# Improved Formability by Control of Strain Distribution in Sheet Stamping Using Electromagnetic Impulses

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## Abstract

*Stamping failures consist of, broadly speaking, either tearing (excessive local strain energy) or wrinkling (insufficient or inappropriate local strain energy). Good parts are produced when the strain energy or plastic work is effectively distributed during the forming process such that tears and wrinkles are eliminated. The process window framed by tearing and wrinkling limits can be rather small for some materials, notably aluminum alloys. At present, there are no established methods of directly controlling the forming energy distribution within the tool during a stamping operation. All current commercial methods attempt plastic strain control at the sheet boundary by various binder geometries and pressure profiles. While improvements by active control of draw beads and binder pressure have led to improved stamping performance, these methods still broadly rely on tool geometry to set the energy distribution.*

*We have recently developed and demonstrated a method for more directly controlling the distribution of forming energy in a stamping operation based on an extension of electromagnetic (EM) impulse forming. We now have techniques for embedding and operating EM pulse actuator coils in stamping tools. These coils can be operated in a single high power pulse or as a series of lower energy pulses occurring several times during the forming stroke. A single high power pulse can provide the advantage of increased material forming limits of high velocity forming. However, applying a series of lower power pulses can increase forming limits without exposing the tooling and coil to large shock loads. Multiple pulses reduce the maximum strain levels by engaging more of the part material in the forming process which mimics (eliminates) the use of lubricants. Conventional production stamping rates are technically obtainable with proper integration of the EM impulse circuit with the forming press and tooling.*

*This paper focuses on the basic design approach of our multiple pulse technique and integrated process forming results. Comparisons to other augmented stamping processes as well as conventional stamping are presented in terms of both simple metrics, such as draw depth and strain distributions.*

## Keywords:

Deep drawing, Aluminum, Electro-impulse

# 1 Introduction

In conventional metal stamping a flat sheet of steel is transformed by the tooling geometry into a three dimensional part, such as an automotive fender, in a second or so. Stamping tools can be thought of as a type of lens that spatially directs energy from the press to the workpiece to generate the shape change. Press energy is absorbed by the sheet in the form of plastic work. The essential problem in sheet metal forming is that the energy is provided remotely (from the press as force and displacement through the tool) and this energy is focused by a passive but complex interaction between properties of the sheet and tool. In improving the ability to make a given part, stamping process augmentations are all attempts to better distribute the forming energy over the part (i.e., reducing strain localization). Even strain energy distribution is particularly important in aluminum alloy stampings due principally to the lack of strain rate hardening effect in these metals. We have developed a general approach to the problem of optimizing strain energy distribution in sheet metal stamping based on an overarching concept of integrating dynamic impulse events with conventional quasi-static processes. Detailed discussion of the fundamental aspects of this general approach and its various physical implementations have been published elsewhere [1-2]. Herein we will concentrate on a technique at the lower end of our hybrid process spectrum since it employs rather small impulse energies.

The most conventional methods employed to distribute strain energy are the use of lubricants and multiple sequential forming operations. Lubricants are one of the oldest means to help spread the press energy over the sheet, and thus augment the stamping process [3-4]. As the coefficient of friction between the part and die is reduced, the stress and strain distribution in the sheet is generally improved. However, lubricants must usually be removed before final part finishing and are often environmentally objectionable materials. The typical concept of multiple forming operations is to first draw and stretch the appropriate amount of sheet material into a precursor shape and then use other tools and operations to redirect press energy to more effectively form the detailed final shape [5-6]. The obvious drawback here is the increased cost and complexity of using multiple tools and presses. More recently developed methods attempt to improve stamping performance by independent active control of tool components. Some of the more successful methods, as reported in the available literature, are listed below. The performance of our method will be compared to the available performance data of these other methods.

- Active blankholder force control [7-8] - Restraining pressure on the sheet feeding into the die is controlled as a function of press stroke and, in some cases, location on the binder surface.
- Active draw bead penetration [9-10] - Draw bead height, and thus sheet feed control is varied as a function of press stroke.
- Ultrasonic vibration of tooling [11] - Ultrasonic generators are mounted in the stamping tools and tuned to change the effective friction between the sheet and tool in a controllable fashion.

## 2 Description of the New Process Approach

All of the approaches listed above essentially conform to the paradigm of remotely applying the forming energy and tweaking the boundary conditions to enable or improve the production of a given part. The present approach is based on the idea of delivering the deformation energy directly where it is required in the part. Figure 1 illustrates the desired effect on deformation energy distribution that is the goal of this new stamping method.

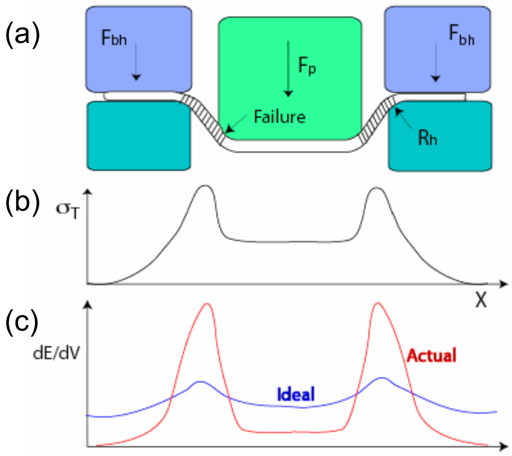


***Figure 1:***
*(a) Schematic of a simple draw & stretch stamping operation.*
*(b) $\sigma_T$ represents the tensile stress on the sheet.*
*(c) dE/dV represents the local dissipation of forming energy in an element of the sheet with change in volume swept by the punch in the sheet as a function of location in a typical (actual) and improved (ideal) metal forming situation.*

Reliable generation of the ideal forming energy dissipation in a part should enable the economical production of lighter (smaller gage) components of the needed strength with fewer operations, while decreasing or eliminating the reliance on lubricants. The key enabler of this new method is the incorporation of EM actuator coils within otherwise relatively conventional stamping tools. Before describing this integrated approach it is worthwhile to review the essential elements of EM forming.

Electromagnetic forming is a process that has been well known since the 1960's, but has never seen very extensive use [12]. The basic experimental scheme is shown in Figure 2 where capacitor(s) with capacitance $C_1$ are charged to an operator specified voltage in the kilovolt range. These capacitors are connected to circuit with a primary coil that has an inductance $L_1$ and system resistance $R_1$. When the main switch is closed the current through the actuator produces a transient magnetic field that will induce eddy currents in the nearby metallic workpiece. The magnetic energy transfer is determined by the system coupling which is related to the mutual inductance, $M$, between the coil and workpiece. This process is governed by the classical coupled differential equations [13]:

$$\frac{d}{dt}\left(L_1 I_1 + M I_2\right) + R_1 I_1 + \frac{Q_1}{C_1} = 0\,;\ \frac{d}{dt}\left(L_2 I_2 + M I_1\right) + R_2 I_2 = 0 \qquad (1)$$

The currents in the actuator and metallic workpiece travel in opposite directions generating a natural electromagnetic repulsion. To calculate this precisely for a moving deforming 3-D situation problem is quite difficult, but the magnetic pressure can be approximated as [13]:

$$P_m = \frac{1}{A}\frac{dM}{dh} I_1 I_2 \tag{2}$$

where $A$ is the area of the workpiece adjacent to the actuator. The spatial configuration of the coil directly controls the EM pressure distribution. The pressures attained can easily exceed the pressure needed to produce plastic deformation and can accelerate, within a few millimeters, the sheet to velocities of hundreds of meters per second. Process efficiency increases directly with increasing workpiece conductivity. Materials with lower conductivity, such as stainless steel, can be assisted by driver sheets or cladding of copper or aluminum. One important observation (not central to this paper) is that, at deformation velocities over about 50 m/s, the basic phenomenology of sheet metal forming is quite different than that in quasi-static forming. In particular, inertial effects in the workpiece can serve to dramatically increase the limit strains to values significantly greater than predicted by the standard forming limit diagrams. Our group at Ohio State, and others, have been actively investigating this area of velocity and strain rate effects in limit strains [14-18].

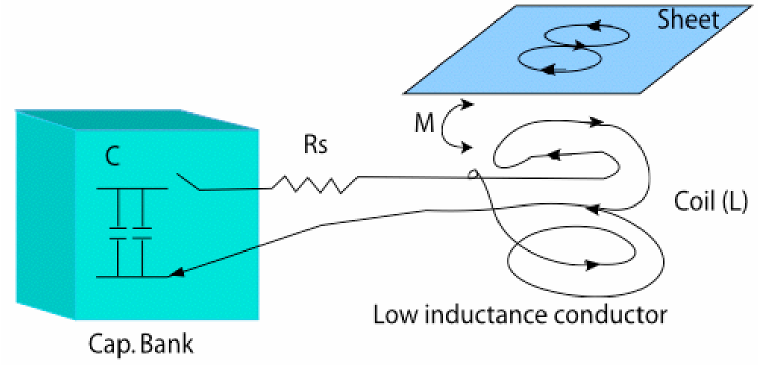


***Figure 2:**. Schematic diagram of electromagnetic forming of a sheet component*

## 2.1 Electromagnetically Assisted Incremental Stamping (EAIS)

This new approach to augmenting conventional production stamping (Figure 3) is conceptually simple. The primary goal is to provide forming energy to regions that are receiving too little strain or draw-in. Starting with the blankholder, the function of actuator 1b is to draw in the outer region of the blankholder surface taking advantage of the unbalanced forces over the surface and possibly to extend the material in the x-direction. The 'bubble' that 1b could form can be actively pulled into the die cavity using actuator 1a. These can be run sequentially to create what is in essence a controllable electromagnetic pump that can feed material into the die cavity. The function of actuators 2 and 3 is to stretch these regions essentially in the x-direction to provide the increase in line length needed to create the part.

The key idea is to energize the actuator coil many times where a small work increment is done in each cycle. In practice, it would not be a difficult matter to charge a group of capacitors while loading a part and then discharge the capacitors sequentially as the punch moves into the die. There are no fundamental reasons this cannot accommodate a total part-to-part cycle time on the order of 5 or less seconds (as is typical in auto body panel stamping).

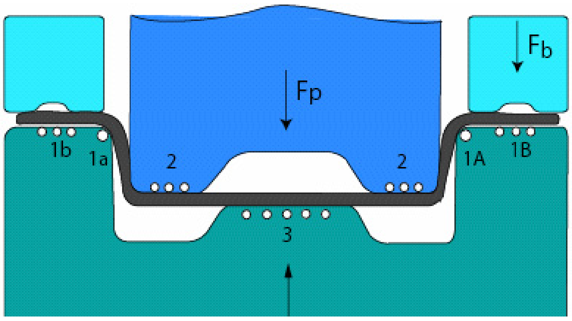


***Figure 3:**. Schematic of full implementation of electromagnetically assisted stamping: EM actuators are used to assist draw and stretch either by a single high energy pulse or incrementally with multiple low energy pulses*

## 2.2 Experimental Results of EAIS Trials

We carried out the first true hybrid electromagnetically assisted stamping operations by embedding EM actuators within conventional stamping tool and integrating the press and capacitor bank operations. These operations were performed using many relatively small EM impulses as opposed to the single high energy pulse used in our previous work [1-2]. An existing tool set for generically “difficult” pan part, originally developed by Hasida and Wagoner [7], was modified for these experiments. For the presented experiments only a single actuator coil was integrated in the tool set. A replicate punch was cast from a special iron filled epoxy. The punch face was then grooved to accept the actuator. Two simple configurations were tested. The first configuration (coil I) made a single loop around the punch face just inside the nose radius. Configuration II included additional path length in the center of the punch face. Each actuator coil was fabricated from 6 mm x 18 mm commercial copper bar bent to the appropriate configuration and inserted into the machined punch face groove. Figure 4 displays the photos of the cast punch inserted with the actuators I and II. The embedded actuators have demonstrated robust performance suffering no damage after well over 1000 shots.

The tooling was set up in an Interlaken computer controlled double acting hydraulic press. A flexible coaxial cable connected the capacitor bank to the actuator coil embedded into the punch. A Maxwell Magneform capacitor bank supplied the current pulses to the actuator. In the forming process, we set a constant blank clamp load at the level for best standard forming. The punch was then advanced a prescribed incremental distance and EM pulse discharged. The cycle was repeated until part failure occurred.

The typical result of forming is shown in Figure 5. The draw depth increased by 44% (from 4.4 cm to 6.35 cm). Figure 5 illustrates that the draw depth of the parts can be dramatically increased using the EAIS process and without any reliance on lubricants. This experiment verifies that the approach of placing forming energy where required, can dramatically increase the ability to make aggressive sheet metal parts. The effect of the embedded EM actuator coil is to produce tensile strain across the top surface of the part and tooling system constrains the part shape in the usual way.

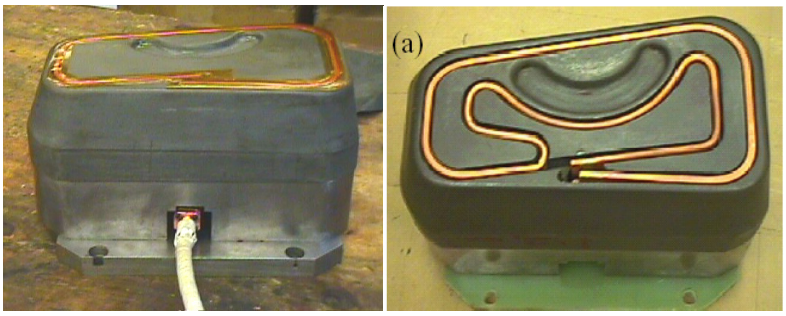


***Figure 4:**. Punch with Configuration I and II actuators (left and right).*

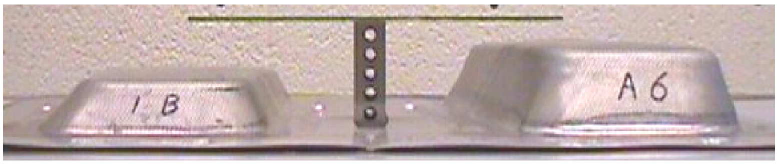
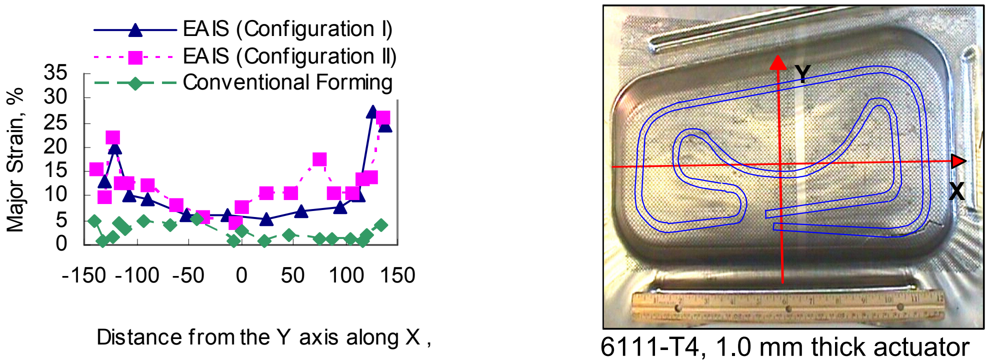


***Figure 5:** 6111-T4 aluminum formed conventionally (left) and using 22–5.4 kJ pulses, without lubrication (Draw depth increased from 4.4cm to 6.35 cm. Clamp load 35 k pounds, coil II used*

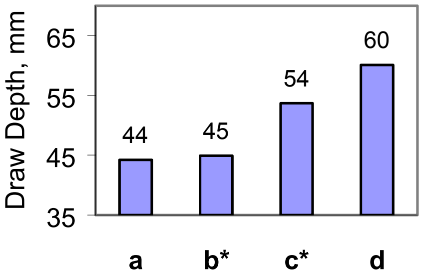
Figure 6 compares the strain distribution along the part longitudinal center between conventional forming and EAIS sheet forming. The electromagnetic energy added can produce much larger strain on the top surface of the part which allows a significantly deeper draw depth. In conventional forming, this area has little deformation because of the lock-out effect of friction between the sheet and tool at the punch nose radius. Now by the new EAIS approach, electromagnetic energy is delivered to this area generating an improved strain distribution and greater draw depth. In the case of Figure 5, draw depth increased by 44% (from 4.4 cm to 6.34 cm), and the average major strain of the top surface increased by 6.8 times (from 2.4% to 16%). The strains at walls change little because there is no electromagnetic energy delivered to those areas.

It should be noted that the conventional and EAIS process strain distributions shown in Figure 6 are for “as received” blank material. Trials investigating the effect of a medium weight oil showed that common blank oiling had little effect on the draw height (Figure 7). A special high performance blank lubricant might produce a greater effect generating a strain distribution somewhat similar to that of EAIS but of lower magnitude. Lubricants reduce the friction lock-out of material in a passive way that cannot produce the effect of direct application of deformation energy. The magnitude of the improvement available with EAIS would be very difficult to attain with the best lubricants even for simple axisymmetric, domed parts. The curious effect of lubrication reducing draw depth when employed in the EAIS process has not been thoroughly investigated as yet. Our current speculation is that oil lubrication provides a more air-tight seal between the punch and part that allows a higher vacuum to exist there. The vacuum between the punch and part restrains the local movement of the sheet away from the punch during the EM pulse event.



6111-T4, 1.0 mm thick actuator configuration II, path shown

***Figure 6:*** *Comparison of strain distribution along the test part centerline between conventional forming and EAIS forming .*



**a** - Conventional forming, no lubrication
**b** - Conventional forming with lubrication
**c** - EAIS process with lubrication
**d** – EAIS process , no lubrication
* two part average

***Figure 7:*** *Effect of oil lubrication of part blanks on draw depth*

## 2.3 Effect of Process Parameters

The process parameters, such as clamp load, punch advance, and EM pulse energy, significantly effect the draw depth and the strain distribution as well as the propensity of the sample to wrinkle. For example, in the experiment of Figure 5 the punch was advanced incrementally 2.5 mm after each discharge pulse until the punch load reached about 156 kN. Then, the punch advance was reduced to a displacement of 1.3 mm after each pulse until failure. This protocol generated the greatest draw depth of the trials.

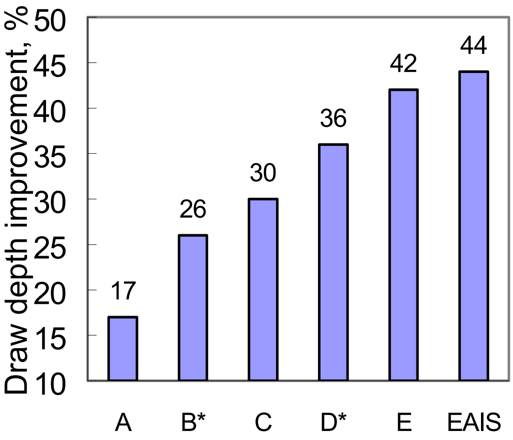
Aluminum stampings also experience greater problems with springback. An extension of the EAIS method can be envisioned to provide a means of controllable springback reduction. For actual parts the tooling could be designed to nearly bottom-out at the end of the forming sequence. In such tool sets a final pulse can be used to drive the workpiece material adjacent to the actuator against the die surface. With the proper pulse energy, a through thickness compressive plastic strain can be generated. EAIS actuator paths will generally run just inside the punch (male form) nose radius. A through thickness compressive straining of this region of the part will reduce the tendency of the part to open (springback) when released from the tooling. A variation of this technique has long been used in conventional stamping (most safely using hydraulic presses) by precisely under sizing the punch nose radius with respect to the matching die radius and material thickness so as to generate the compressive “coining” strain at the punch nose radius when the tooling is bottomed. The EAIS implementation brings the added advantages of the reducing tool form precision, press loading, and the ability to tune the effect during production by simply changing pulse energy.

## 2.4 Required Design Methodology

The progress with the stretched and drawn pan show that this process basically does work. Forming depths can be increased by broadly moving deformation energy to areas of a part that would not otherwise plastically strain. The coil configuration used was chosen based largely on convenience, rather than on an analysis of the required energies or strains. We will seek to develop a formal design methodology based largely on the concept of mapping the required deformation energy onto the blank and then designing coils and schedules of punch advancement and pulse energy that will optimize the ability to make the part.

## 2.5 Comparison with other methods

The EAIS process as described here was specifically developed to increase formability of otherwise difficult aluminum alloy stamping. Ideally, we would like to make comparisons to other processes using 6111-T4. In all cases, results included baseline data for the non-augmented process so that an internally consistent, percent improvement figure of merit could be generated. Of the stamping augmentation methods compared with the EAIS process in Figure 8, two were found (A and E) that used the same material and gauge as the EAIS trials (6111-T4, 1.0 mm). To broaden the comparison, it was decided that other processes could be included since the data was normalized, in a sense, by the use of an internal percent improvement figure. A more rigorous comparison would require data from the application of the EAIS method to the other materials. EAIS experiments with materials such as steel have not yet been conducted, so the total applicability of this process is unknown. The reduction of the process efficiency with reduction of workpiece conductivity is known from the underlying physics and our previous work. Lower EM efficiency may, however, not be critical in the application of the EAIS method to cases where the available virtual anti-friction effect is of greatest benefit. Further, the use of highly conductive driver sheets or claddings may be an option for optimizing the performance of EAIS with lower conductivity sheet metals.



A) Ref. [9] Li, Rui: Active draw bead, Non-symmetric Al-6111-T4 parts with 1mm thickness, Clamp Load: 36.65kN
B*) Ref. [3] Zhang, Z.: Lubrication, Deep drawing cup test, using steel type 08F with 0.4mm thickness, LDR increases from 1.84 (dry) to 2.00 (lubrication)
C) Ref. [8] Obermeyer, E. J.: Segmented blank-holders, aluminum alloy sheet cups
D*) Ref. [11] Takashi, J.: Ultrasonic vibration, deep drawing cups, average effect on SPCC (cold rolled steel), SPCE (cold rolled steel for deep drawing) and SUS304 (304 stainless steel) with a thickness of 0.5 mm.
E) Ref. [10] Bohn, M.: Active draw bead, Symmetric Al-6111-T4 parts with 1 mm thickness, Clamp load: 9.7 Mpa

***Figure 8:*** *Comparison of draw depth improvement of several advanced stamping methods and EAIS with lubrication only (B) included for reference*

## 3 Conclusions

Electromagnetically Assisted Incremental Stamping (EAIS) may offer the following advantages:

- A reduced reliance on forming lubricants, or possibly their elimination. There are large spin-off benefits if lubricants can be eliminated. Equipment for application and removal would disappear, as would a waste stream. Lubrication also causes problems for joining (spot welding) and coating application, especially with aluminum alloys.
- Fewer forming steps and/or tools will be required to make a component of the same complexity. For somewhat different reasons this translates to much lower cost both in short run manufacture and mass production. Conversely parts of higher complexity and performance (such as possibly including ribs to increase section modulus) could be made on essentially the same tooling systems that made their less complex counterparts.
- The ability to directly fabricate stronger and less formable materials. This can reduce materials cost in addition to the obvious large benefit for automotive work of being able to reduce mass and increase vehicle performance.
- The same tools used to augment the forming process can be used to reduce springback. This provides improved dimensional tolerance, again reduces die development time, and can be used to compensate for differences in the hardness or thickness of incoming materials.

## References

[1] *Vohnout,V.J.*: "A Hybrid Quasi-Static-Dynamic Process For Forming Large Sheet Metal Parts From Aluminum Alloys", Ph.D. Thesis, The Ohio State University, 1998, found at www.mse.eng.ohio-state.edu/~Daehn/vohnout/.

[2] *Daehn, G.S.; Shang, J.; Vohnout, V.J.*: Electromagnetically assisted sheet forming: enabling difficult shapes and materials by controlled energy distribution, Proceedings from Fourth MPMD, TMS, San Diego, 2003, p. 117-128, (2003).

[3] *Zhang, Z.; Chen, L.*: Study of the friction characteristics of lubricants and their affecting factors during drawing. J. of Mat. Proc. Tech. 63 (1997), p.144-147.

[4] *Wall, C.G.*: The laboratory evaluation of sheet-metal forming lubricants, Lubric Eng, 40, 139-147, (1984).

[5] *Peterson, D.A.*: "Progressive Dies: Principles and Practices of Design and Construction", SME, Dearborne, MI, (1994).

[6] *Goodwin, G.M.*: Applications of strain analysis to sheet metal forming in the press shop, SAE paper, No 680093, (1968).

[7] *Hashida, Y.; Wagoner, R. H.*: Experimental Analysis of Blank Holding Force Control in Sheet Forming, SAE Paper 930285, Sheet Metal Stamping Symposium, SAE SP-994, pp. 93-100, Warrendale, PA, (1993).

[8] *Obermeyer, M.; Majlessi, S.*: A review of recent advances in the application of blank-holder force towards improving the forming limits of sheet metal parts. Journal of Materials Processing Technology 75 (1998), p.222-234.

[9] *Li, Rui; Weinmann, Klaus J.*: Non-symmetric panel forming of AA 6111-T4 using active drawbeads, Proc. of TMS symposium , San-Diego, p.39-52 (1999).

[10] *Bohn, M.; Xu, S.; Weinmann, K.; Chen, C.; Chandra, A.*: Improving formability in sheet metal stamping with active drawbead technology. J.of Engineering materials and technology, Vol. 123, Oct., 2001, p.504-510.

[11] *Takashi, J.; Yukio, K.; Nobuyoshi, I.; Osamu, M; Eiji, M; Katsuhiko, I.; Hajime, H.:* An application of ultrasonic vibration to the deep drawing process, Journal of Materials Processing Technology 80–81 (1998), p.406–412.

[12] *Bruno, E.J.*, ed.: "High Velocity Forming of Metals", American Society of Tool and Manufacturing Engineers, Dearborne, MI, (1968).

[13] *Feynman, R.P.; Leightman, R.B.; Sands, M.L.* :"The Feynman Lectures on Physics", Addison-Wesley, Chapter 17, 2, (1989).

[14] *Wood, W.W.:* Experimental mechanics at velocity extremes, Exp. Mech., 19, 441, (1967).

[15] *Grady, D. E.; Benson*, *D. A.*,: Fragmentation of metal rings by electromagnetic loading., Experimental Mechanics: 393-400, (1983).

[16] R*egazzoni; G., Johnson; J.N., Follansbee, P.S.*: Theoretical study of the dynamic tensile test, J. Appl. Mech., 513, 519, (1986).

[17] *Wagoner, R. H.; Hu, X.; Daehn, G. S.; Ghosh S.*: The effect of inertia on tensile ductility, Metall. Trans., 1994, 25A, 2723-35.

[18] *Balanethiram, V. S.; Daehn, G. S.*: Hyperplasticity-increased forming limits at high workpiece velocities, Scripta Metall., 1994, 31, 515-520.