In-situ M[illegible]mability Improvement in Stamping of High Strength Steel and Titanium Alloy Sheets

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Abstract

The information and visualization of deformation behaviour of the high strength steel sheet during the stamping process are useful for designing tools and processes in metal forming industry. However, it is not easy to measure the deformation behaviour during stamping processes because a deforming sheet is generally surrounded with complicated tools during a stamping operation, and thus, application of sensors for the in-situ measurement has been still limited. Borescopes consisting of a small camera and a flexible cable have possibility of application to forming processes as an imaging sensor and the installation of the borescopes inside tools enables the in-situ measurement. The three-dimensional deformation behaviour of the sheet and tools were successfully measured using borescope.

The use of the ultra-high strength steel sheets for automobile body-in-white parts is increasing, whereas it is not easy to form the the ultra-high strength steel sheets. A gradually contacting punch was developed to reduce a tensile stress during the forming process with controlling a stress state around sheared edges undergoing plastic deformation. However, the punch stroke increased for stretch flanging, i.e. increases in production time and cost. In order to reduce the punch stroke, a 2-stage process using a recessed punch was developed for stretch flanging.

In order to increase the safety of cars, the structure of body members was optimized. Front rail hollow sections act as an energy absorber during collision, and are permanently deformed in order to absorb the kinetic energy during the crash. These hollow sections typically joined by resistance spot welding have insufficient energy absorption, because the joint are not continuous. In order to overcome this problem, the hollow section is joined by hemming. Since the hollow section having hemmed joins is overlapped, the strength is increased in comparison with resistance spot welded joins.

Although titanium alloy sheets are widely used for airplane parts due to its properties of high strength at high temperatures, low density and high corrosion resistance, ductility of the titanium alloy sheets is very low, and thus it is difficult to form the titanium alloy sheets at room temperature. The sheets are generally formed at elevated temperatures. Hot hat-shaped bending of the Ti-6Al-4V titanium sheet using the resistance heating was carried out. The titanium alloy sheet was successfully formed at the elevated temperatures, the bending load was reduced and the springback and oxidation are prevented.

Table of contents

Chapter 1

Introduction

1.1 An overview

1.1.1. In-situ measurement using borescope

The transformation of the cars toward the lower CO2 emission and higher safety of the cars is associated with considerable changes in the stamping processes, requiring new solutions for the inherent conflict in design between weight and strength [1]. Future requirements of stamping process will be characterised by trends in measurement system and development of a sensor technology. The scientific and technical challenges do not lie entirely in the capability to produce stamped parts with greater precision, but also mass produced the parts at reasonable production costs. One fundamental initiative to find a solution in the area of process development is the application of the sensors technology for early detection of the defect in the stamping process. This must be accomplished by increasing the flexibility of the sensors for applications during the stamping process. Although many such sensors were employed for the applications of the measurement during the stamping process, the results obtained are very limited for specific purpose. Figure 1.1 shows an example of the application of the piezo sensors in the stamping process to measure a punch pressure.

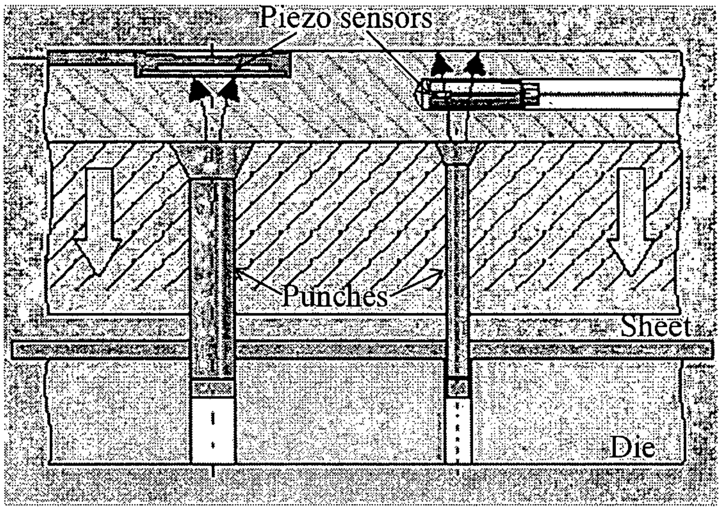
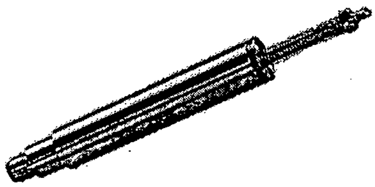
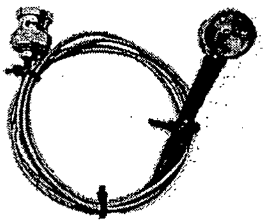
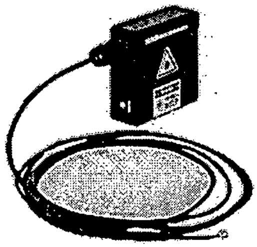
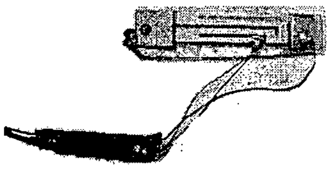
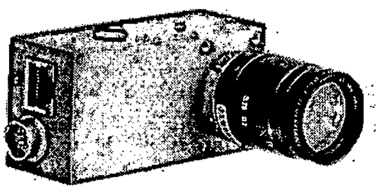


Fig. 1.1. Application of piezo sensors in stamping tool to measure punch pressure.

In order to obtain the deformation behaviour of the sheet during the stamping process, finite element simulation is established as a developmental method for such situations, and today it constitutes the key element in designing stamping tools. However, calculated results by the finite element simulation are reaching the limit of the accuracy, because the simulation includes some approximations and assumptions. It is not easy to accurately measure material constants used in the simulation such as the flow stress curve or the coefficient of friction. When elastic deformation of tools and press machines is taken into consideration in the simulation, the computing time becomes extremely long due to huge number of elements. Even constitutive equations used in the finite element simulation are not highly accurate for large strain and anisotropy. Not only the finite element simulation, but also in-situ measuring methods are required to design stamping processes at present. The finite element simulation has been remarkably developed with the advancement of computer and is an attractive tool of designing stamping processes.

Table 1.1 Several types of sensors used for in-situ measurement.

Sensors	Images	Minimum size	Measuring range
LVDT		Ø5 x 15 mm	0.01 - 5 mm
Dial gauge		Ø3 x 25 mm	0.01 – 5 mm
Acoustic emission		Ø3 x 8 mm	300 – 800 kHz
Laser displacement		15 x 20 x 5 mm	0.01 - 5 mm
Stain gauge		30 x 0.3 x 0.1 mm	0 – 0.03 mm
CCD camera		15 x 25 x 10 mm	5 - 25 mm

Although a deformation of the sheets and deflection of the tools is useful information of designing forming processes, it is not easy to measure the deformation and deflection during forming due to small space of the tool cavity. The current inspection practices and monitoring technologies in stamping industry are still based on contact and non-contact measurement [2]. The equipment such as the coordinate measuring machine (CMM), laser displacement devices and CCD camera were among general equipment used for this purpose. Since these devices are too large to be installed inside the tools in general stamping processes, the applications were limited for measuring the parts after the stamping processes. A deforming sheet is generally surrounded with complicated tools during a stamping operation thus; the in-situ measurement is not easy. Table 1.1 shows several types of sensors used for in-situ measurement for the stamping process.

Sensors used for the application of in-situ measurement of deformation behaviour of the sheet and tools during the stamping operations are shown in Figure 1.2. A laser type sensor and dial gauges were used to measure the displacement of a die during deep drawing. Although laser displacement sensors and dial gauges are accurate in measuring the displacement, many sensors are necessary to measure three-dimensional deformation behaviour. Pin type sensors embedded with the strain gauges were used to measure contact pressure and movement of the sheet [3-5]. Conical cantilever sensors having strain gauges were used to measure three-dimensional contact pressure in rolling [6]. However, for the strain gauges, the measuring range is limited to local and small strain. A piezoelectric load sensor was used to measure a blank holder force and performed a closed-loop control of a stamping process [7]. The acoustic emission sensor was used to detect friction sources during deep drawing [8]. However, for these measurements, fine machining with tools is required for the installation and the obtained results are local.

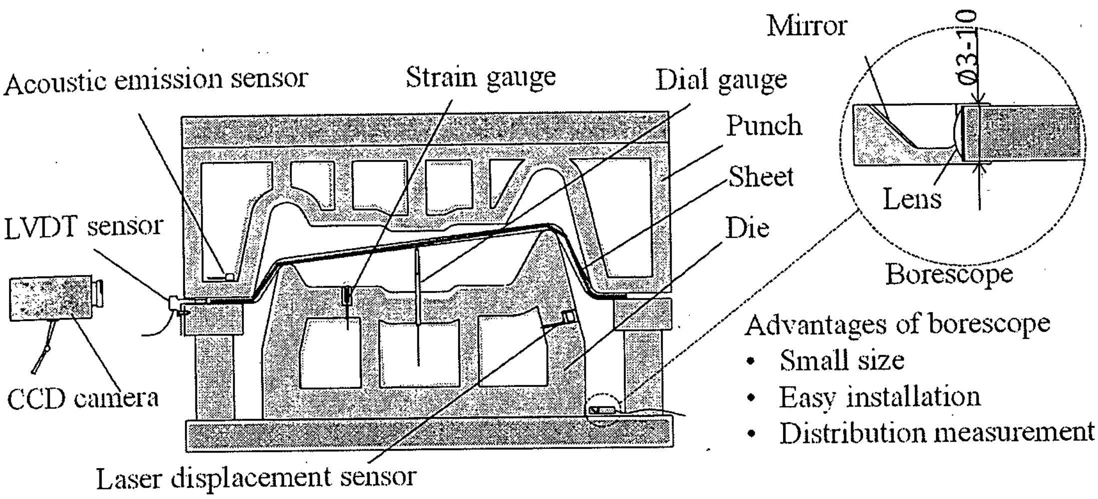


Fig. 1.2. Sensors used for in-situ measurement of deformation behaviour of sheet and tools in stamping operations.

In order to obtain the three-dimensional pictorial data, CCD camera is used. The CCD cameras are attractive in three-dimensional in-situ measurement in metal forming. The CCD is found to be used in obtaining the data of the deformation behaviour of the sheet and tools during the forming process [9-15]. Although the conventional CCD camera is successful in measuring the deformation behaviour during the stamping processes, it is too large to be installed inside the dies. On the other hand, the borescope having a small camera connected with a flexible thin cable can be installed in a small space surrounded with dies without machining. Various types of the borescopes are shown in Figure 1.3. The small camera is set inside the dies, and the cable is taken outside through small gaps between the dies.

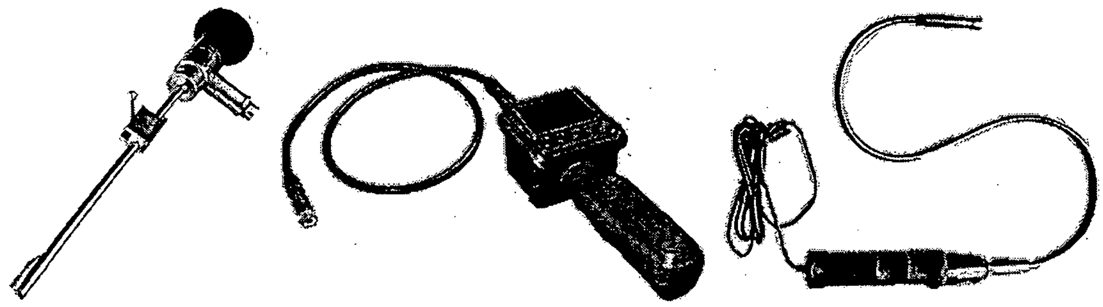
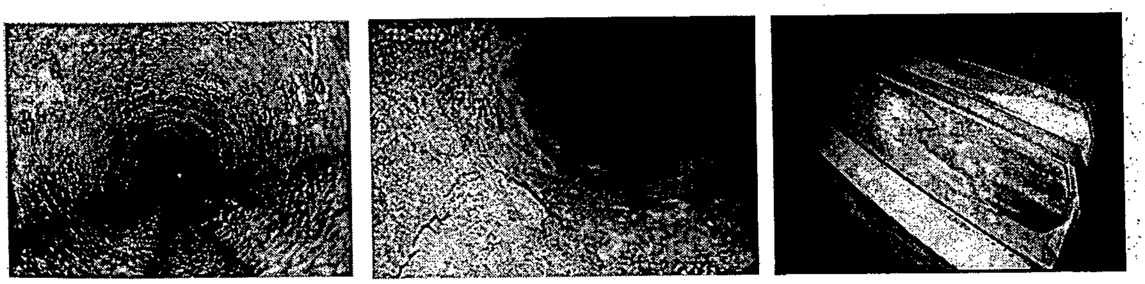


Fig 1.3. Various types of borescopes.

Borescopes and endoscopes having a small CCD camera and thin cable are generally used in the medical field, and the application of the borescope has been recently extended to engineering fields. Applications of borescope in different engineering fields are shown in Figure 1.4. The borescopes have been used to inspect wear and damage of components in a turbine engine without dismantling the engine [16], measure the surface profile of a turning tool [17] and obtain the surface roughening behaviour of a hole machined by water jet [18]. The borescope is applicable as a sensor for in-situ measurement in stamping because of the small size.



(a) Corrosion of boiler tube (b) Crack of manifold (c) Wear of gear

Fig 1.4. Applications of borescope in engineering field.

1.1.2. Formability improvement of high strength steel sheets in flanging process

To improve the fuel consumption of automobiles, the development of lightweight automobiles is in global competition. The two approaches for the weight reduction are structure optimisation and lightweight materials. The body structure is optimised so as to reduce the weight under a desired strength. The uses of hollow parts are effective in reducing the weight, and tube hydroforming is increasingly employed. On the other hand, aluminium and titanium alloy sheets are attractive lightweight materials for automobiles [19-21]. Although the application of these sheets to the automobile parts offers a high potential for the reduction of the automobile weight, high cost and small formability are crucial problems [22,23]. In stamping of the aluminium alloy sheets, large springback is the main problem, whereas a small formability and high cost for titanium alloy sheet are also problematic, thus the industry still has a great interest in steel sheets.

The application of the high strength steel sheets to the structural body parts which need higher strength is thought of as a measure for reducing the weight of automobiles. The areas of the body structures which are considered for applying the high strength steel sheets are shown in Figure 1.5. By applying high strength steel sheets replacing the mild steel sheets, the reinforcement parts are eliminated and the sheet thickness is decreased, thus the body mass is reduced. However, for the high strength steel sheets, dimensional accuracy of formed products deteriorates due to large springback and die deflection, and the formability is small [24,25]. The design of stamping processes of high strength steel sheets becomes difficult. Studies for improving the formability of the high strength are carried out by several researchers. For example, a gradually contacting punch is used in order to improve formability of the high strength sheets during the flanging process of the ultra-high strength steel sheets [26]. A conical punch is used to improve the expansion of a hole of a punched ultra-high strength steel sheet by smoothing fracture surface of the sheared edge [27], thus minimized the occurrence of the crack.

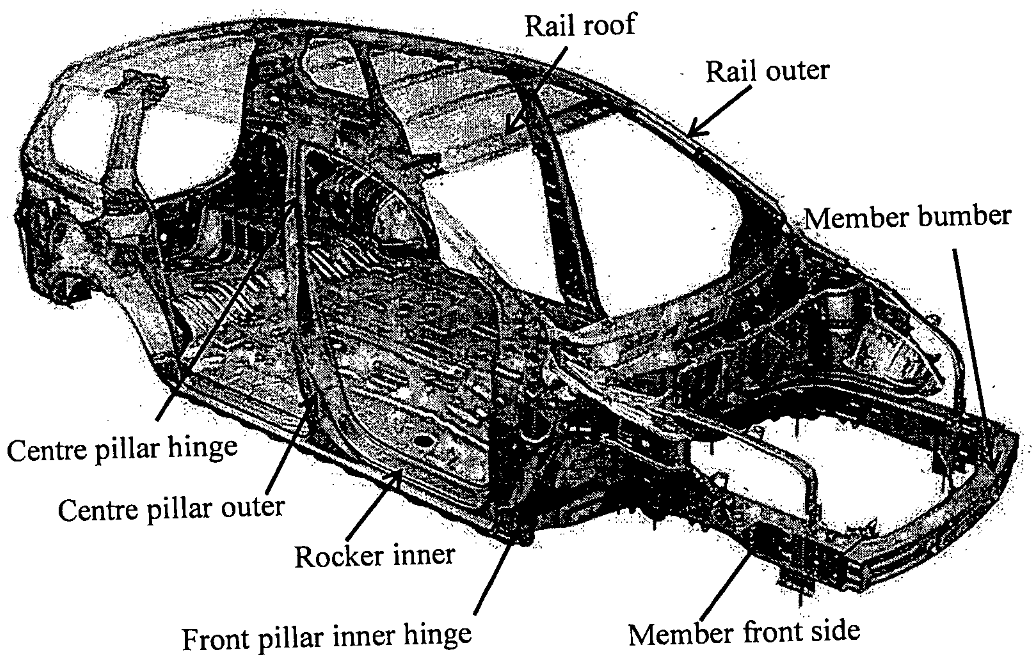
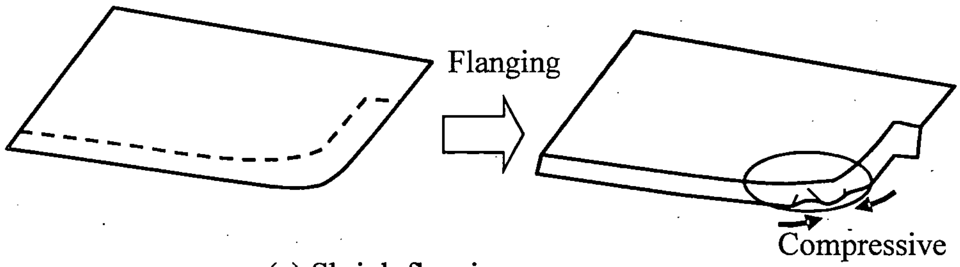


Fig. 1.5. Application of high strength steel sheets to automobile parts [28].

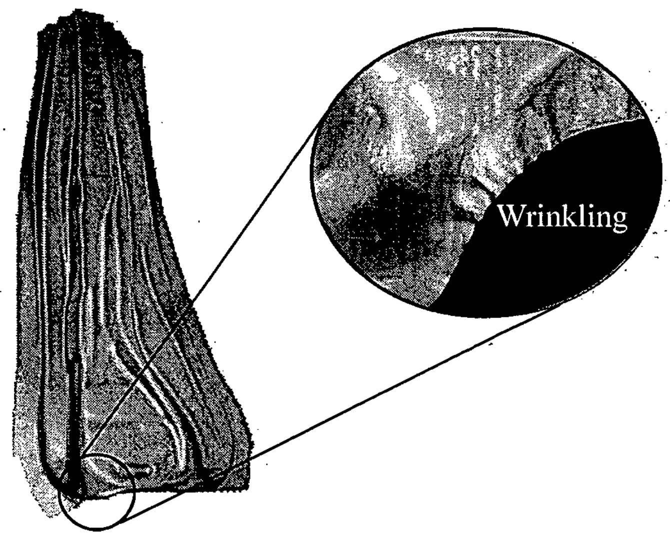
Although the function of the car is to provide comfort to the driver while driving, the safety of the car is important and need to be improved. The application of the high strength steel sheets in the car has improved the safety of the vehicles since the strength of the parts is increased. The high-tensile strength steel sheets 440-980 MPa classes are mainly used in present car body parts. For the outside body panel, 440 MPa class is used, for structures such as door beams and member bumpers, materials in class of

590-780 MPa are used [29]. However, for the centre pillars and member front rails, it requires ultra-high strength tensile strength of 980 MPa class for good crash protection reasons. The problems of using the ultra-high strength steel sheets are the large springback and low formability due to high strength and low ductility of the ultra-high strength steel sheets [30,31].

A flange bending is common forming for the high-tensile steel sheets in car body parts. Instead of bending the flange in a straight line, the parts are bent in convex (shrink) shape which caused the product to wrinkle due to the compressive stress as shown in Figure 1.6. The shrinkage flange of the ultra-high strength steel sheets not only defects the product by the occurrence of the wrinkling, but also causes the seizure and wear of the dies and shorten the life of dies [32]. Since the formed part with wrinkling defect requires to be trimmed at later stage using the trim dies, it will also shorten the life of the trim dies. Although using the thin high strength steel sheet gives advantages in manufacturing the lightweight car, it is less stiff and tendency to become wrinkle is high. To prevent the wrinkling in the shrinkage flanging of the high-strength steel sheets, the punch having gradual contact shape was proposed. The sheet was gradually bent from the corner to reduce the compressive stress.



(a) Shrink flanging process



(b) Wrinkle in 980 MPa class steel shrink flanged sheet

Fig. 1.6. Shrink flanging for ultra-high strength steel sheets.

The stretch flanging is shown in Figure 1.7. The high strength steel sheet is bent in concave (stretch) shape and the tensile stress at the edge of the sheet increased due to the low ductility of the sheets crack that occurred once exceeded the tensile strength limits. The shears conditions of the edge of the sheet with low ductility property are the main factors that contribute to the occurrence of the crack [33]. To prevent the occurrences of the crack and improve the formability of the flange, the gradual contact punch was used [26]. However, the punch strokes for the stretch flanging of the dies structure of the automobiles [34] and the shape of the structures of the hollow sections are optimized to increase crashworthiness of the vehicles for human safety. A front rail hollow section during crash situations is shown in Figure 1.8. In the crash situation, a kinetic energy is absorbed by the hollow section. The hollow sections typically joined by resistance spot welding have insufficient energy absorption because the joints are not continuous. Although laser welding is a better approach to overcome this problem, high heating temperatures reduce the quality, accuracy and reliability of joined parts [35].

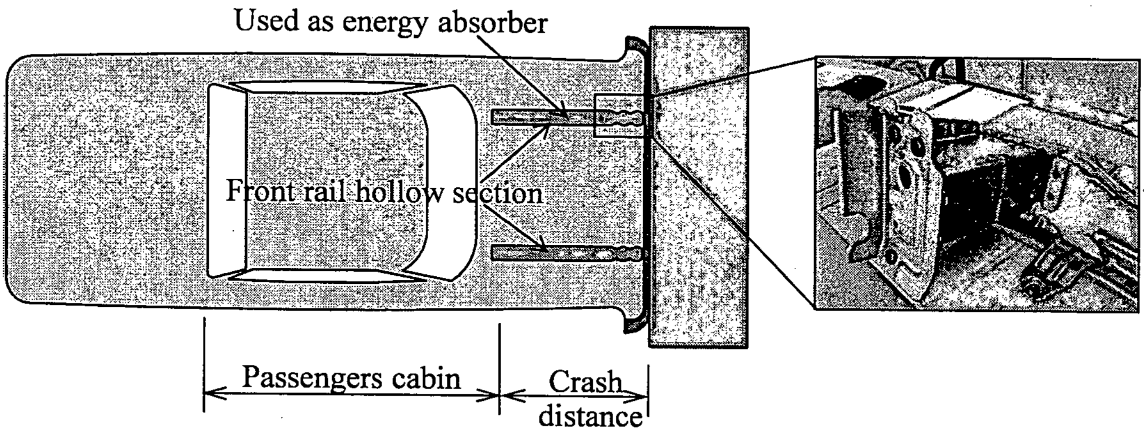
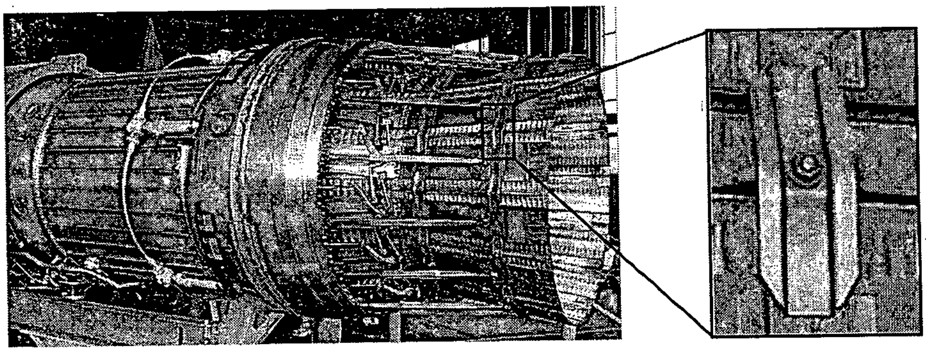


Fig. 1.8. Front rail hollow section.

In order to improve the joint strengths, both edges of hollow sections are joined by hemming. Therefore it produces a continuous joining without external heat supply. Since the hollow section having hemmed joins is overlapped, the strength is increased as compared to the resistance of spot welding joins. Thus, hemming is effective for increasing energy absorption during the crash test.

The usage of titanium alloy sheets for airplane parts increases due to the high strength at high temperatures, low density and high corrosion resistance. In Figure 1.9, it shows an aircraft engine and an example of a structure component made of titanium alloy sheet. Since the cold formability of the titanium alloy sheets is low, the sheets are generally formed at elevated temperatures. Although the conventional hot stamping process using a furnace indicates the effectiveness for reducing the stamping load [36, 37] and improving the formability of the sheets, additional apparatus preheating and cooling systems, low productivity, and oxidation for the heating [38] become problems, thus resistance heating is preferable.



(a) Aircraft engine (b)Structure component

Fig. 1.9. Structure component made of titanium alloy sheet for aircraft engine [39].

The rapid resistance heating was effective in the hot stamping, only a short time is required for heating the sheet up to 900°C [40]. The resistance heating is generally employed for the preheating of forging billets. The warm and hot stamping using resistance heating are used in the tailor die-quenching for producing ultra-high strength steel formed parts having a strength distribution and to the spline forming of ultra-high strength steel gear drums [41-43], respectively. The local resistance heating of a shearing zone is used in a punching process of the ultra-high strength steel sheets [44]. The hot stamping using the resistance heating is also applied to the titanium alloy sheets, however forming results were hardly shown [45].

1.2. Research objectives

1.2.1. In-situ measurement of deformation behaviour of sheet and tools during stamping process.

The aim of this dissertation is to develop an in-situ measurement of deformation behaviour of the sheet and tools during stamping process. The borescopes having a small CCD camera and thin cable are used and placed inside the tools. The three-dimensional deformation behaviour of the sheet and tools is measured.

1.2.2. Formability improvement of high strength steel and titanium alloy sheets

Although the applications of high strength steel and titanium alloy sheets to the automobile and airplane parts respectively, offer a high potential for the reduction of the weight, the dimensional accuracy of formed products deteriorates due to large springback and small formability are crucial problems. In order to improve the formability of the sheets and reduce the defects of the products, new types of the punches are proposed for the flanging and hemming of the high strength steel sheets. In addition, the hot forming using resistance heating is applied to form the titanium alloy sheet.

1.3. Outline of dissertation

This dissertation discusses about the in-situ measurement of deformation behaviour of the sheet during stamping process using the borescopes, followed by the prevention of the occurrence of the wrinkle and cracks during the shrink and stretch flanging respectively. The improvement of the formability of the titanium alloy sheet using hot bending is discusses in following chapter. Finally, the improvement of the joints strength and the absorbed energy in crash test of the high strength steel sheets by the joined by the hemming method are presented.

This dissertation consists of seven chapters:

Chapter 1 presents the general introduction for the overall contents of the thesis.

Chapter 2 presents the new method of in-situ measurement for the stamping process. The borescope with a tiny camera and a small cable is installed in a small space surrounded with tools to measure a deforming sheet and punch during shrink flanging. The variation of the distance between the sheet and die during the process is measured and compared with the result obtained from the laser displacement equipment. The distribution measurement is obtained using borescope.

Chapter 3 presents the in-situ measuring method using two borescopes to measure the three-dimensional deformation behaviour during a flanging process of sheets. The small size borescopes with a flexible cable is placed inside the tool to measure three-dimensional deforming edge of the sheet. The distribution of the springback is increased and more data were obtained when measuring using the two borescopes. The height of wrinkling for different strokes is also measured using the borescope.

Chapter 4 presents the prevention of the occurrence of the wrinkle and cracks during the shrink and stretch flanging respectively. A shape of a punch having gradual contact was used in order to prevent the wrinkling in shrinkage flanging of ultra-high strength steel sheets. The sheet was gradually bent from the corner of the sheet to reduce the compressive stress. For the stretch flanging, the operation is divided into 2 stages, peripheral bending and corner bending in order to reduce the punch stroke of the press and the tensile stress around the corner edge. In the 1st stage, the periphery of the corner is bent with the punch having a recessed in the middle and in the 2nd stage, the residual portion is bent with the flat bottom punch, and the tensile stress around the corner edge is reduced by restraint of the bent periphery.

Chapter 5 presents the joining of ultra-high strength steel sheets by hemming and improvement of joint strength. The high strength steel sheets are joined by hemming method to form a hollow section. The punch with a stopper is used to prevent the crack during the hemming process. The crashing behaviour of the high strength steel hollow sections joined by hemming is examined through an experiment by crushing the hollow section at a high speed stroke in a press machine. The absorbed energy obtained from the crash test is compared between hollow section joined by hemming and spot welding.

Chapter 6 presents the hot bending process of a titanium alloy sheet using resistance heating. Besides to increase the formability and to reduce the forming load, the hot bending process using the resistance heating method is also used to prevent the occurrence of the oxidation to the titanium sheet. The springback and hardness of the hot bent sheet were also measured.

Finally, the concluding remarks and future perspective are given in Chapter 7.

Chapter 2

In-situ measurement of deforming shapes of sheet and tools during stamping using borescope

2.1. Introduction

Deformation of sheets and deflection of tools are useful information of designing forming processes, however it is not easy to measure the deformation and deflection during forming due to small space of the tool cavity. A strain gauge is used by several researchers for in-situ measurement in the stamping process. Yoneyama and Tozawa [3] measured histories of contact pressure and temperature in die forging with a pin sensor having strain gauges and thermocouples embedded in a die. Jeswiet and Nyahumwa [6] used some conical cantilever sensors having strain gauges embedded in a roller to measure three-dimensional contact pressure in rolling. Siegert et al. [7] performed closed-loop control of a stamping process by blank holder force measured with piezoelectric load sensors. The installation of strain gages for measuring deflection of tools becomes complex, and it is not easy to measure a distribution of deflection.

CCD cameras are attractive in three-dimensional in-situ measurement in metal forming. Azushima [10] developed a microscope video system with a CCD camera to observe contact behaviour at the interface between a transparent glass die and workpiece during drawing. Bech et al. [11] used a similar approach to observe trapping behaviour of lubricant in extrusion. Mori et al. [2] measured two-dimensional springback behaviour in V-shaped bending of ultra-high strength steel sheets with a CCD camera outside tools. Jäger et al. [12] measured depth and length of the bulge profiles of a tube during electromagnetic forming using a CCD camera. The conventional CCD cameras are too large to be installed inside tools.

Hamedon et al. [46] have used a borescope with a tiny camera and a small cable for in-situ measurement of deformation behavior of a sheet during shrink flanging. Since the size of the borescope is small, it is comparatively easy to install the borescope in a small space surrounded with tools. In this study, deforming shapes of high strength steel sheets and a punch during shrink flanging were measured by means of a borescope having higher resolution.

2.2. Procedure of in-situ measurement using borescope

A borescope consisting of a CCD camera with flexible cable having specifications as shown in table 1 was used to measure a deforming sheet and punch during shrink flanging. Since the sizes of the camera and cable are small, the borescope is installed in a small gap surrounded with tools.

Table 2.1 Specifications of borescope.

Size	Ø8 x 40 mm
Resolution	640 x 480 pixels
Display speed	30 fps
Focusing	Auto-focusing (20 – 80 mm)
Cable size	Ø3 x 2,000 mm (extendable)