Advances and Challenges in Sheet Metal Forming Technology

T. Altan, A. Groseclose, E. Billur, S. Subramonian, T. Mao,

Engineering Research Center for Net Shape Manufacturing (ERC/NSM), The Ohio State University, Columbus OH, USA.

Abstract

Requirements for light weight and crush resistance vehicles require the use of AHSS (DP, TRIP, TWIP) and Al alloys to form complex shapes. This paper discusses the practical determination of material properties and lubricants for optimum forming conditions and FE simulations. Case studies from recent research at CPF are presented including bulge and dome tests to determine flow stress, cup draw tests to evaluate lubricants, effects of punched hole quality on fracture limits in flanging, FE simulation of hot stamping to obtain tailored properties, springback in bending, and application of servo drive presses to improve formability in forming of AHSS and Al alloys.

Keywords:

Metal forming, Finite element method (FEM),

1 INTRODUCTION

The automotive industry is under considerable pressure to reduce vehicle weight and costs. As a result companies, OEMs as well as first and second tier suppliers, invest in R&D to form new materials (Al alloys, AHSS, Boron Steels) to reduce weight and improve safety requirements. New materials require advances in lubrication, die materials and coatings as well as new equipment. It is well-accepted practice to save weight and increase safety using advanced high-strength steel (AHSS), as well as hot pressed and quenched boron steels. AHSSs include dual-phase grades (DP 600 to DP 1200) with tensile strength up to 1,200 MPa (175 ksi), as well as transformation-induced plasticity (TRIP), martensitic (MS), and twinning-induced plasticity (TWIP) steels. Hot pressed boron steels may reach 1,500 to 16,00 MPa (215 to 230 ksi) tensile strength after quenching.

This paper reviews some of the recent developments in sheet forming and discusses advances and trends in the evaluation of materials, lubricants as well as critical sheet forming processes such as blanking and hole expansion, hot stamping and servo press applications.

2 MATERIAL PROPERTIES

Industry uses the finite element method (FEM) widely for process design to predict metal flow and defects in stamping. The accuracy of the input data affects the accuracy of the FEM results, so it's important to use a test that defines the stress-strain behavior of materials for stamping conditions (biaxial stretching). [1]

The viscous pressure bulge (VPB) and limiting dome height (LDH) biaxial tests offer several advantages over the conventional tensile test. Flow stress curves are essential for simulation and analysis purposes. Usually, these are determined using tensile test. However, data obtained in a tensile test is for relatively small strains and therefore must be extrapolated. Bulge test, on the other hand, can give more reliable strain-stress data, and eliminate the need of extrapolation. Figure 2 is a comparison of flow stress curves determined by tensile and bulge tests. Note that, the maximum strain in tensile test is around 0.15, and in bulge test is 0.5. [2]

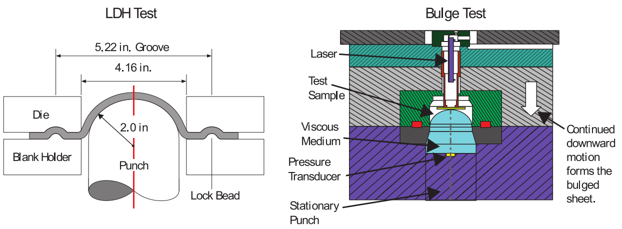

Figure 1: Schematic of the biaxial LDH and VPB tests

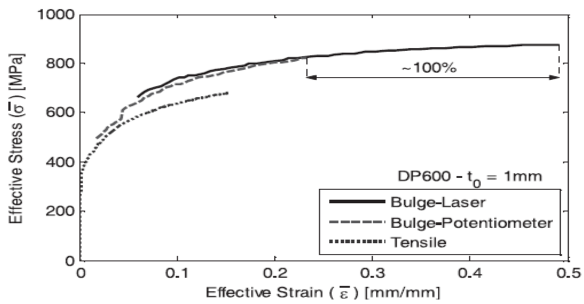

Figure 2: Comparison of flow curves determined to determine flow stress curves for larger strains. [1] by VPB and tensile test [3]

In a study performed with Honda R&D, the LDH and VPB tests were used to determine the flow stress for JAC 270E steel sheet material. The material model was assumed to be the Hollomon law: $\sigma = K\varepsilon^n$, where σ is true stress, ε is true strain, K is the strength coefficient, and n is the strain-hardening exponent. Comparing the two methods, it was determined that the experimentally determined K and n, were approximately the same for both methods (see Figure 3). [1]

Parameter	VPB Test	LDH Test
K	691 MPa	711 MPa
n	0.265	0.25

Figure 3: Comparison between the K and n values obtained from the VPB and LDH tests [1]

3 FRICTION AND LUBRICATION

Many factors need to be considered in the analysis of a lubricant's applicability to a certain process. It is not sufficient to select a lubricant with low coefficient of friction for the stamped part. It is necessary to consider the workpiece material, the tooling, the tool/workpiece interface, the deformation zone, the equipment, the finished part, and the environment (which includes the handling and pre- and poststamping processing). [4]

Consideration of the system approach is important. If a lubricant gives a low coefficient of friction but causes corrosion of the workpiece or tooling, causes degradation of the environment, or cannot be cleaned off, then the lubricant cannot be considered effective for application. Therefore, the laboratory tests should emulate the practical stamping conditions and processes so they can be taken into consideration when choosing a lubricant for a given stamping operation.

Two tests are conducted at ERC/NSM evaluating the lubricity and coefficient of friction of lubricants related to galling, tool materials, and coatings:

Cup drawing test—A round blank is drawn into a round cup (see Figure 4). The performance criteria are the maximum drawing load, the maximum applicable blank holding force (BHF) without fracture, measurement of draw-in length or flange perimeter of the drawn cup, and visual inspection of buildup on dies during use of dry lubricants. After cup drawing, the flange can be removed and the part is ironed, if desired.

•**Strip drawing test**—This test is similar to the cup drawing test, except a 14-inch by 1-inch strip of material is used instead of a round piece. The strip is drawn into a hat shape, and maximum drawing load and measured draw-in length are used for evaluation. The test was developed to evaluate AHSS, which is difficult to use with the cup drawing test. It also is cheaper and faster to run than the cup test, so it is practical for evaluating a large number of lubrication conditions quickly.

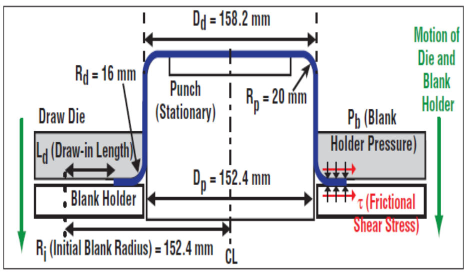

Figure 4: Cup drawing test schematic [4]

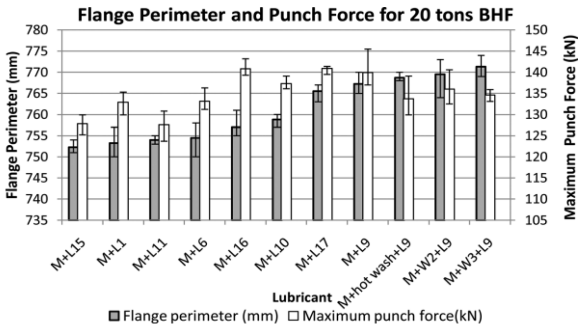

Figure 5: Flange perimeter and punch force recorded for 20 tons BHF (one lubricant condition failed at 20 tons) [5]

In a study with Honda Manufacturing, the strip drawing and cup drawing tests were performed to analyze lubricants for forming galvanealed DQS-270D-GA steel. The strip draw test was conducted for 18 lubricant conditions and narrowed the cup drawing test down to only 12 lubricant conditions (after the "failed" lubricants were removed from testing due to their performance in the strip drawing test). The cup drawing test was then performed at 20, 22, and 24 tons blank holder force (BHF), the results for 20 tons BHF are shown in Figure 5. [5]

4 BLANKING AND HOLE EXPANSION

4.1 Blanking Tests to Obtain Flow Stress Data of Materials

Blanking is a very high deformation forming process with a significant temperature increase in the sheet especially when thick and high strength materials are blanked. In the deformation zone of the sheet the strains may reach values as high as 2-3. This also translates to high strain rate which can be anywhere between 10^3 sec^{-1} to 10^5 sec^{-1} depending on the blanking velocity. The temperature in the sheet can also go up to 300°C depending on the thermal conductivity, strength and thickness of the material. Figure 6 shows an FE model with the details of the deformation generated using the software DEFORM 2D.

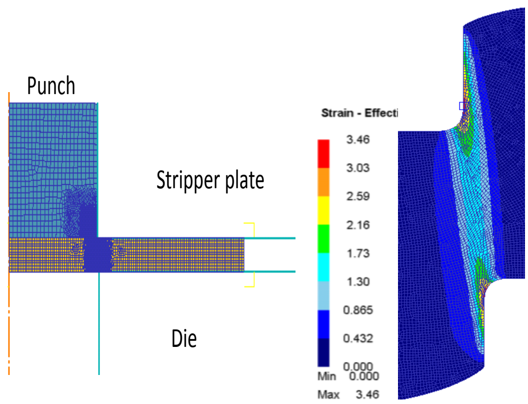

Figure 6: (left) FE model setup;(right) strain distribution in the sheet during blanking of 0.2 mm thick C51100 sheet

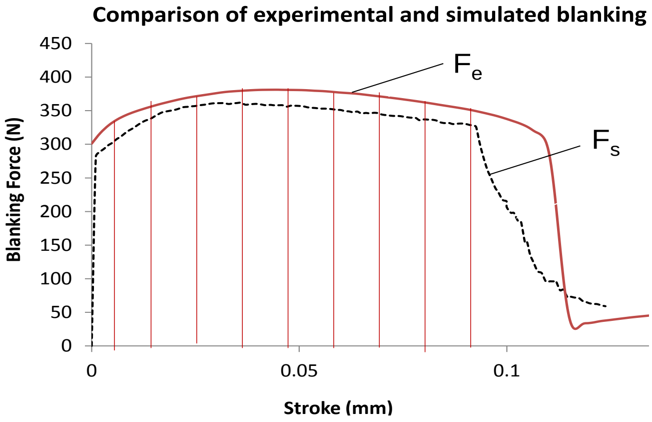

Figure 7: Comparison of experimentally obtained and simulated blanking force at small intervals of stroke to obtain high strain and strain rate flow stress

Flow stress curves for materials to be input into blanking simulations are generally obtained by conducting uniaxial tensile tests or biaxial dome test or bulge test. These methods give the flow stress of the material for strain values less than 1 in most cases. Very high strain rates of 10^4 - 10^5 are not very commonly achieved in these tests either. Hence, the common practice is to extrapolate the curves to higher strains by fitting an equation, assuming that the material continues to follow the stress-strain relation. In this study, blanking is investigated as a potential test to obtain flow stress data for large strains and strain rates simultaneously and a methodology is proposed. A combination of blanking experiments and simulations is used to determine flow stress and is explained in the following steps.

1. Obtain blanking force-stroke curve from experiments conducted at low speed (quasi-static condition)
2. Conduct blanking simulation using extrapolated flow stress curve obtained using uniaxial or biaxial test.
3. Obtain the force F_s, average stress σ_s, average strain ε_s, average strain rate $\acute{\varepsilon}_s$ and average temperature τ_s in the sheet at small intervals 'i' of stroke.
4. Compare the experimental ($_{Fe}$) and simulated force ($_{Fs}$) at each step 'i' of stroke, as shown in Figure 2.
5. At each step 'i', if $F_s \neq F_e$ → $\sigma_{s\ new} = \sigma_s*(F_e/F_s)$
6. Average (of all steps 'i') strain rate for the process $\acute{\varepsilon}_{speed}$ is calculated. Flow stress curve for $\acute{\varepsilon}_{speed}$ is obtained.

The procedure is repeated with different blanking speeds corresponding to different strain rates to obtain flow stress data for different higher strain rates.

4.2 Effect of punch/die clearance on tool life

Experiments were conducted by Högman [6] to study the influence of punch-die clearance on the punch wear along the corner radius of a rectangular punch shown in Figure 8. The sheet material used in this study is Docol 800DP, 1mm thick and the tool material used was Vanadis 4 with a hardness of 60 HRC. Blanking tests showed that the corner of the punch with 0.2mm radius chipped after 45,000 strokes while the corner of the punch with 0.5mm radius did not chip after 200,000 strokes. FEA simulations of the experiments showed that the maximum punch stress increased beyond the ultimate compressive stress of the material of ~2200 MPa in the case of 0.2mm radius, while it remained below 2200 MPa in the case of 0.5mm radius. This study shows that using variable punch-die clearance gives a significantly less and more uniform wear on the punch compared to using a uniform punch-die clearance.

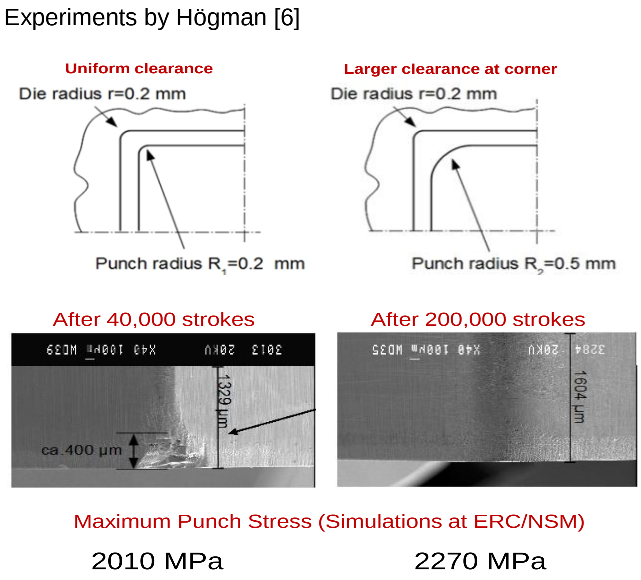

Figure 8: Effect of punch-die clearance on tool wear in experiments and tool stress in simulations

4.3 Hole Flanging or Expansion Test

During a hole expansion test, a blanked hole is stretched under tension stresses so that the hole diameter increases (see Figure 9). This hole flanging operation stretches the edge material that already has been subjected to large amounts of plastic deformation and temperature changes from the previous blanking operation. Thus, edge cracking during flanging is highly dependent on the material characteristics at the blanked/sheared edge. In practical stamping and hole flanging, the burr locations are randomly oriented. The blanked hole can be located so that the burr will be in contact with the hole flanging punch (burr down), similar to the schematic in Figure 9, or so that the burr has no contact with the punch (burr up).

Most investigators who attempt to model hole flanging using finite element modeling (FEM) ignore the influence of blanked edge geometry and its strain history while assuming a perfect edge without initial strain. At the Engineering Research Center for Net Shape Manufacturing (ERCNSM), simulations of hole expansion tests with a conical punch were conducted to illustrate the influence of sheared edge deformation resulting from blanking. The sheet material used in the tests was DP 590, burr up. The effect of strain at the blanked edge was considerable. The effective strain at the edge of the flange was quite large, up to 1.6, and increased continuously with the punch stroke. At the same stroke and Hole Expansion Ratio (HER), much larger strains were observed at the blanked edge when modeling hole expansion. Undoubtedly, these large strains affect formability and edge cracking.

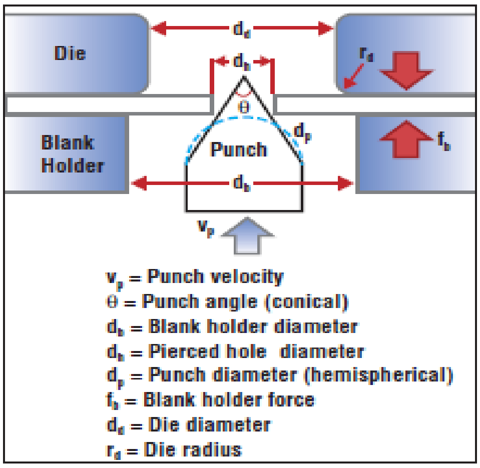

Figure 9: Hole expansion test schematic

5 HOT STAMPING

Hot stamping (also known as press hardening or hot press forming) is a relatively new technology which allows ultra-high strength steels (typical 22MnB5) to be formed in complex shapes, which is not possible with regular cold stamping operations. This can be achieved by either of these two processes.

1) Indirect Process: the blank is formed, trimmed and pierced in cold condition (i.e. state 1 in Figure 10). It is later heated and quenched in a die to get high strength property.

2) Direct Process: the unformed blank is heated in a furnace, formed in hot condition (state 2 in Figure 10) and quenched in the die to get the properties.

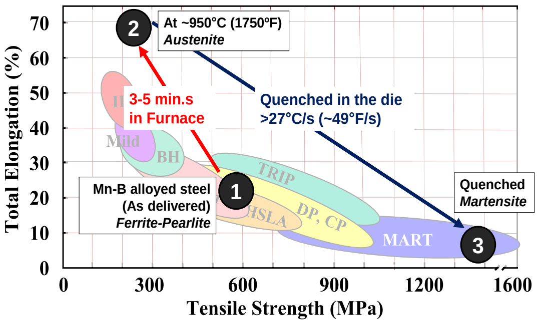

Figure 10: Summary of hot forming process

Selection of the process depends on part complexity and blank coating (Zn based coatings typically require indirect process). In either method, the blank is formed in much softer and formable state and later is hardened in the dies, which have drilled cooling channels. [8] With hot stamping, generally ultra-high strength (in the order of UTS > 1400 MPa (>200 ksi)) is achievable. However, high strength causes several problems, especially in the automotive applications: (1) strength reduces the elongation and thus the energy that can be absorbed and (2) welding of very high strength steel to mild steel creates a heat affected zone which initiates cracks. To solve these problems, in hot stamping parts can be tailored, such that some areas can be fully hardened (martensite) and some areas can be left soft (bainite or ferrite+pearlite) or TWB/TRB's can be used, Figure 11. [9]

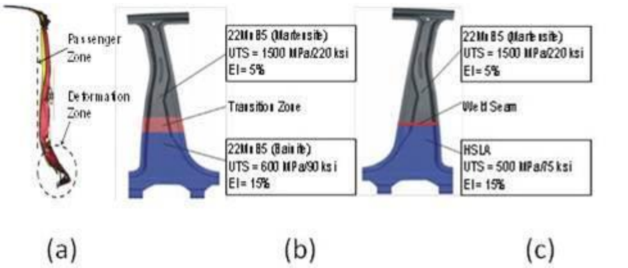

Figure 11: (a) Side view of a B-pillar after crash, (b) Tailored properties or (c) TWBs may improve elongation in the deformation zone[9]

6 SERVO PRESS APPLICATIONS

The stamping industry is developing advanced die design and manufacturing techniques to help reduce the splitting and scrap associated with stamping. The use of servo-driven presses also can help to address the formability and springback issues in both forming of AHSS and Al alloys.

Major challenges in forming AHSS

These are:

- lower formability (ductility), compared to low carbon steels. As seen in the "banana" curve, Figure 10, with increasing yield/tensile strength
- the elongation (or ductility or formability) decreases
- the usual methods of predicting when fracture (splits) may occur (using Forming Limit Diagrams) do not work for AHSS, as they do in forming low strength steels
- variations in the properties (yield, tensile, elongation) of incoming material from batch to batch and supplier to supplier
- higher forming loads, and energy requirements, tool stresses, tool wear require the use of tool steel inserts in the dies and larger (stiffer) presses with larger energy capacity
- higher contact pressure at the sheet/die interface causes larger temperatures in the dies and require new lubricants, with high pressure additives
- larger springback, due to higher strength (yield, tensile) of the material (Figure 12).

While all the challenges, listed above, need consideration, the most difficult issue seems to be the control of springback.

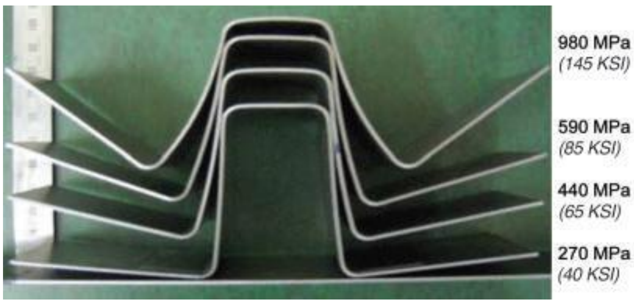

Figure 12: Servo-hydraulic cushion with power regeneration [10]

Characteristics of Servo-Drive Presses

The main advantages of electro-mechanical servo-drive presses include: [10]

a) Precise ram position and velocity control, in stroke which allows for (a) easier set up, (b) preventing noise and shock when contacting the workpiece and during upstroke (silent deceleration), (c) improved formability for reducing the ram velocity during part deformation, i.e. drawing or blanking, (d) reduction of reverse tonnage in blanking

b) Adjustable stroke length (TDC-BDC). (This provides flexibility so that in the same press drawing and blanking can be conducted with increased stroke/min. Also the press can be run in pendulum motion.)

c) Ram position/velocity can be synchronized with automatic (or robotic) part transfer. Thus, strokes/min can be increased.

d) Part/min produced is larger than in mechanical presses of comparable capacity because of rapid down and upstroke, while reducing ram speed during deformation.

e) Savings in energy, since there is no flywheel which is driven continuously.

f) Possibility of dwell anywhere in the stroke and mainly at BDC and re-striking capability (this allows reduction in and control of springback)

g) Max motor torque (press load) may be available during the entire stroke, depending on press linkage design.

It appears that most new users of servo-presses utilize the advantages (a), (b) and (d), listed above. In installing new large capacity presses (2,000 to 3,000 ton), used in forming auto-skin parts, the main considerations appear to be productivity increase, i.e. increased strokes/min. The largest (2,500 ton) servo press lines can run up to 17 or 18 strokes/min, which is larger than the production rate obtainable in comparable mechanical press lines (10-12 strokes/min).

Several press manufacturers and servomotor suppliers have applied the servomotor drive principle to the design and control of die cushions (see Figure 13). The position of the die cushion is controlled by a pressure sensor within the servo die cushion. Therefore, the operation is similar to that of a hydraulic cushion, which commonly is used in mechanical and hydraulic presses. [11]

Servo-driven die cushions also can be incorporated on multiplepoint die cushions, so that the individual cushions can be controlled separately to optimize metal flow in the flange between the die and blank holder. In addition, the servo die cushion can be used to regenerate energy when the cushion is pushed down by the upper die and slide.

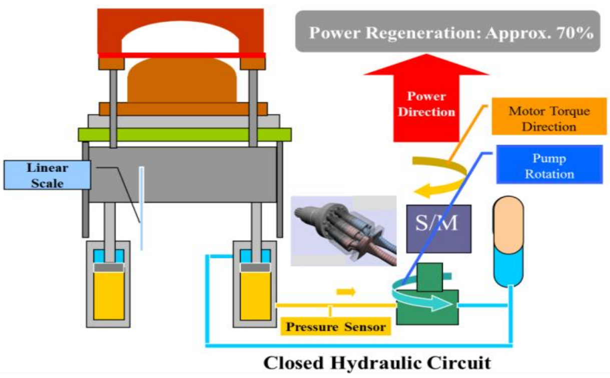

Figure 13: Servo-hydraulic cushion with power regeneration [courtesy Aida]

The use of servo-Drive Presses in Forming Aluminum

Stamping of Al alloys presents new challenges in obtaining good part definition (corner and fillet radii) and formability (fracture and resulting scrap), due to the lower formability. Servo-drive presses, having the capability to have infinitely variable and adjustable ram speed and dwell at Bottom Dead Center (BDC), offer a potential improvement in quality and part definition, especially when the infinitely adjustable slide motion is used in combination with a CNC hydraulic cushion.

It is known that the formability of aluminum alloys can be improved with the increase in forming rate by using servo press. Figure 14 shows the modified inner door panels formed by using servo-press at different slide motion patterns. It shows that 1) this part can be formed with a large fracture with an average velocity of 41 mm/s, and 2) it can be formed without any fracture and necking with an average velocity of 103 mm/s (see Figure14). [12]

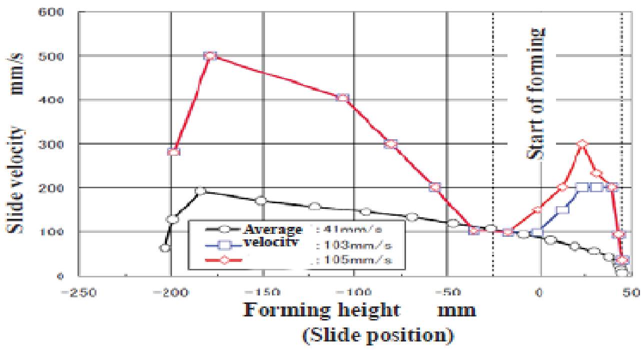

Figure 14: different slide motions used to form panels [12]

Figure 15: panel formed at (a) 41 mm/s and (b) 103 mm/s [12]

R&D to Increase the Application of Servo Presses in Forming AHSS and Al alloys

The experience of present servo press users indicate that in AHSS applications, the following observations (in accordance with advantages listed under section 5 above) are valid: [11]

a) ram deceleration minimizes impact shock on the blank holder and helps to maintain lubrication on the blank.

b) slow down of the ram (a) reduces shock/vibration in blanking, thereby improving tool life, and (b) improves formability in deep drawing.

c) slow forming speed reduces heat generation at the die/sheet interface and improves lubrication and die life.

d) multiple hits or dwell reduces springback

While the above listed observations are certainly valid, there is no scientific and quantitative information on these issues. Therefore, considerable trial and error is still necessary to identify optimum forming conditions. Very few university and/or research laboratories are conducting R&D on these issues, for example IFU at the University of Stuttgart, Germany (Prof. Matthias Liewald) that recently installed an AIDA press, Fraunhofer Institute for Machine Tools and Forming Technology (IWU) in Chemnitz, Germany (Prof. R. Neugebauer), and the Engineering Research Center for Net Shape Manufacturing (ERCNSM) at The Ohio State University (Prof. Taylan Altan).

7 SUMMARY/FUTURE OUTLOOK

This paper summarizes some of the recent R&D projects that are being conducted at the Engineering Research Center for Net Shape Manufacturing (ERCNSM – www.ercnsm.org) at The Ohio State University. This research covers Al alloys, AHSS, die design using process simulation and the use of servo drive presses. The R&D is conducted in cooperation with a group of international companies, including OEM's, first tier suppliers and sheet material producers. The objective of this research activity is to contribute to reduction of weight, cost, and scrap rate in present and future production of automotive sheet metal parts.

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