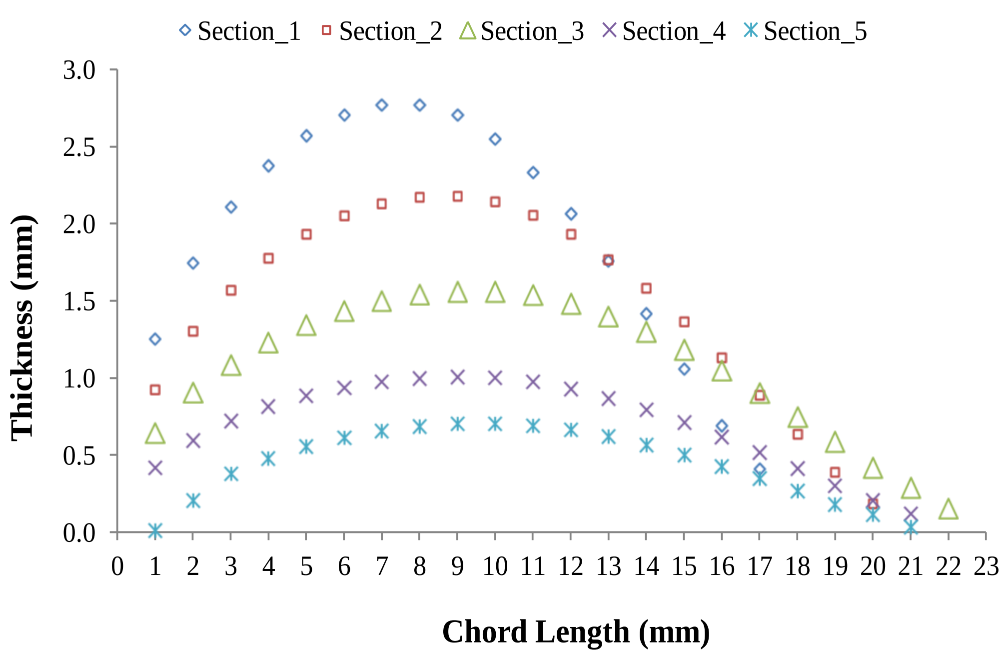


Figure 7. The thickness pattern of the blade along the chord length.

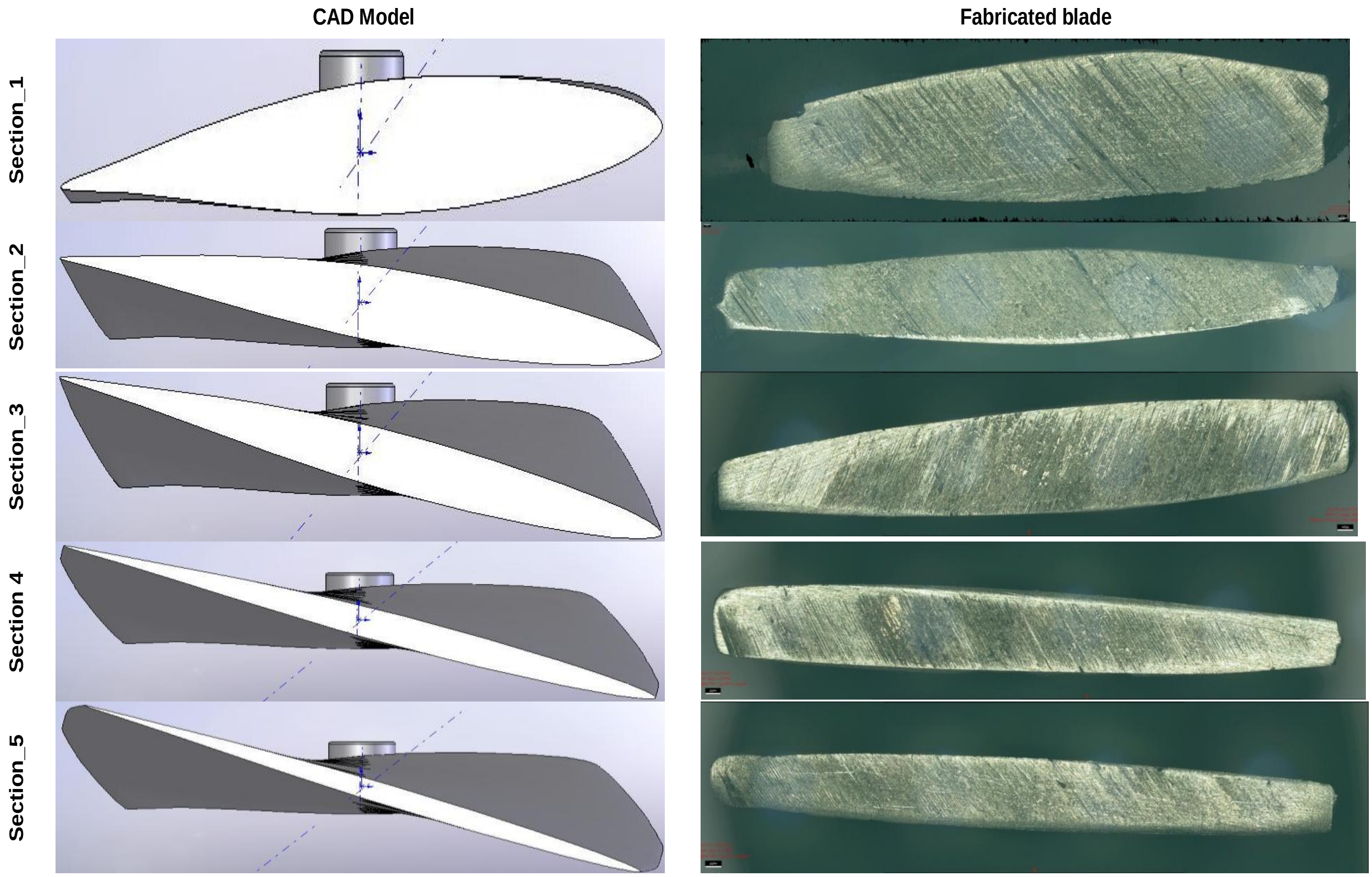


Figure 8. The profile of the cut sections compared to the CAD model.

error, respectively. For validation, the blade was mounted on a special custom-made fixture to ensure accurate measurements and quick workpiece setup. The fixture also allowed faster datum determination since the blade had a complex profile. As can be seen in Figure 10, the maximum deviation was approximately 0.5 mm or less than 17%, which is still lower than the total profile deviation.

Conclusion

The current study presented the accuracy analysis on cold forged AUV propeller blade and the effects of die shape modification. The measurements were based on the difference between the forged blade and punch profiles obtained using the commercial surface measurement technique, namely the *Alicona* system, and the nominal shapes of the blade and the punch. Validation was performed using CMM, and the error was measured on the selected sections of the blade. The main contributions of this study are as follows:

The modifications made on the die and punch profiles to obtain the targeted shape were significant to the geometrical and dimensional errors of the blade. Therefore, these modifications should be taken into account in quantifying the total amount of error.

The optical technique can be used to assess the geometrical and dimensional errors effectively, even with limited data.

These findings can eliminate or at least minimize the modification stage, and thus, they may be useful for a die designer during fabrication.

Exploration of the effect of profile complexity and the relationship of the formation of error subject to the requirement of die modifications will be investigated in future studies.

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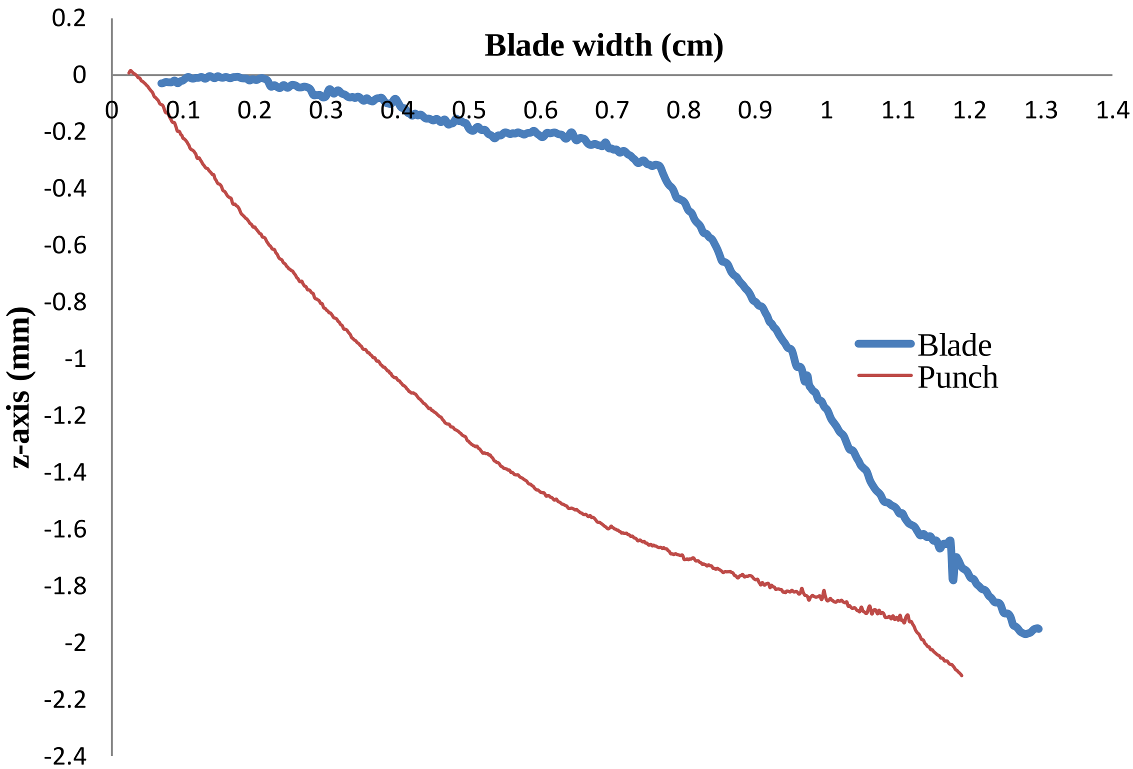
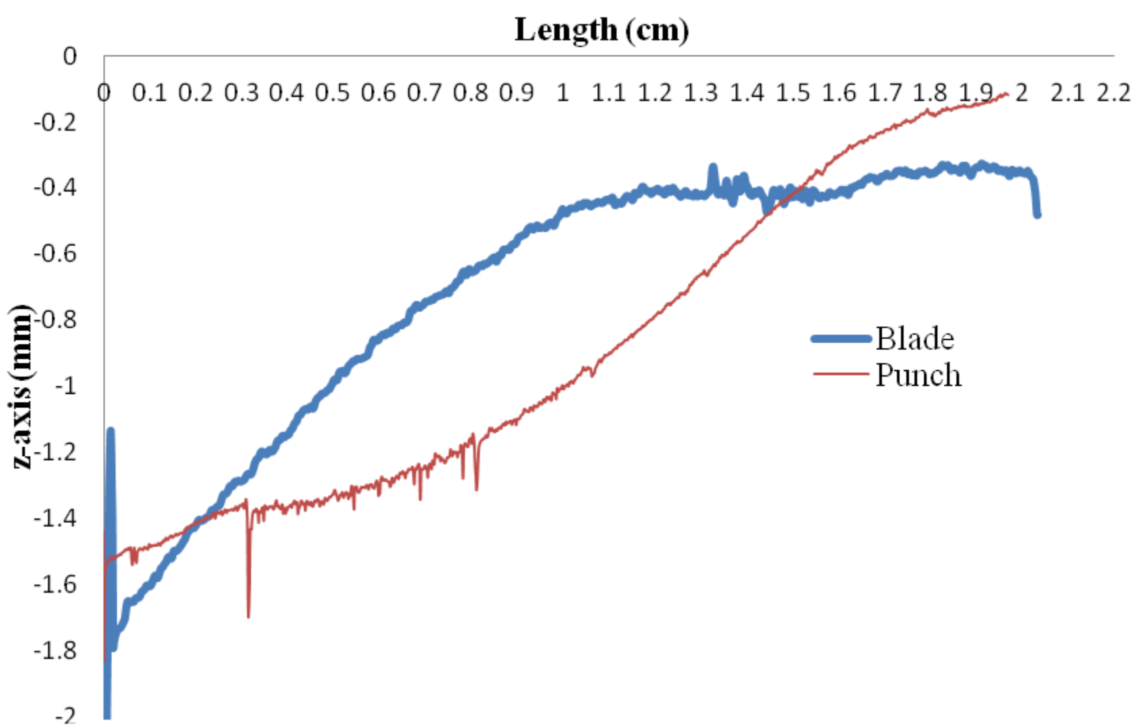


(a)



(b)

Figure 9. Profiles of the blade and the punch for deviation measurement.

Table 2. Detail measurement result using Alicona.

Section #	Die/punch, Alicona	Percentage	Final blade, Alicona	Percentage	Total error
1	0.125	28.09	0.32	71.91	0.445
2	1.470	67.12	0.72	32.88	2.190
3	2.265	74.14	0.79	25.86	3.055
4	2.315	72.23	0.89	27.77	3.205
5	2.173	72.12	0.84	27.88	3.013
	Average	70.10	Average	29.90	2.382

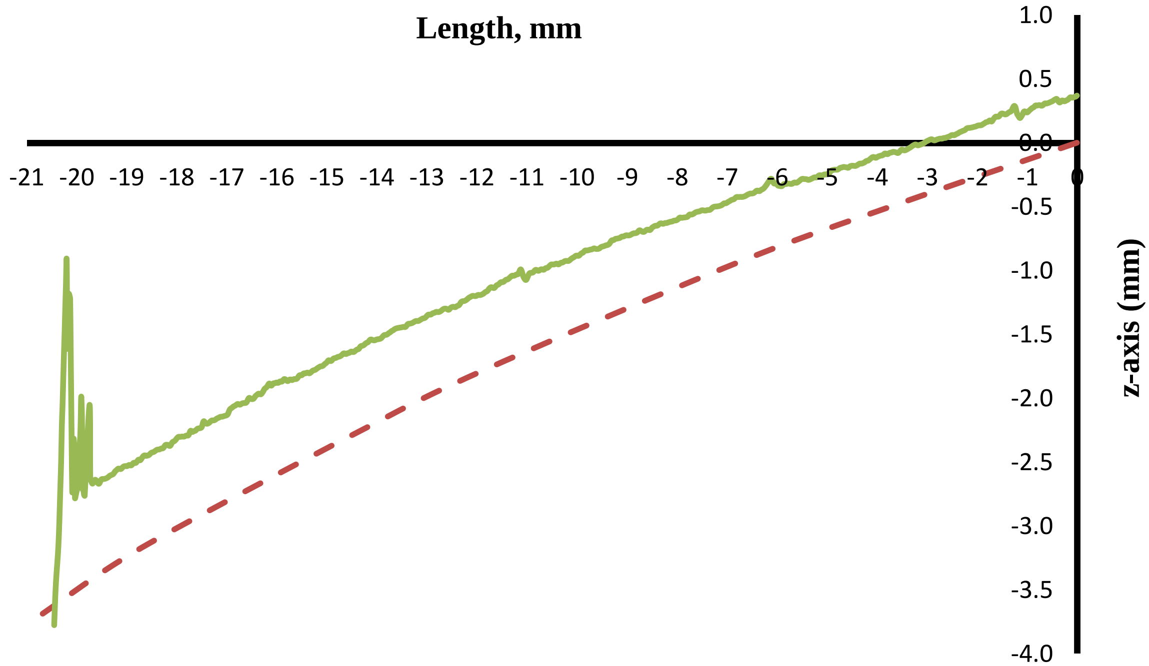


Figure 10. The comparison between the profiles obtained from Alicona (continuous line) and the CMM (dotted line).

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