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Next generation stamping dies — controllability and flexibility

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Abstract

In sheet metal forming, external energy is transferred to sheet metal through a set of tooling to plastically deform a workpiece. The design of the tooling and its associated forming process parameters play important roles in this manufacturing process since they directly affect the quality and cost of the final product. With increasing demands from customers, government regulations, and global competition, the controllability and flexibility of stamping dies have been challenged. In this paper, we will summarize the research activities conducted at the Advanced Materials Processing Laboratory at Northwestern University in the area of sheet metal forming. An overview of our approach towards the system will be given followed by a summary of individual projects in the areas of failure prediction, design and control of a variable binder force, and the segmented die design with local adaptive controllers. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Sheet metal forming; Process control; Tearing failure prediction

1. Introduction

The old adage says 'Knowing the past is the first step for preparing ourselves for the future'. As we enter the next century, it is beneficial to look back and review how technologies evolved through the years. Take sheet metal forming for example, in the past, it heavily depended on the skills of metal workers. Each piece was hammered artistically to provide a personal touch to the product. However, with increased production demands, this procedure was replaced by an automated stamping operation, which today is one of the most widely used manufacturing processes to plastically deform materials into desired shapes. The popularity of stamping is mainly due to its high productivity, relatively low assembly costs and the ability to offer high strength and lightweight products. Interestingly, the transformation of external forces into the sheet metal deformation is quite different from other manufacturing processes, such as machining or layered manufacturing, where external energy is focused on the spot at which certain deformation is required by the use of a cutter or laser beam for example. In a stamping/deep-drawing process, tooling consists of a binder, a die and a punch. In the first step of the process, energy is applied through the binder to the periphery of the sheet metal as shown in Fig. 1. By applying this binder force to the workpiece, a restraining force is produced in the plane of sheet metal under the binder. This restraining force consists of a frictional force between the workpiece and tooling and/or the force to overcome material hardening due to stretching and bending/unbending through the draw bead radii. As the process proceeds, external energy is applied as the punch forms the material, and the restraining force prohibits material from flowing into the forming cavity. Once the tooling is produced, the controllable process variables are binder force, lubricant and punch speed. In the production environment, setting the punch speed to the maximum possible press value is desired to reach the highest production rate. As stamping applications are moving towards a lubricant-free operation to produce a more repeatable process and to address environmental concerns, binder force is left as the only control parameter in a deep drawing process. In the cases where these changes are not sufficient to manufacture parts successfully and ensure repeatability, tooling modification is required and this could be very costly and time consuming.

With the demands of better quality and rapid tooling configuration on the manufacturing floor, tooling modification is undesirable and could be eliminated through enhanced controllability and flexibility in our next generation stamping tooling. Controllability in this paper consists of two aspects, the ability to control how

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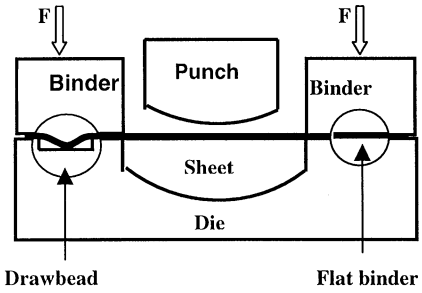


Fig. 1. Schematic of sheet metal forming.

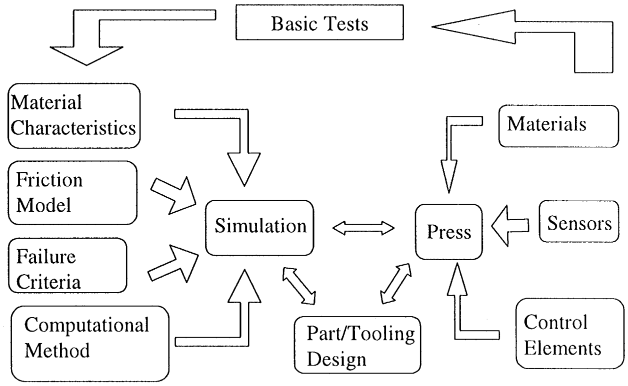


Fig. 2. A schematic representation of a computer-integrated system for sheet metal forming.

material deforms through the determination of tooling and process parameters during the design period and the ability to vary process parameters during the forming process using an open- and/or closed-loop controller. Compared to machining or layered manufacturing, the flexibility of one tooling set in stamping is limited by its rigidity and the way that energy is applied to the sheet material as described in the above paragraph. Recently, a novel tooling design was proposed by Cao and Kinsey [1] that has the promise of forming many unformable geometries and/or materials if the conventional stamping process were used. In each of the subsections below, a review of a particular research topic is given followed by the recent research results obtained in the Advanced Materials Processing Laboratory (AMPL) at Northwestern University. In general, the ultimate goal is to eliminate soft prototype tooling in a computer integrated system as illustrated in Fig. 2. The system typically involves (1) utilizing computer aided design (CAD) data throughout the entire design process (including part design and the design of subsequent manufacturing processes) and part inspection; (2) using numerical simulations to design tooling and forming parameters; (3) providing for a computer-controlled forming process; and (4) incorporating a computer-aided post-process measurement system, etc. However, the complexities of forming processes create many technical and practical challenges to the development and realization of such a computer-integrated system. In this paper, these challenges will be outlined briefly together with our recent research results to overcome these obstacles. Emphasis will be given to parts 2 and 3 in the above list.

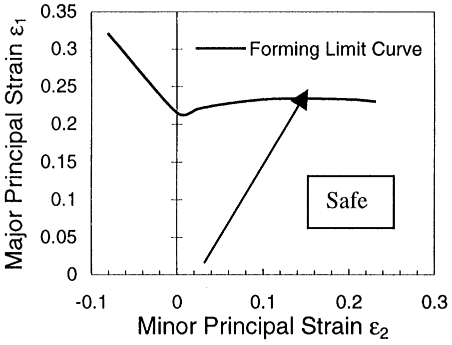


Fig. 3. A typical forming limit curve.

2. Controllability — prediction of failure

The goal of Numerical simulations is to produce failure free forming process and to reduce or eliminate engineering changes of the tooling. Typical failure modes include tearing and wrinkling.

It is believed that tearing in sheet metal forming is dominated by localized deformation, which is related to the current strain and strain history of one particular material point. The forming limit diagram (FLD) proposed by Keeler and Backofen [2] is widely used for measuring acceptable strain states of material deformation without failure. A typical FLD has a forming limit curve (FLC) as shown in Fig. 3. Material subjected to linear in-plane tension ($\varepsilon_1/\varepsilon_2 = \text{const.}$, $\sigma_{33} = 0$) can be safely stretched until the FLC is reached. Experiments have shown that changes to the strain path could substantially alter the forming limits. Experimental determination of the forming limits in all sheet metal forming processes is not only tedious but also nearly impossible, since the strain paths of material points are quite nonlinear and distinct from each other. Therefore, the ability to accurately predict FLDs is in great demand. One of the most common methods is the Marciniak–Kuczynski (M–K) analysis [3]. A large amount of research work has been performed to numerically predict the FLD using the M–K method [4,5]. One of the findings is that the shape of the yield function used plays a significant role in the accuracy of calculated FLDs. Research in the area of yield description started in 1864 [6], when Tresca provided a phenomenological description about the yielding of materials. This was followed by von Mises's work [7] for isotropic materials and Hill's research [8] for orthotropic anisotropic materials. With the increasing number of aluminum sheet metal applications, which typically possess a FCC structure, it is found that the non-quadratic yield function proposed by Hosford [9] has a better representation. However, Hosford's criterion is applicable only for isotropic material, while Barlat [10] extended the analysis to represent the orthotropic behavior. A more generic K–B criterion was proposed by Karafillis and Boyce [11]. The K–B yield criterion was constructed by mixing two yield functions, ϕ_1 and ϕ_2. As shown in Eq. (1), ϕ_1 represents a yield locus located between the von Mises yield locus and the Tresca yield locus and ϕ_2 varies from the von Mises to a theoretical upper bound as m changes from 2 to ∞.

$$\phi = (1-c)\phi_1 + c\phi_2 = 2\,Y^m, \tag{1}$$

where

$$\phi_1 = |S_1 - S_2|^m + |S_2 - S_3|^m + |S_3 - S_1|^m,$$

$$\phi_2 = 3^m/(2^{m-1}+1)(|S_1|^m + |S_2|^m + |S_3|^m),$$

and S_i is the principal value of the isotropic plasticity equivalent (IPE) stress tensor as further defined below and Y is the average yield stress in uniaxial tension obtained experimentally. A fourth-order tensorial operator, $\boldsymbol{L}$, introduces the material anisotropy, i.e., $\boldsymbol{S} = \boldsymbol{L}(\boldsymbol{\sigma} - \mathbf{B})$ where $\boldsymbol{\sigma}$ is the Cauchy stress in the anisotropic material, $\boldsymbol{S}$ is the IPE stress tensor, $\boldsymbol{B}$ is an irreducible symmetric traceless tensorial state variable of the second order, and $\boldsymbol{L}$ is a fully symmetric and traceless fourth-order tensor. Barlat and his co-workers [12,13] adopted the same approach of handling the anisotropy to improve their previous yield criterion. In all the above cases, a phenomenological yield function approach was utilized to describe the initial yielding behavior, whereas the plastic flow of the material is determined by the flow rule. Another approach is based on Taylor's [14] polycrystalline plasticity model, which describes both the initial yielding behavior and the subsequent evolution of anisotropy with deformation [15,16], etc. However, the use of this approach is time consuming and it becomes unrealistic to use in simulations of sheet metal forming.

Using the K–B yield criterion discussed above and following the standard M–K analysis procedure, the FLD with non-linear strain paths was calculated in [17,18] and compared with experimental results published in [19,20]. As shown in Fig. 4, very good agreements were obtained. In particular, two levels of equal biaxial pre-straining straining, ε_0, were applied. Fig. 4 demonstrates that the combination of K–B yield criterion and M–K analysis can be a powerful tool for accurately detecting tearing failure in the numerical simulations of sheet metal forming processes, where non-linear strain path is almost always the case at the critical areas (near punch radii or some feature lines, etc.).

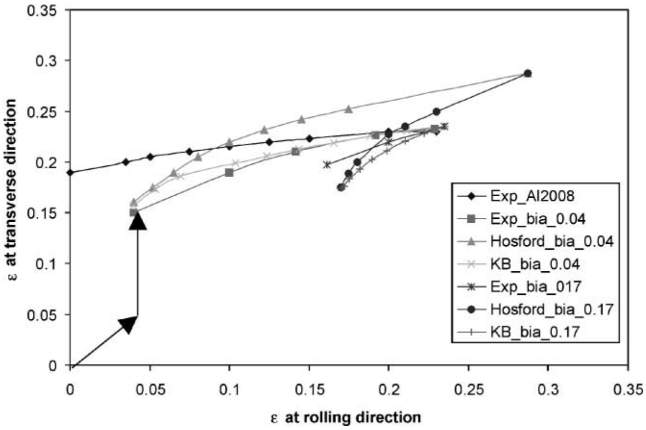


Fig. 4. Comparisons of the experimental and numerical FLDs of Al2008-T4 prestrained in equal biaxial tensions of 0.04 and 0.17 and tested perpendicular to the rolling direction. (Hosford's numerical results and experimental data was published by Graf and Hosford [19,20]).

Unlike fracture which is a local phenomenon depending only on the strain history of the material point, the occurrence of wrinkling depends on the current stress states of that material point as well as the part geometry and the boundary conditions. Due to the page limitation of this paper, a detailed review and our findings can be found in [21,22], where a hybrid approach, which utilizes analytical solutions combined with the finite element method (FEM), provides accurate predictions even for complicated geometries.

3. Controllability — variable binder force

By understanding the mechanics of metal deformation in sheet metal forming and having confidence in numerical simulations, the next logical step is to design the process using numerical simulations. Very early attempts utilized the slip line theory [23], upper bound analysis, and lower bound analysis. An inverse method using deformation theory was developed for designing the initial blank shape in [24]. Based on the minimum plastic work principle, Chung and Richmond [25] proposed an ideal forming theory to design the optimal blank shape and forming procedures [26]. With the development of data acquisition systems and computer hardware, the concept of variable binder force was first introduced by Hirose et al. [27]. More recently, the ability to change the binder force during the forming process is no longer limited to a research apparatus but is also available in commercial stamping presses, which can be found in all the major automotive companies' stamping plants. However, most of the work found in the literature utilized a force trajectory generated by a trial-and-error approach. Using a control element in their FEM model, Cao and Boyce [28] monitored the tendency of wrinkling and tearing and thereby, designed a single variable binder force trajectory (see Fig. 5) for a conical cup forming using

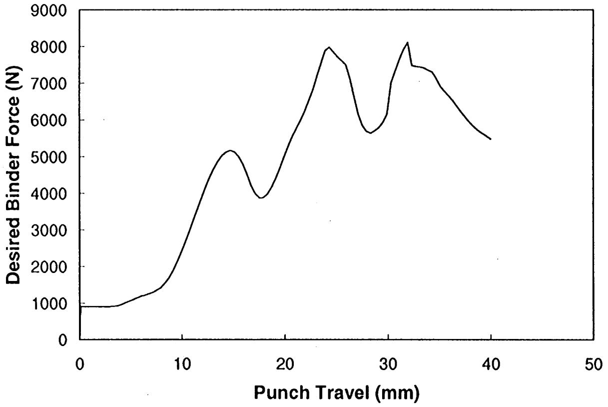
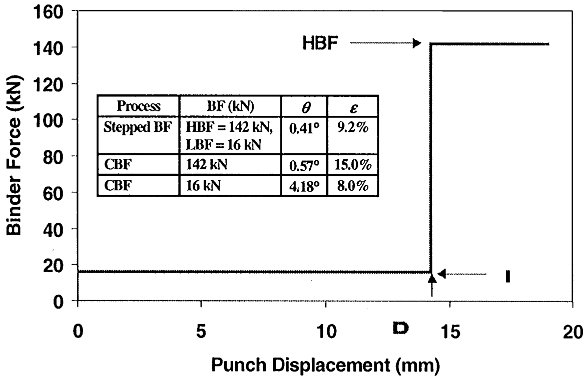


Fig. 5. An optimal VBF trajectory for conical cup forming [28].



Process	BF (kN)	θ	ε
Stepped BF	HBF = 142 kN, LBF = 16 kN	0.41°	9.2%
CBF	142 kN	0.57°	15.0%
CBF	16 kN	4.18°	8.0%

Fig. 6. A stepped binder force in channel forming reduces springback at a moderate strain.

numerical simulation. This trajectory was implemented in experiments and led to a 16% increase in the ultimate forming height of the cup over the traditional processes.

The loop of a computer-integrated system is not completed until the inclusion of an active process control. Although efforts from computational mechanics, solid mechanics and tribology have resulted in much more accurate predictions for a certain forming process, numerical simulations cannot, and are not intended to, cover all the normal process variations which occur in the production plant. Such incoming variations should be accommodated by effective process control to reduce the final part variations. To achieve these goals, Fenn and Hardt [29] developed a real-time closed-loop control system to alter the binder force during the forming process using the actual punch force or material draw-in as inputs. They obtained consistent forming heights despite the presence of variations in the lubricant, blank location and initial binder force. This approach was adopted successfully by Jalkh et al. [30] for aluminum cup forming. At around the same time, Cao and Boyce [31] proposed to use drawbead penetration as another control element for varying restraining force. The idea was tested by the Weinmann group [32] and showed promising controllability. One trade-off of the closed-loop control system is the increasing complexity of the system. In recent studies [33,34], we used a neural network to provide another avenue for process control. The neural network determined the optimal processing parameters to accommodate for variations in binder force, material thickness, friction condition and material properties. The results show that, the neural network was successful at providing high binder force (HBF) and the punch location (PD%) values for the stepped binder force trajectory (Fig. 6) which produced acceptable values of springback (θ), 0.2–0.6°, and maximum strain (ε), 8–10%, in the final product when faced with variations in the material strength hardening (K) of $\pm$ 20%, the strain hardening component (n) of $\pm$ 16%, the sheet thickness (t) of $\pm$ 25%, and the friction coefficient (μ) of $\pm$ 65%. Experimental implementation of this control system is successful and being reported.

4. Flexibility — segmented die with local adaptive controllers

As mentioned in the introduction, the geometry and flexibility of stamping is largely limited by the way that the external force is applied. A novel forming concept was proposed by Cao and Kinsey [35] as shown in Fig. 7 to address the flexibility issue. Instead of limiting ourselves to applying the external force through only the binder, we proposed to have internal segmented dies to provide additional constraints inside the forming area. The segmented dies are controlled by a hydraulic cylinder above and below the blank, incorporated into the punch and lower die, respectively. While Fig. 7 only shows one set of opposing hydraulic cylinders, multiple sets could be used to clamp in several locations.

One immediate application for the SDLAC system is the forming tailor welded blanks (TWBs). The term, TWB, is derived from the notion that the automobile designer is able to “tailor” the location in the stamping where specific material properties are desired. These differences can be in the material's grade, gauge thickness, strength, or coating, for example galvanized versus ungalvanized [36]. Forming TWBs changes the traditional forming-welding sequence to a welding–forming sequence. TWBs add flexibility into the design process and have generated enormous interest in the automotive industry as of late due to the substantial benefits they produce. These include reduced manufacturing costs due to fewer forming dies, elimination of downstream spot welding operations, and reduced scrap; weight reductions due to the combining of parts into a single component; improved dimensional part consistency from the reduction of inaccurate spot welding processes; improved corrosion resistance through the

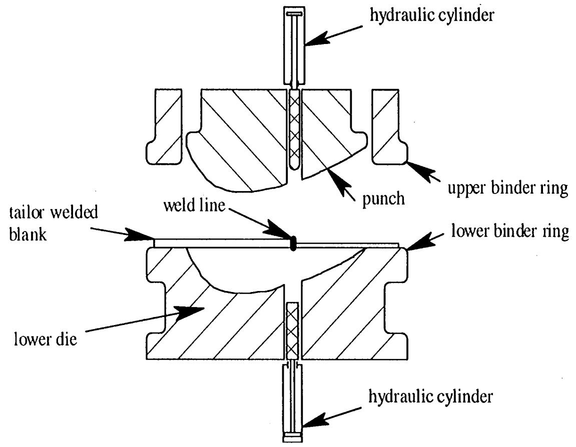


Fig. 7. Schematic representation of segmented die with local adaptive controllers.

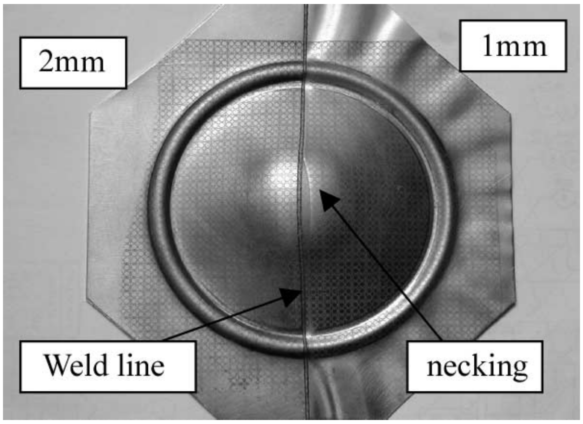


Fig. 9. Limit dome height sample.

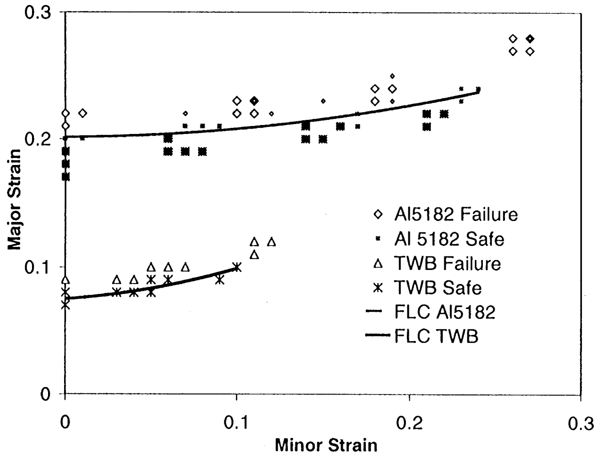


Fig. 8. FLD for Al5182 and Al5182 TWB.

elimination of lap joints by integration of reinforcements [36]; and improved crash test results due to the increased stiffness of laser and mash-seam welds in comparison to traditionally used spot welds [37].

While TWBs provide more flexibility in blank design and a great potential for cost savings, the forming of TWBs is more challenging due to material property changes in the heat affected zone and the weld itself. Significant reduction in the potential elongation of the TWBs has been reported. For a 6XXX Series Al Alloy, the tensile strength in the HAZ can be reduced by as much as 40% of the base metal's value [38]. In our recent limit dome tests (Fig. 8) on Al5182, we found that the forming limit at the plane strain loading condition dropped to 8% compared to the original 20%. In the biaxial limit dome height tension specimen shown in Fig. 8, the material tears along the weldline at around 10% compared to 23% for the base material case. This reduction varies greatly based on the filler alloy used in the welding, post weld heat treatment or aging, and other welding process parameters, such as amount and length of weld heating. As shown in Fig. 9, the original centered weld line has displaced towards the thicker material side during the forming process. This is due to the thinner material undergoing more deformation than the thicker material. However, an ideal forming case would involve a uniform deformation. In order to overcome the failures encountered during forming, attempts have been made to modify a traditional forming process to improve the formability of TWBs. Ahmetoglu et al. [39] investigated forming round cups with TWBs. In their work, the circular blank holder plate was cut, or segmented, in two with respect to the side with the thicker, stronger material and the side with the thinner, weaker material. Three nitrogen cylinders were positioned under each portion of the blank holder plate to vary the blank holder force applied to the two different material gauges. The thicker material was subjected to a lower blank holder force, thus allowing more material to flow into the die cavity. This process modification was successful at reducing the weld line movement and delaying tearing failure along the weld line compared to the case where a uniform binder force was applied to the TWB. In another effort to improve TWB formability, Munzen [40] used the lower die cushion from a production triple action stamping press to clamp on the weld line during the forming process. The die cushion supported the weld line when the blank was initially placed across the die cavity. The part of the punch opposite the die cushion would then contact the blank prior to or just as deformation of the blank occurred. Once clamped, the part was formed entirely before the weld line was released. This clamping prevented the weld line from moving during forming. However, this process required that the weld line be at the highest point on the stamping in order for the clamping to occur successfully. Using our system shown in Fig. 7, the weld line can be anywhere in the curvature of the formed part, not necessarily at the peak of the punch. Furthermore,

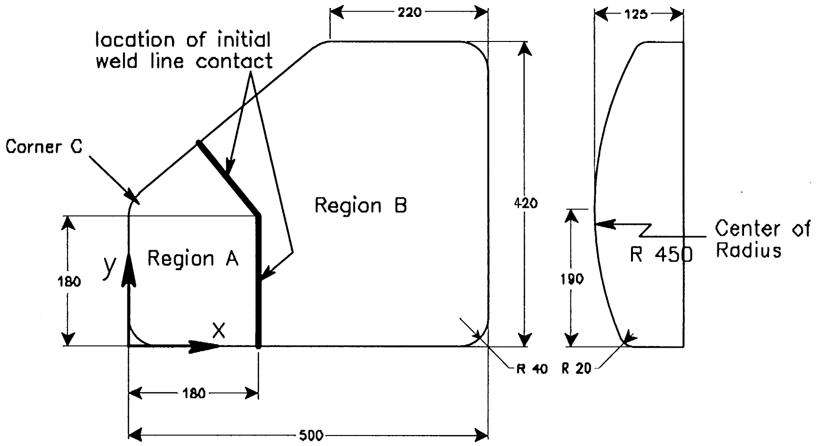


Fig. 10. Door inner.

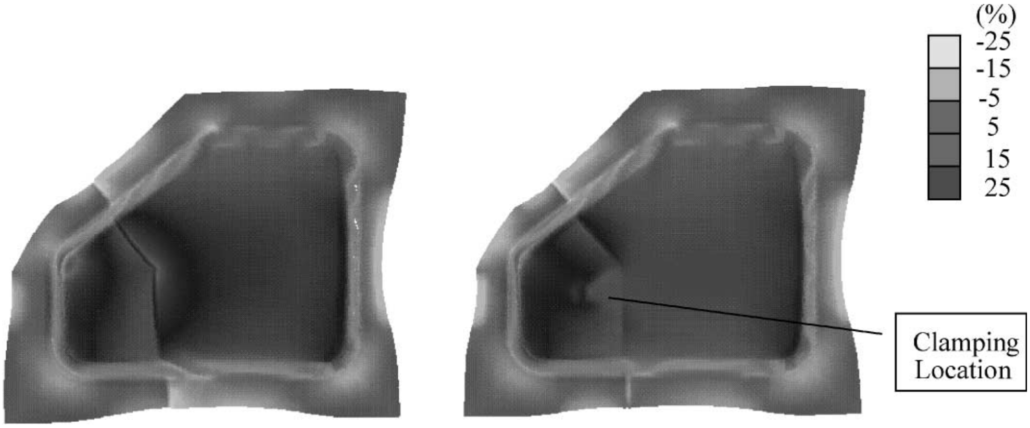


Fig. 11. Thickness contours of (a) the traditional tooling, Free Case and (b) the new proposed segmented tooling, Fixed Case.

the hydraulic cylinders would allow the weld line to be released prior to reaching the final forming depth in order to produce limited strain in the material near the weld line, which is desirable for part integrity.

In order to examine the potential of our proposed clamping mechanism for improving the formability of TWBs, metal forming simulations of a geometry similar to a door inner were conducted. A schematic of the punch used in the simulations is shown in Fig. 10. The various dimensions were scaled to that of door inners found in industry [41] including the curvature of the stamped part. Fig. 10 also shows the location where the weld line will initially contact the punch. Note that the weld line is in the direction of the punch curvature; therefore, opposing cylinders will not necessarily contact the punch at its peak. Also, notice that the weld line is more complicated than simply a uni-directional straight line, thus optimizing material usage of the thicker gauge material. In most of the current applications, there is only one vertical weld line in the door inner [41]. This design is due to the limitations of current forming technology, not because of functional requirements. Two cases were simulated. A traditional metal forming process without a weld line clamping force, the Free Case, and the Fixed Case where the nodes in a circular area were restricted from moving in the *x*- and *y*-directions to simulate the segmented tooling. This finite element analysis was performed on the commercially available software package, LS-DYNA3D. Details of the simulation can be found in Kinsey et al. [42]. Fig. 11 shows the thickness reduction contour plots for (a) the traditional tooling Free Case and (b) the proposed segment tooling Fixed Case. Note that the location of the weld line is visible on the Free Case plot due to the large thickness reductions near the weld line in the thinner gauge material while the thicker material has significantly less thickness reduction. The maximum thickness reduction was 20.8% in the thinner gauge material element located at the intersection of the slanted and vertical weld lines. This indicates that tearing failure would likely initiate in the sheet. In comparison,

Fig. 11(b) shows the distribution of the thickness reduction for the Fixed Case. Note that the location of the clamping mechanism on the thicker material side just below the weld intersection is discernible in the Fixed Case plot. The maximum percent thickness reduction along the weld line for the Fixed Case was reduced to 6.3%. Significant improvements in other forming parameters were also obtained.

The SDLAC concept improves the formability of TWBs as demonstrated above. Furthermore, this system can be applied to form regular blanks. The important concept introduced here is that local control of metal flow into the forming cavity can be achieved through this clamping device, which provides greater flexibility to the process. In addition, the clamping system could be utilized on multiple forming dies providing for reusable tooling.

5. Conclusion

Sheet metal forming is a widely used manufacturing process in the automotive, aerospace and appliance industries due to its high productivity, low manufacturing costs, and the high strength to weight ratios of its final products. Therefore, a complete computer integrated system to optimize the process which incorporates all aspects of manufacturing from tooling design to process parameter determination to final part inspection would be beneficial. Two of the areas in the complete integrated system that need to be addressed are the controllability and flexibility of the process. In this paper, an overview of research projects at Northwestern University's Advanced Materials Processing Laboratory are presented which address these concerns. In particular, efforts to address material modeling, failure criteria, and process design and control were discussed. Excellent results were obtained in each of the areas improving the current state of sheet metal forming. However, many issues still need to be investigated to reach the goal of a completely integrated manufacturing system.

Acknowledgements

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References

[1] Cao J, Kinsey BL. Adaptive method and apparatus for forming tailor welded blanks. US Patent No. 5,941,110, 1999.

[2] Keeler SP, Backofen WA. Plastic instability and fracture in sheets stretched over rigid punches. ASM Trans Quart 1964;56:25–48.

[3] Marciniak Z, Kuczynski K. Limit strains in the processes of stretch-forming sheet metal. Int J Mech Sci 1967;9:609–20.

[4] Wagoner RH, Chan KS, Keeler SP, editors. Forming limit diagrams: concepts, methods, and applications. The Metallurgical Society, 1989. p. 183–202.

[5] Burford DA, Wagoner RH. A more realistic method for predicting the forming limits of metal sheets. In: Wagoner RH, Chan KS, Keeler SP, editors. Forming limit diagrams: concepts, methods, and applications, The Metallurgical Society, 1989. p. 183–202.

[6] Tresca H. C Rnd Acad Sci 1864;59:754.

[7] Mises, R. von. Gottinger Nachr. Math Phys Klasse, 1913;582.

[8] Hill R. A theory of the yielding and plastic flow of anisotropic metals. Proc Soc London Ser A 1948;193:281–97.

[9] Hosford WF. A generalized isotropic yield criterion. J Appl Mech 1972;39:607.

[10] Barlat F, Lege DJ, Brem JC. A six component yield function for anisotropic materials. Int J Plast 1991;7:693.

[11] Karafillis AP, Boyce MC. A general anisotropic yield criterion using bounds and transformation weighting tensor. J Mech Phys Solids 1993;41:1859–86.

[12] Barlat F, Becker RC, Hayashida Y, Maeda Y, Yanagawa M, Chung K, Brem JC, Lege DJ, Matsui K, Murtha SJ, Hattori S. Yielding description for solution strengthened aluminum alloys. Int J Plasticity 1997;13:385.

[13] Barlat F, Maeda Y, Chung K, et al. Yield function development for aluminum alloys sheets. J Mech Phys Solids 1997;11/12:1727.

[14] Taylor GI. Plastic Strains in Metals. J Inst Met 1938;62:307.

[15] Asaro RJ, Needleman A. Texture development and strain hardening in rate dependent polycrystalls. Acta Metall 1985;33:923.

[16] Dawson PR, Beaudoin AJ, Mathur KK. Simulation of deformation-induced texture in metal forming. In: Cheno J-L. et al., editors. NUMIFORM'92, France: Sophia-Antipolis, 1992. p. 25.

[17] Cao J, Karafillis A, Boyce MC. Prediction of forming limit diagram using the K–B yield criterion. Proceedings of Plasticity 97. 1997. p. 379–80.

[18] Cao J, Yao H, Karafillis A, Boyce MC. Failure prediction based on M–K analysis using general anisoptropic yield criterion. Int J Plast 2000;16:1105–29.

[19] Graf A, Hosford WF. Calculations of forming limit diagrams for changing strain paths. Metall Trans A 1993;24:2497–501.

[20] Graf A, Hosford WF. Effect of changing strain paths on forming limit diagrams of Al 2008-T4. Metall Trans A 1993;24:2503–12.

[21] Cao J, Wang X. An analytical model for plate wrinkling under tri-axial loading and its application. Int J Mech Sci 1999; 42(3):617–33.

[22] Wang X, Cao J. On the prediction of side-wall wrinkling in sheet metal forming processes. Int J Mech Sci 2000;42/12:2369–94.

[23] Hill R. The mathematical theory of plasticity. Oxford: Clarendon Press, 1950.

[24] Guo YQ, Batoz JL, Detraux JM, Duroux P. Finite element procedures for strain estimations of sheet metal forming parts. Int J Numer Methods Eng 1990;30:1385–401.

[25] Chung K, Richmond O. Ideal forming — II sheet forming with optimum deformation. Int J Mech Sci 1992;34:617–33.

[26] Chung K, Barlat F, Brem JC, Lege DJ, Richmond O. Blank shape design for a planar anisotropic sheet based on ideal forming design theory and FEM analysis. Int J Mech Sci 1997;39:105–20.

[27] Hirose Y, Hishida Y, Furubayashi T, Oshima M, Ujihara S. (1990) Part II: application of BHF-controlled forming techniques. Proceedings of the Fourth Symposium of the Japanese Society for the Technology of Plasticity.

[28] Cao J, Boyce M. A predictive tool for delaying wrinkling and tearing failure in sheet metal forming. J Engng Mater Tech 1997;119(4):354.

[29] Fenn R, Hardt DE. Real-time control of sheet stability during forming. ASME J Eng Industry 1993;115(3):299–308.

[30] Jalkh P, Cao J, Hardt D, Boyce M. Optimal forming of aluminum 2008-T4 conical cups using force trajectory control. J Mater Manuf 1993;102(5):416–27.

[31] Cao J, Boyce M. Drawbead penetration as a control element of material flow. J Mater Manuf 1993;102(5):694–702.

[32] Xu SG, Bohn ML, Weinmann KJ. Drawbeads in sheet metal stamping — a review. SAE paper no. 970986, 1997.

[33] Ruffini R, Cao J. Using neural network for springback minimization in a channel forming process. developments in sheet metal stamping. J Mater Manuf 107(5):65–75.

[34] Cao J, Brad Kinsey, Sara Solla. Consistent and minimal springback using a stepped binder force trajectory and neural network control. ASME J Engng Mater Technol 2000;122:113–8.

[35] Cao J, Kinsey BL. Adaptive method and apparatus for forming tailor welded blanks. US Patent No. 5,941,110, 1999.

[36] Kubel E. Manufacturers want more tailored blanks. Manuf Engng Nov 1997;119:38–45.

[37] Am Mach. More parts from welded blanks. Manuf Engng May, 1992;136:19–20.

[38] Stasik MC, Wagoner RH. Forming of tailor welded aluminum blanks. aluminum blanks. Aluminum and Magnesium for Automotive Applications. The Minerals, Metals & Materials Society, Cleveland, OH, 1996;69–83.

[39] Ahmetoglu MA, Brouwers D, Shulkin L, Taupin L, Kinzel GL, Altan T. Deep drawing of round cups from tailor-welded blanks. J Mater Process Technol 1995;53:684–94.

[40] Munzen W. Stretch controlled forming mechanism and method for forming multiple gauge welded blanks. US Patent # 5,600,991, 1997.

[41] Auto/Steel Partnership. Tailor welded blank design and manufacturing manual. Technical Report, 1995.

[42] Brad Kinsey, Zhihong Liu, Cao J. A novel forming technology for tailor welded blanks. J Mater Process Technol 2000;99: 145–53.