NON-ISOTHERMAL DEEP DRAWING OF ALUMINUM AND MAGNESIUM USING SERVO PRESSES

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ABSTRACT
Servo presses are recently introduced metal forming machinery and they are in many ways, a hybrid of mechanical and hydraulic presses. They are designed to combine the strengths of conventional mechanical and hydraulic presses, and at the same time to minimize their constraints. The advantages of servo presses in metal forming technology are discussed briefly. Advantages they offer in warm forming are discussed more in detail and demonstrated experimentally. By using the flexibility that the servo press offers, the effect of contact pressure on temperature change and surface roughness of aluminum and magnesium sheet is experimentally investigated. Non-isothermal warm forming is introduced and studied experimentally. Combined advantages of the non-isothermal approach and the servo motor controlled press are demonstrated by introducing a variable forming speed concept. As a result, 60 % savings in cup drawing time is achieved experimentally. Measured temperature curves were used in FEA to determine heat transfer coefficients. Effect of the determined heat transfer coefficients on deep drawing was analyzed using FEA and good agreement were obtained between FEA predictions and experimental measurements.

INTRODUCTION
Electro-mechanical servo-drives have been used in machine tools for several decades. Recently, several press builders, mainly in Japan and Germany, developed gap and straight-sided sheet metal forming presses that utilize the mechanical servo-drive technology. The mechanical servo-drive press offers the flexibility of a hydraulic press (infinite ram speed and position control, availability of press force at any ram position) with the speed and reliability of a mechanical press. Thus, this new drive technology has considerable potential in present and future applications in blanking, bending, stamping and coining Nakagawa, et.al. 2006 [1]. More than 1000 servo drive presses are already in operation in stamping and in automotive plants all over the world. Nakagawa, et.al. 2006 [1] and Aida America Corp. [10].

This drive offers great flexibility and accuracy in controlling the speed and position of the press slide. Thus, for a given stamping application, the press operation can be optimized to:

a) increase stroking rate and productivity

b) control the velocity of deformation during the forming stage of the stroke which results in reduced friction and heat generation as well as improved quality and reduced scrap rate

c) reduce impact speed and noise

d) improve edge quality in blanking and shearing and increase tool life

e) reduce springback and improve part dimensions by controlling the dwell time at the BDC (Bottom Dead Center) of the slide stroke

f) allow assembly and other secondary operations in the same press by slowing down or stopping the press slide anywhere during the slide stroke to allow for additional secondary tool motions.

In a servo drive press, the slide motion can be adjusted to "optimize" the press cycle for different applications and part transfer requirements. This is illustrated in Figure 1, Miyoshi 2004 [2], where the press cycle of a servo press is compared conceptually with that of a mechanical press. The flexible programming of the servo drive press allows to (a) obtain the "most suitable" forming velocity for the given material and forming operation, (b) dwell the slide anywhere at the desired stroke position, (c) carry out secondary operations such as painting, punching or assembly, and (d) provide the necessary time for part transfer.

Servo drive presses were initially used for blanking, coining and stamping of small parts in gap presses. Another major initial application was in die-try out and die set up since these presses allow very precise slide motion control at vary low speeds Huelshorst, 2008 [3].

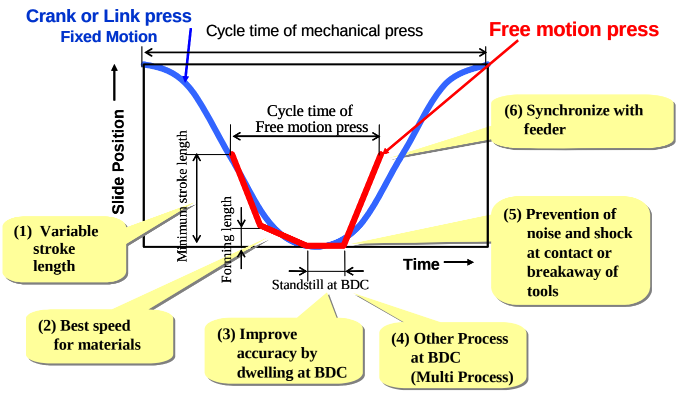


FIGURE 1- THE FLEXIBILITY OF SLIDE MOTION IN SERVO DRIVE (OR FREE MOTION) PRESSES [2]

One of the main advantages of servo presses can be seen in blanking operation. Using a hydraulic servo press, Otsu et al. 2003 [4] conducted experiments in blanking carbon steel, stainless steel, titanium and copper sheets using a 15 mm diameter punch and 50 micrometer punch/die clearance. In their study, the authors investigated two schemes of punch motion, i.e. constant speed and variable speed, named as continuous “two steps blanking”.

Blanking studies were conducted by Miyoshi 2004 [2] using the same tools in conventional mechanical and comparable servo drive presses. The strokes per minute (SPM) in both presses were kept approximately the same while the actual blanking velocity was reduced considerably in the servo drive press. In this study, the punch used in the mechanical press needed regrinding after blanking 30,000 pieces while in the servo press the punch needed regrinding after 100,000 blankings. The increase in the number of blankings is due to controlled velocity and reduced impact. Applications in precision blanking can be found in Miyoshi 2004 [2]. The servo motor drive principle has been applied to the design and control of die cushions by several press manufacturers as well as by servo motor suppliers. GE/Fanuc, [5].

USING SERVO PRESSES IN WARM FORMING

Flexibility of the servo press can also be very advantageous in warm forming, especially in non-isothermal deep drawing, in which the die and the blank holder are heated and the punch is cooled by running water internally (Figure 2). In non-isothermal deep drawing, the temperature of the sheet during forming is not constant. In other words, sections of the sheet are subject to different temperatures during the operation. This is due to having a cold punch (that is kept at room temperature by circulating water through it), a heated die and a heated blank holder. While the heated die and the blank holder promotes the easy flow of the material into the die cavity, the cold punch increases the strength of the sheet by reducing the sheet temperature in the punch area.

The advantage of a servo press is mainly from the fact that the press can be programmed to stop during the stroke in order to heat the sheet between the heated upper and lower tools and the press motion can be programmed. It also needs to be noted that the speed of forming in non-isothermal forming determines the amount of heat transfer that takes place between the cold punch and heated sheet, therefore the adjustment of speed has direct effect on the formability.

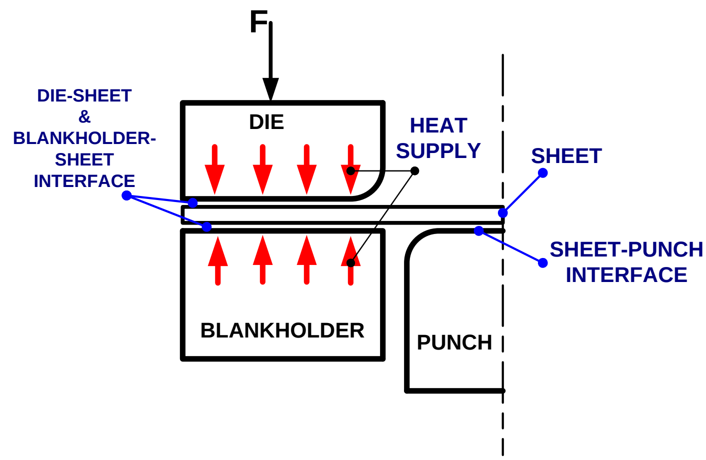
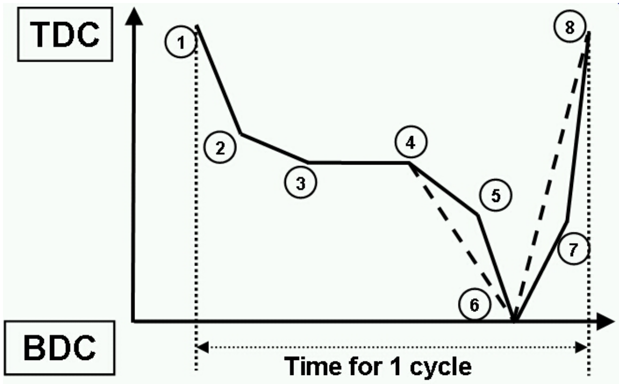


FIGURE 2- SCHEMATIC VIEW OF NON-ISOTHERMAL DEEP DRAWING

Contact pressure and surface roughness of sheet are some of the main parameters that affect the heat transfer in warm forming. Pressure and temperature conditions generate microscopic changes (roughness and micro-welding) in the contact area conditions and significantly affect the heat transfer phenomena. Semiatin et.al. 1987 [6] in the forging area, have experimentally demonstrated that the interface HTC is a function of interface pressure. Interface heat transfer coefficient (HTC) is a process specific constant and most of the time it is not easy to obtain due to specific tooling and machine requirements.

For a better understanding of warm forming of sheets, experiments were planned that would utilize the unique characteristics of the servo press. By stopping the press motion and applying various contact pressures, the change in temperature and the surface roughness values were investigated. Also, since the motion of the press can be programmed, the effect of variable forming speed on the quality of the part is studied. All experimental results in this paper were obtained by using the round cup deep drawing tooling shown in Figure 4 and an AIDA 110 ton servo press. Further details on the tooling and the servo press are provided in Kaya et.al. 2008 [7].

Figure 3 is a warm forming process specific press motion curve that was adopted for the planned experiments. Please note that the sheet is heated within the tool by stopping the press between points 3 and 4, and the speed of the press can be adjusted. Being able to heat the sheet within the tool eliminates the need for an outside furnace, transfer of the sheet from furnace to the tool and the temperature inhomogeneity that would occur as a result of the transfer.



1-2	Fast approach
2-3	Slower approach reduces impact and vibrations. Both tools are in contact at 3.
3-4	Dwell (press is at a stop for a defined amount of time for heating of the blank)
4-5	Slower punch velocity for forming sharp corner radii
5-6	Higher velocity for faster forming
6-7	Slower exit from the tool reduces impact and vibrations
7-8	Faster return to TDC

FIGURE 3- SERVO PRESS MOTION CURVE FOR WARM FORMING

Effect of contact pressure on temperature

In order to determine the effect of contact pressure on temperature change, a fixture from aluminum (2.3 mm in thickness and 80 mm in diameter) was designed (Figure 5). This fixture had four holes (each 2 mm in diameter) drilled vertical to its thickness towards its center. Depths of these holes were 20 mm, 25 mm, 30 mm and 40 mm. 40 mm hole was used for temperature measurements while other holes were used to check the homogeneity of temperature. Schematic view of the experimental setup is given in Figure 6.

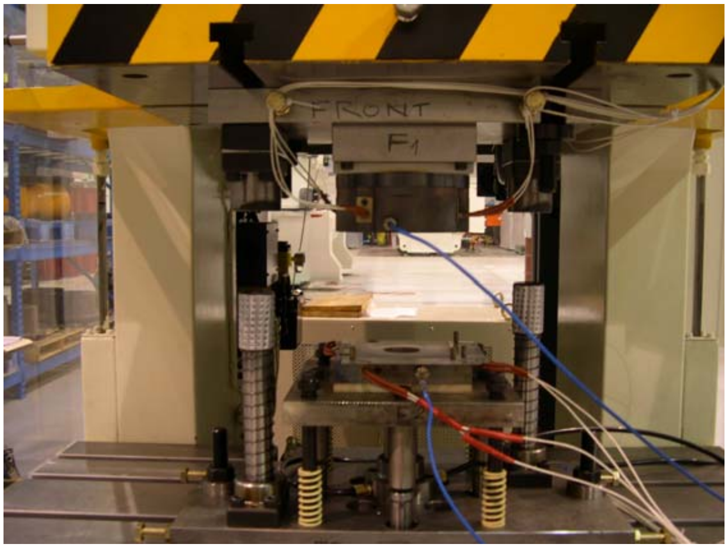


FIGURE 4- NON-ISOTHERMAL ROUND CUP TOOLING (PUNCH DIAMETER: 40 MM, PUNCH RADIUS: 4 MM. DIE RADIUS: 6MM) IN THE AIDA SERVO MOTOR CONTROLLED PRESS [7]

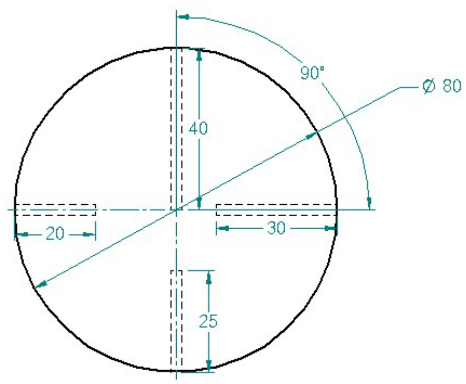


FIGURE 5- TOP VIEW OF THE FIXTURE USED TO DETERMINE THE DWELL TIME NECESSARY TO HEAT THE BLANK (THICKNESS 2.3MM)

Figure 7 shows that when the specimen was under 26 MPa of BHP, it reached to 250 ^{o}C 7 seconds earlier than the one conducted at 1.5 MPa of blank holder pressure (BHP).
Figure 7 also shows the calculated temperature-time curves. Calculated temperature-time curves are obtained by modeling the exactly same experimental setup using the finite element code Deform2D. Various heat transfer coefficients were input in order to compare the predicted temperature curves with the experimental ones. It is seen that, heat transfer coefficients between 2-8 kW/m^{2}C seem to represent a reasonable range for use in finite element analysis of warm forming. Validity of these calculated coefficients are tested by modeling an actual deep drawing case. Results will be discussed in the upcoming sections.

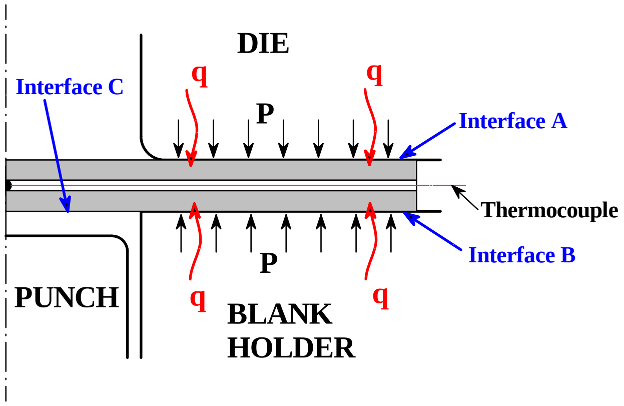


FIGURE 6- SCHEMATIC VIEW OF THE EXPERIMENTAL SETUP WITH THE AFFECTED INTERFACES

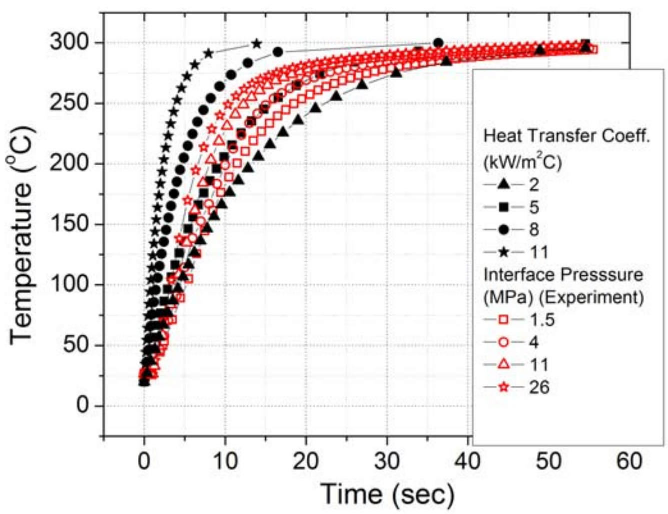


FIGURE 7- MEASURED AND CALCULATED TEMPERATURE-TIME CURVES

Surface roughness measurements

Aluminum and magnesium alloys that are common interest to industry such as, Al 5052-H32, Al 5754-O, Mg AZ31-O (Supplier A), Mg AZ31-O (Supplier B) sheet were selected to conduct surface roughness measurements before and after applying various contact pressures. Same Mg alloy sheets from two different suppliers were tested due to their obvious differences in surface properties (roughness, color) and mechanical properties.

Figure 8 and Figure 9 show the as received surface roughness values of the sheets along the rolling and the transverse directions (RD and TD). It is noticeable that the surface roughness values for the Mg AZ31-O (Supplier A) are quite high compared to the one from Supplier B.

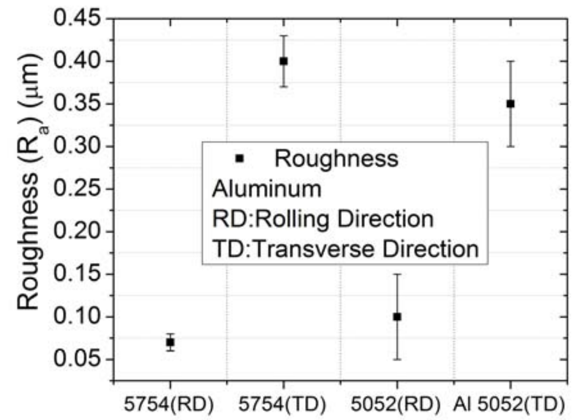


FIGURE 8- R_A VALUES FOR AL 5754-O AND AL 5052-H32

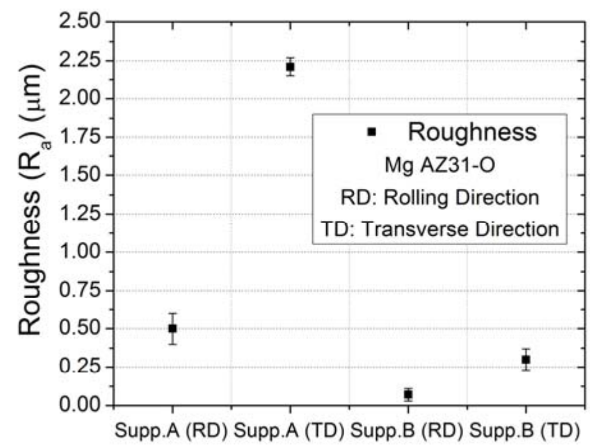


FIGURE 9- R_A VALUES FOR MG AZ31-O (SUPPLIER A) AND MG AZ31-O (SUPPLIER B)

Tool temperature was set to 300 °C and the dwell time was selected to be 90 seconds to make sure that the whole sheet reaches approximately to the same temperature.

Table 1 shows the surface roughness measurements before and after the experiments. For these experiments, surface roughness measurements were made only in the transverse direction (90° to the rolling direction). Measurements were made at a point on the sheet (diameter of 100 mm) that is ~10 mm off the edge. Results indicate that there is almost no change in the surface roughness of Al5052-H32 since it already has a low surface roughness. However, the amount of change in the Mg alloys from different suppliers is quite noticeable.

TABLE 1- R_A VALUES BEFORE AND AFTER APPLYING VARIOUS CONTACT PRESSURES

	5052-H32		Mg AZ31-O (Supp. A)		Mg AZ31-O (Supp.B)	
BHP (psi /	Before	After	Before	After	Before	After

Mpa)						
91 / 0.6	0.33	0.3	2.24	2.12	0.22	0.22
269 / 2	0.4	0.4	1.57	1.13	0.2	0.17
752 / 5	0.35	0.33	2.27	1.7	0.37	0.27
1739 / 12	0.33	0.29	2.13	1.64	0.43	0.26

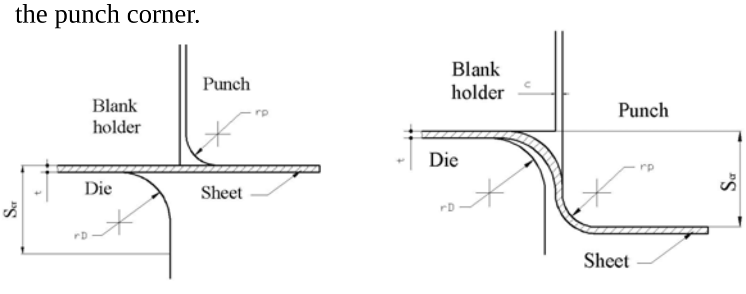
While higher contact pressure increases the surface area and helps in reducing the sheet heating time, it also decreases the surface roughness of the sheet which might have a negative effect on the already challenging lubrication condition during forming.

Effect of variable forming speed

In deep drawing, considerably severe deformation takes place around the punch and the die corner. In warm forming, severity of this deformation can be even higher depending on the punch/sheet temperature and the forming speed. Therefore, in order to minimize this in elevated temperature forming, different velocities could be set between points 4-5 and 5-6 (see Figure 3). For example, a slower velocity between 4 and 5 for forming around the punch and the die corner, and a faster velocity between points 5 and 6 to complete the stroke could be programmed. The main unknown in the 4-5-6 path is the amount of stroke needed to apply the slower velocity between points 4 and 5. Therefore, an approximate stroke named "critical stroke" (S_{cr}) is defined in equation [1] as:

$$S_{cr}=r_D+r_P+t \qquad [1]$$

where, r_D: die corner radius, r_P: punch corner radius, t: sheet thickness. Figure 10a and Figure 10b show the schematic view of deep drawing process at initial stage and at the critical stroke, respectively. As it is seen from Figure 10b, at the end of the critical stroke, the bending process has been completed at the punch corner.



a) b)

FIGURE 10 - SCHEMATIC VIEW OF THE "CRITICAL STROKE" CONCEPT

In the experimental tooling, since r_D is 6 mm, r_P is 4 mm and the sheet thickness, t, is 1.3 mm, the critical stroke is calculated to be approximately 12 mm. Experiments were conducted to investigate the effect of variable velocity on the thickness distribution for Al 5754-O and Mg AZ31-O. The idea is to draw the sheet at a slower speed until the end of the critical stroke so that necessary cooling takes place to strengthen the sheet around the punch corner zone, while still being within the formability limits. Figure 11 and Figure 12 show the effect of variable velocity on the thickness distribution. In these graphs, "5/40 mm/s" means the cup was drawn with 5 mm/s during the first 12 mm of stroke (critical stroke) and the rest of the stroke was completed with 40 mm/s. Results show that instead of forming with a slower constant velocity for the full stroke, a slower velocity within the critical stroke and a faster velocity after this stroke can be used and a successful cup still can be drawn. A lower constant punch velocity used for the complete stroke will provide the best thickness distribution at the expense of the drawing process to be very slow. With the variable forming velocity approach, the process will be slower until the end of the critical stroke but the velocity could be increased for the post-critical stroke, which will decrease the total drawing process time significantly.

In Figure 12, the difference in the thickness of the cup formed at 40 mm/s is smaller compared to the 5 mm/s. However, there is significant similarity in the thickness distributions of cups formed at 5 mm/s and 5/40 mm/s. Therefore, instead of forming the cup at 5 mm/s, results show that it can also be formed using 5/40 mm/s. The benefit of this approach in drawing time savings is shown in Figure 13.

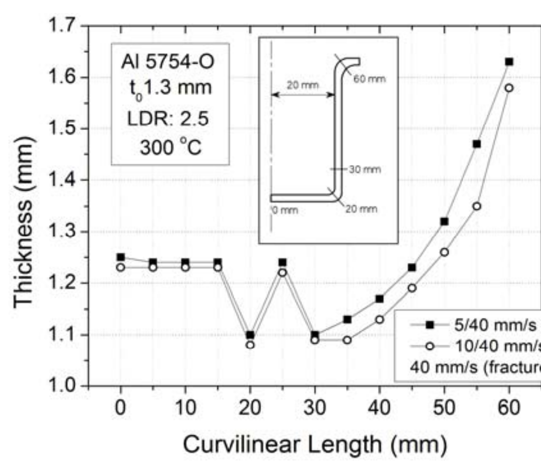


FIGURE 11- EFFECT OF VARIABLE FORMING SPEED ON THE THICKNESS DISTRIBUTION OF AL CUPS

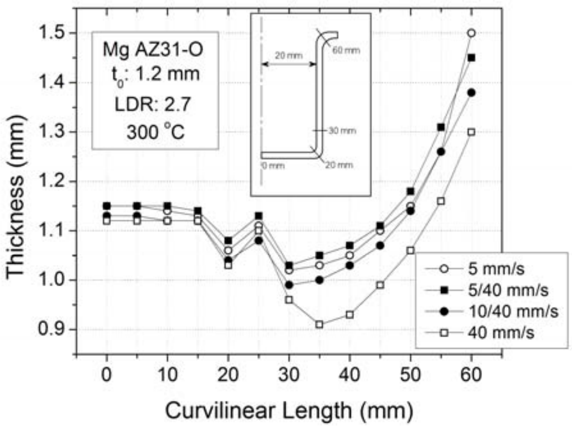


FIGURE 12- EFFECT OF VARIABLE FORMING SPEED ON THE THICKNESS DISTRIBUTION OF MG CUPS

Punch velocity (mm/s)	Total cup drawing time (s)
5	9
5 / 40	2.4 + 1 =3.4 s
40	1.1

} **5.6 sec**. time savings per cup while obtaining the same thickness profiles

FIGURE 13- TIME SAVINGS WHEN CONSTANT AND VARIABLE FORMING SPEED IS USED FOR DRAWING A 45 MM CUP

FINITE ELEMENT ANALYSIS OF WARM FORMING

In order to investigate the effect of heat transfer coefficient on the deep drawing process and to check the accuracy and the applicability of the previously calculated heat transfer coefficients (Figure 7), an experimental case was selected. Experimentally measured thickness distributions and punch loads were compared with the predicted ones using finite element analysis code DEFORM 2D. Table 2 provides related tool geometry and process data.

TABLE 2- LIST OF RELATED GEOMETRICAL DATA AND INPUT PARAMETERS TO THE FE MODEL

Punch shoulder radius (mm) r_p	4
Punch diameter (mm) D_p	40
Die shoulder radius (mm) r_d	6
Punch-die clereance (mm) D_d	2.3
Initial sheet thickness s_0 (mm)	1.3
Initial sheet temperature (°C)	250
Initial punch temperature (°C)	60
Friction coefficient, μ	0.04
Heat transfer coefficients (kW/m^2 C)	4 /6/11

Flow stress data for the Al 5754-O alloy sheet, used in this study, was obtained from Boogard, 2001 [8]. Necessary thermal data such as thermal conductivity and heat capacity are obtained from Incropera, 2002 [9]. For the FEA, selection of the friction coefficient is based on a) previous experimental experience on testing PTFE lubricants b) through comparison of predicted and measured punch load and thickness distributions using this lubricant.

Various heat transfer coefficients were used to investigate their effect on the punch load and thickness distribution of the cup. It was found that when heat transfer coefficients of 2 kW/m^2 C and 3 kW/m^2 C were used the cup showed excessive thinning at the first 15 mm of the stroke. This showed that such lower coefficients of heat transfer did not allow the sheet to cool down enough (due to the contact with the cold punch) and withstand the stresses generated in the cup wall. Punch load and thickness distribution curves are shown in Figure 14 and Figure 15, when every parameter is kept same except the heat transfer coefficients. Results show that the effect of the heat transfer coefficients on the punch load is negligible. This is because there is not enough contact between the sheet and the punch to decrease the sheet temperature and cause the punch load to increase. However, difference in thickness distribution of the cup between 0 mm to 30 mm curvilinear length (this is the punch-sheet interface in which there is considerable contact pressure) is affected by the heat transfer coefficient. Higher coefficient provides a better match compared to the lower ones. After 30 mm (this is the cup wall–punch interface and there is no contact pressure) since the sheet is not touching the punch, the effect of heat transfer coefficients is not seen.

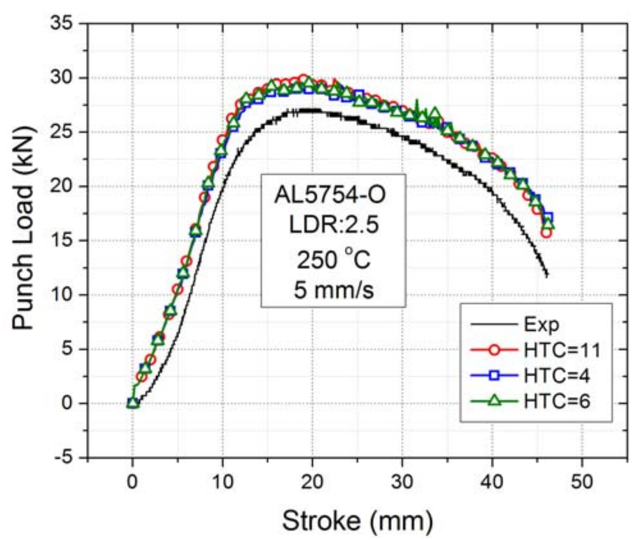


FIGURE 14- COMPARISON OF PUNCH LOAD PREDICTIONS USING VARIOUS HEAT TRANSFER COEFFICIENTS (HTC: KW/M2 C) WITH EXPERIMENT (5 MM/S AT 250 ^{O}C)

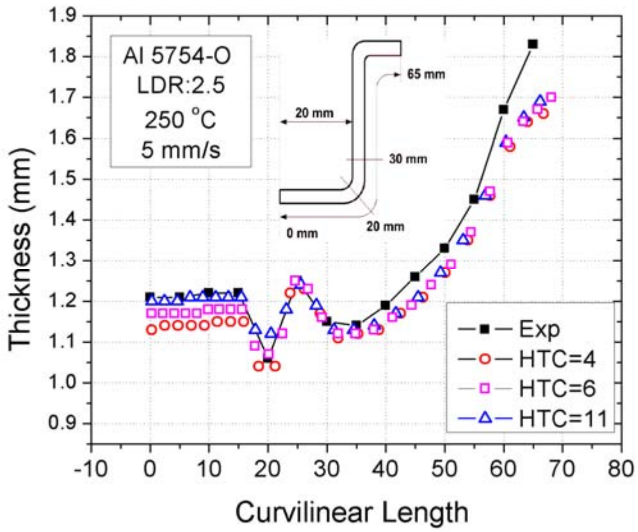


FIGURE 15 - PREDICTED THICKNESS DISTRIBUTION COMPARISON WITH VARIOUS HEAT TRANSFER COEFFICIENTS (5 MM/S AT 250 ^{o}C)

SUMMARY AND CONCLUSIONS

Advantages of servo motor presses in metal forming were summarized briefly and their specific advantages in warm forming were discussed in detail. It is well known that in isothermal (all tools are heated) warm forming, Limiting Draw Ratio (LDR)/ formability of lightweight cups can be increased to a great extent. In this paper, uniquely, a non-isothermal (dies are heated punch is cooled) warm forming approach using a servo motor controlled press is introduced. By utilizing the combined advantages of non-isothermal approach and the servo motor controlled press, a variable forming velocity concept is introduced and 60 % savings in cup drawing time is achieved experimentally.

Following conclusions can be drawn from this study;

1) A servo motor controlled press was successfully used in warm forming by programming the press slide to stop during the stroke for heating the sheet. This has eliminated the heating equipment and the sheet transfer equipment needed outside of the press while at the same time eliminating the unwanted temperature variations in the sheet.
2) It is shown that the incoming MgAZ31-O from two different suppliers can have significant variations in surface quality and mechanical properties.
3) Effect of contact pressure on the dwell time (rate of temperature change) is found to be significant. Results indicated that the fixture under 26 MPa of contact pressure reaches to 250 ^{o}C approximately 7 seconds faster than when it was tested under 1.5 MPa of contact pressure. This could be considered in production for a more efficient process.
4) Generally, it is difficult to obtain heat transfer coefficients from tests that are closer to the actual forming conditions. By taking the advantages that a servo press offers it is shown that heat transfer coefficients in warm forming seem to be within 2 kW/m^2 C and 11 kW/m^2 C for contact pressures of 1.5 MPa and 26 MPa based on the comparison of predicted and experimentally measured temperature curves. Different values within this range can be used as input to FEA and by validating the punch load, sheet temperature and thickness, acceptable results can be obtained.
5) Variable forming speed concept (slower at the initial stages of drawing and faster afterwards) is introduced, It is found that the total forming time can be reduced 60 % with respect to a constant forming speed. More importantly, while the forming time is reduced significantly (from 9sec to 3.4sec), the thickness distribution for the part obtained using variable forming speed is almost same with the cup's thickness obtained using a constant/slower forming speed.

ACKNOWLEDGEMENTS

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