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Comparison of quasi-static and electrohydraulic free forming limits for DP600 and AA5182 sheets

Christopher Maris[a], Amir Hassannejadasl[a], Daniel E. Green[a,*], Jia Cheng[a], Sergey F. Golovashchenko[b], Alan J. Gillard[c], Yiteng Liang[a]

[a] Department of Mechanical, Automotive and Materials Engineering, University of Windsor, 401 Sunset Ave., Windsor, ON N9B 3P4, Canada
[b] Mechanical Engineering Department, Oakland University, 2200 North Squirrel Road, Rochester, MI, 48309, USA
[c] Ford Motor Company, Ford Research and Innovation Center, P.O. Box 2053, Mail Drop 3135 RIC, Dearborn, MI 48121-2053, USA

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ABSTRACT

Electrohydraulic forming is a pulsed metal forming process that uses the discharge of electrical energy across a pair of electrodes submerged in fluid to form sheet metal at high velocities. Pulsed metal forming processes, including electrohydraulic forming, have been shown to increase the formability of sheet metals. Although significant formability enhancement has been reported for electrohydraulic die forming, there have been conflicting reports about the formability in electrohydraulic free forming (EHFF). Numerical modeling was used to design sheet metal specimen geometries to generate data for specific regions of the EHFF forming limit curve. The electrohydraulic free forming specimens were formed with the precise amount of input energy to cause a neck at the center of the gauge section. The quasi-static and EHFF forming limit curves for both AA5182-O and DP600 sheets were determined in accordance with the conventional North American formability evaluation method to allow for direct comparison. It was found that the forming limits in EHFF increased by approximately 5% major strain for DP600 and 8% major strain for AA5182, relative to their respective as-received FLC.

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1. Introduction

Reducing vehicle weight, through the use of high strength steels and/or lower density materials such as aluminum (Cheah and Heywood, 2011), is one method that automotive manufacturers can employ to meet contemporary fuel economy targets. One of the barriers that limits the implementation of both high strength and low density materials is their relatively low formability compared to broadly-used mild steels. For this reason, considerable research is being carried out to develop pulsed forming processes, such as electromagnetic forming (EMF) and electrohydraulic forming (EHF). These processes, whose duration is on the order of hundreds of microseconds, are based on the high voltage discharge of capacitors through a conductive coil or a water filled chamber as described by Bruno (1968).

Recent interest in pulsed forming processes was stimulated by the results of Balanethiram and Daehn (1992, 1994) that indicated that formability could be enhanced by a factor of 5.5 for AA6061-T4, a factor of 3.5 for interstitial free (IF) iron and a factor of three for copper. More recently, Samei et al. (2013) observed that high-velocity impact of the sheet against the die in EHF leads to suppression of void nucleation and growth in dual phase steels and significantly delays the onset of failure. However, analysis of stresses in the die for pulsed pressure forming, performed by Ibrahim et al. (2013) indicated that the high-velocity of the blank required to achieve significant formability improvement causes significant plastic deformation that leads to fracture and accordingly shortens the lifespan of the forming dies.

In the EHF process (Fig. 1), a blank can be progressively formed into its final shape in one tool by multiple discharges of the electrode system in order to extend the life of the die, as described by Mamutov et al. (2015). Similarly, newer electrode systems, as described by Golovashchenko (2014), are capable of lowering the load on the electrode system if the discharges are conducted in multiple steps. However, in such a multi-pulse configuration, the blank is initially formed in free forming conditions without taking advantage of very high strain rates that are generated when the sheet contacts the die at high velocity. In order to produce a safe part with the EHF process, it is necessary to take into consideration the difference in formability of a sheet material when it is deformed in free-forming conditions (EHFF), where the strain rates

* Corresponding author.
E-mail address: dgreen@uwindsor.ca (D.E. Green).

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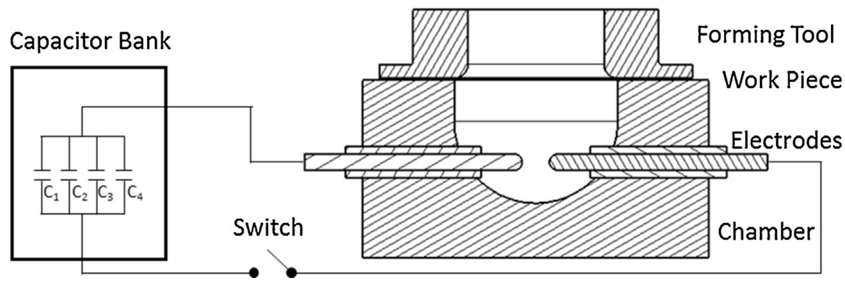

Fig. 1. Schematic of electrohydraulic forming.

Table 1
Chemistry of DP600 steel in weight percentage.

C	Mn	P	S	Si	Al	Cu	Ni	Cr
0.107	1.497	0.011	0.001	0.175	0.038	0.057	0.015	0.181

Sn	Mo	V	Nb	Ti	B	Ca	N	W	Sb
0.004	0.214	0.004	0.002	0.025	0.00022	0.0026	0.0061	0.0025	0.0013

are rather moderate, and in die-forming conditions (EHDF) where strain rates are much higher and through-thickness compressive and shear stresses have a significant effect.

The formability of sheet materials when there is significant impact between the workpiece and forming tool has been extensively studied, as outlined by Psyk et al. (2011). However, there are conflicting reports about the formability improvement that can be expected in high-velocity forming when the sheet-die interaction is insufficient or non-existent. Golovashchenko et al. (2013) reported no formability increase in radially split biaxial DP590 blanks that failed to completely fill the die in EHF. EMF experiments on aluminum alloys by Imbert et al. (2005), Oliveira et al. (2005), and Golovashchenko (2007) showed no formability improvement in free forming. In contrast, Dariani et al. (2009) showed moderate formability improvement in both AISI1045 steel and AA6061 aluminum using explosive free forming tests. Further complicating the evaluation of formability is the fact that the majority of the previous high-velocity formability investigations have reported only positive minor strains; this is because this strain state can be easily generated without modifying the blank geometry. To overcome this limitation, Dariani et al. (2009) and Rohatgi et al. (2014) designed specimen geometries to generate strain states with negative and near-zero minor strains in the gauge sections. However, in both attempts, the specimens were susceptible to cracking in the corners of the cut-outs prior to necking in the gauge section, which could result in potential errors.

In light of the incomplete and conflicting formability results that have been reported by several teams of researchers, the objective of the current research was to develop a robust methodology to determine the forming limits of sheet materials deformed in electrohydraulic free forming conditions. First, the quasi-static forming limits of two sheet materials were determined to provide a baseline from which to evaluate any formability changes resulting from EHFF. A numerical model of EHFF was used to design specimens for EHFF tests and then the forming limits of both sheet materials were determined after EHFF tests were conducted. Finally, the quasi-static and EHFF forming limits were compared to identify changes in formability.

2. Sheet materials

Two sheet materials of significant interest to the automotive industry were selected for this study: DP600 steel and AA5182-O aluminum, each having a nominal thickness of 1.5 mm. The chemistry of the DP600 steel is presented in Table 1, and the spectrographic analysis results for the AA5182-O are presented in Table 2

Table 2
Spectrographic analysis of AA5182-O aluminum in weight percentage.

Al	Mg	Mn	Fe	Si	Cu	Ti	Cr	Zn
94.878	5.02	0.37	0.24	0.041	0.015	0.005	0.004	<0.001

Table 3
Quasi-static mechanical properties of AA5182-O and DP600.

Material Parameter	AA5182-O	DP600
Elastic Modulus (GPa)	70	210
Yield Strength (MPa)	130	340
Ultimate Tensile Strength (MPa)	279	587
Strength Coefficient (K) (MPa)	531	963
Strain hardening exponent (n-value) (true strain)	0.286	0.184
Uniform elongation (engineering strain, %)	23.7	19.2
Total elongation (engineering strain, %)	26	29
Lankford coefficient (r_0)	0.727	0.687

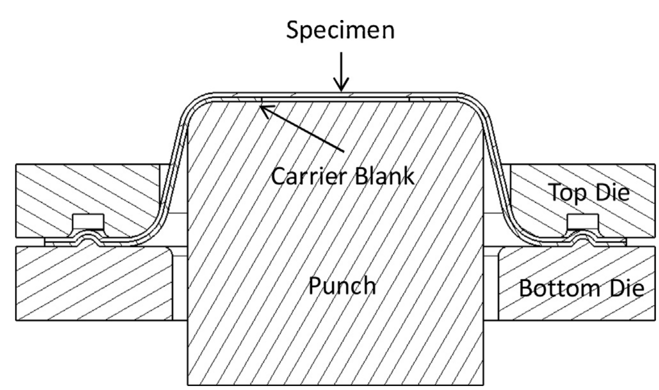

Fig. 2. Schematic diagram of the Marciniak test tooling.

Uniaxial tension tests were conducted to determine the quasi-static mechanical properties for both AA5182-O and DP600 at a strain rate of $8.3 \times 10^{-4}\,s^{-1}$, and these are summarized in Table 3. Tension test specimens were prepared from each of the 1.5 mm thick as-received materials according to the ASTM-E8 standard with gauge section dimensions of 76.2 mm length and 12.7 mm width. Tensile tests conducted by Rahmaan et al. (2014) at strain rates between $0.001\,s^{-1}$ and $1000\,s^{-1}$ showed a positive and small negative strain rate sensitivity for DP600 and AA5182-O, respectively.

3. Quasi-static formability

The Marciniak test (Marciniak et al., 1973) (Fig. 2) was used to determine the quasi-static formability of the two sheet materials in uniaxial tension, plane strain, and biaxial tension (Fig. 3). Although

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