Experimental Investigation of the Formability Improvement of Brass 260 and Al5182-O in Various Strain Rate using Hydrodynamic and Electrohydraulic Forming Methods

Amin Ashrafi Tafreshi*, Mehdi Zohoor
Department of Mechanical Engineering,
University of K.N.Toosi, Iran
E-mail: aminashrafi@mail.kntu.ac.ir*, mzohoor@kntu.ac.ir
*Corresponding author

Received: 11 May 2018, Revised: 10 July 2018, Accepted: 29 November 2018

Abstract: Studying the formability of the sheet metals have been the subject of many researches during the last decades. A number of experimental and numerical approaches were implemented to derive the formability diagrams of different materials. In this study, the formability of two mostly used alloys, Brass 260 and Al5182-O as low and moderate formability materials, were investigated respectively. The forming limit diagrams of both materials were determined by using three experimental approaches such as Nakazima quasi-static as low strain rate method, hydrodynamic forming method as the moderate strain rate method and Electrohydraulic Forming process as high strain rate method. Three experimental results of forming limit diagram with the various strain rate were compared graphically. The results have shown that both of the materials could withstand higher strains when the electrohydraulic forming method was applied on the specimens and consequently, the forming limit diagrams for Brass 260 and Al5182-O shift up by 11% and 14%, respectively. In addition, it was concluded that the hydrodynamic forming method improves the formability of the materials by 4% and 6% for Brass 260 and Al5182-O, respectively. The outcomes of this study indicated that the formability of both materials was improved significantly by increasing the strain rate.

Keywords: Electrohydraulic Forming Process (EHF), Forming Limit Diagrams (FLD), Formability, Hydrodynamic Forming Method, Nakazima Test

Reference: Ashrafi Tafreshi, A., Zohoor, M., "Experimental investigation of the formability improvement of Brass 260 and Al5182-O in various strain rate by using hydrodynamic and Electrohydraulic Forming methods ", Int J of Advanced Design and Manufacturing Technology, Vol. 11/No. 4, 2018, pp. 99–106.

Biographical notes: Amin Ashrafi Tafreshi is a PhD candidate in Mechanical Engineering from K.N. Toosi University of technology. His current research interest includes high stain rate forming and theoretical analysis of deformation. **Mehdi Zohoor** is Associate Professor of Mechanical engineering at K.N. Toosi University of technology. He received his MSc and PhD in Mechanical engineering from Birmingham University of England and a BSc in mechanical engineering from the University of the Bangalore, India. His current research focuses on modern manufacturing processes and automation in manufacturing.

1 INTRODUCTION

The major responsibility of production engineering concerns with the low consumption of fuel and natural resources to build up facilities and other equipment. One of the greatest industry that their products directly affect the environment and determine the quality of living condition of major cities is the car production industry. These facilities consume considerable fraction of sheet metal products to produce varieties of parts. As such, engineers should focus on the weight reduction of automobiles by using new and innovative technologies in the production lines and implementing new and light materials with considerable strength to weight ratio to reduce the fuel consumption of this every-day-growing industry. One of the promising solutions is using high strength alloys that could have a significant impact on the competitive market of car productions. However, forming these materials suffers from low formability issues in comparison to mild steel that is known for its high formability in quasi-static forming processes. In order to overcome this obstacle, lots of scientists have done research on better perceiving the forming process of sheet metals and increasing the formability of them by implementing relatively new high speed forming processes such as Electro-Hydraulic Forming (EHF), Electromagnetic Forming (EM) and Explosive Forming (EF). The formability of high strength alloys could be increased significantly by these processes since they employ very large strain rates during forming time that is limited to a few milliseconds. Among these processes, the EHF process has the potential to be implemented in the industrial companies as a feasible forming method due to its practical advantages over the other two methods. In this process, a very high electrical energy stored in the capacitor banks is released between two electrodes submerged in the water. This sudden electrical discharge energy evaporates the water between two electrodes and generates shock waves that propagate outward [1] and applies pressure on the workpiece.

There has been quite a number of researches focused on the formability study of various sheet metals in the EHF and other high strain rate processes. Balanethiram and Daehn [2], [3] studied the effect of using EHF on the free-forming of interstitial free iron (IF) and copper sheets. They obtained the Forming Limit Diagram (FLD) for both conventional and EHF processes and reported that the formability increased by the factor of 3 and 5.5 for IF and copper, respectively, while the sheet was formed using EHF method in comparison to the conventional forming method. They interpreted the increased formability as the inertia effects in stabilizing neck growth in the sheet material. Formability of Al 6061-T6 and AISI 1045 sheets were assessed by Dariani et al. [4] by obtaining the FLD from both high speed forming and quasi-static forming processes. They reported significant improvement in formability when using the high strain rate deformation state in the forming process. Rohatgi et al. [5] implemented the EHF process on free-forming of AA5182-O sheets. They used digital image correlation (DIC) technique to evaluate the strain, strain rate and velocity that the sheet undergoes during the process and concluded that every location on the sheet has its own unique history. Again, Rohatgi et al. [6] implemented the same technique and quantified the formability of Al 5182-O alloy sheet under free-forming and conical-die forming condition. They reported the relative improvement of 2.5 and 6.5 for free-forming and conical-die EHF process, respectively. A.J. Gillard et al. [7] studied the formability improvement of DP780 and DP980 by means of comparing the dome height of EHF and conventional hydro-formed sheets using V-shaped and conical die. They also used numerical analysis to further investigate the forming process. The authors reported considerable improvement in formability of the sheets using EHF process due to the high strain rate effect. Maris et al. [8] investigated the formability improvement of AA5182-O and DP600 sheets under both quasi-static and electrohydraulic free forming. They evaluated the FLC of DP600 steel sheet that showed approximately 5% improvement in formability in comparison to quasi-static FLC obtained from Marciniak test. Also, they reported that AA5182-O sheet represented 8% improvement in formability when the FLC was calculated from electrohydraulic free forming than implementing the conventional quasi-static process. There are other researches that emphasized on the considerable effect of impact between the die and workpiece on the formability enhancement of various kind of materials [9-12].

As pointed out in the literature, the forming limit diagrams are conventionally used as the representative of formability of materials and were extensively studied by numerous researches via quasi-static and high speed forming processes. In the present study, the FLD of Brass 260 alloy was obtained with several approaches since this alloy demonstrates a large variety of mechanical properties such as low elongation rate. In addition, the FLD of the conventional Al5182-O alloy was also evaluated to better show the formability improvement of different materials under different strain rates. Therefore, beside Nakazima quasi-static method, the hydrodynamic and the electrohydraulic free forming methods were applied on the prepared specimens to determine formability of the deformed sheets under a variety of strain rate values. For the best knowledge of the authors, there has been no report regarding the formability improvement of Al5182-O and Brass 260 by means of implementing three different forming procedures as low, moderate and high strain rate methods.

2 UNIAXIAL TENSILE STRESS TEST

Uniaxial tensile stress tests are conducted on specimens of both Brass 260 and Al5182-O. As the heat treatment of the Brass 260 changes, the mechanical behavior and elongation of the aforementioned alloy vary in a wide range [13]. As such, the uniaxial tensile test is essential to assure the low formability of the material by obtaining the failure elongation of the material during the test. "Fig. 1" demonstrates dimensions of the uniaxial tensile test specimens. These specimens were prepared by the wire-cut process according to ASTM E8 [14]. "Table 1" represents the data obtained from the uniaxial tensile test of the specimens for Brass 260 and Al5182-O.

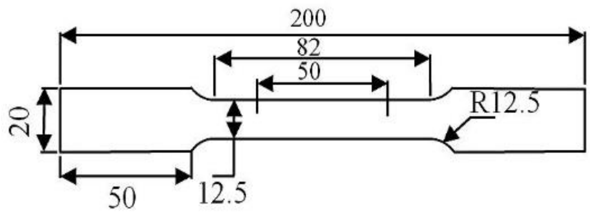


Fig. 1 Dimensions of uniaxial tensile test specimens (mm) [14].

Furthermore, the spectrographic analysis is performed on the Brass 260 and Al5182-O samples to obtain the chemical composition of the implemented material and the results are shown in "Table 2".

Table 1 The results from the uniaxial tensile test of Brass 260 and Al5182-O

	Density (g/cm^3)	Elastic Modulus (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
Brass 260	8.53	110	530	550	3
Al5182-O	2.7	70	130	279	26

Table 2 The chemical composition of Brass 260 and Al5182-O obtained from the spectrographic analysis (% weight)

Cu	Zn	Fe	Pb	Al	Si	Mg	Mn
68.5-71.5	31.5-28.5	< 0.05	< 0.07	-	-	-	-
0.015	-	0.24	-	94.88	0.041	5.02	0.37

3 QUASI-STATIC METHODOLOGY

As pointed out in the literature, the high speed forming methods have a potential in increasing formability of sheet metals. In order to investigate the formability improvement in EHF process, it is essential to have quasi-static forming limit diagrams as the standard FLD of the material and compare the results to indicate the possible formability improvement. So, the uniform circular grids with 2.5 mm diameter were electro-etched on the blanks to measure major/minor strains after necking occurred in the specimen ("Fig. 2"). Two different strain distribution that could occur in the forming process is demonstrated in "Fig. 3". As the specimen deforms, the circular pattern of the grids changes to the oval-shaped pattern in the case of uniaxial tension and plain strain conditions. The closer to the necking region of the specimen, the greater the ellipticity. For the biaxial state, the circular grids are preserved without noticeable inhomogeneous change in diameter of the grids.

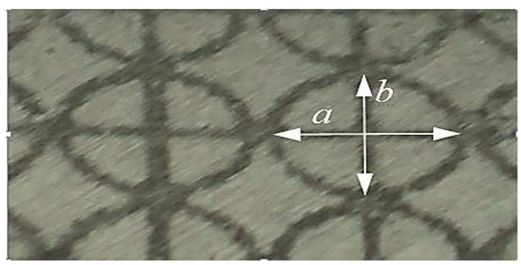


Fig. 2 Specimen after tensile stress test: (a): larger diameter and (b): smaller diameter, of the deformed grid.

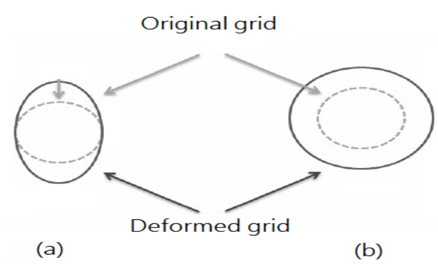


Fig. 3 Two different strain distribution of deformed specimens: (a): plane strain ($\varepsilon_1 > 0, \varepsilon_2 = 0$) and (b): biaxial ($\varepsilon_1 = \varepsilon_2 > 0$) states.

The Nakazima methodology is adopted to have different strain distribution in the necking region of the formed parts and then draw the FLD. The blanks used in Nakazima test has a nominal thickness of 1 mm and diameter of 150 mm. It is noted that a very extensive number of quasi-static experiments were conducted to omit some practical errors due to sudden fracture of sheets under load. “Fig. 4” also shows the schematic configuration of the Nakazima test applied to the specimens.

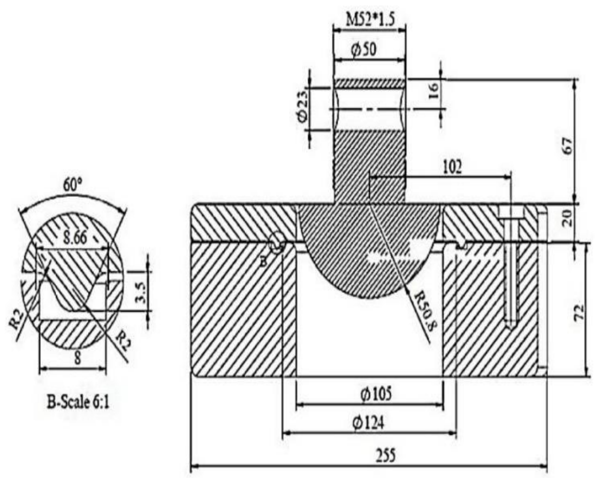


Fig. 4 Schematic representation of the Nakazima test configuration (mm) [15].

The specimens were clamped prior to punch impact with 750 KN force to ensure that there would be no draw-in of the blank into the die cavity. So, the hemispherical punch with the diameter of 100 mm moves toward the carrier blank at the rate of 0.1 mm/s. The punch vertical movement was carefully observed and controlled to prevent the specimens from cracking, since sudden cracking of the deformed part will result in an undesirable error in the measurement of the major/minor strains. Hence, the punch was stopped when necks were noticed or detected by finger touch or visual observation. The punch was immediately stopped to avoid further damage and split.
Using “Eq. (1)”, the strains in three normal directions were calculated assuming incompressible condition:

$$\varepsilon_l = \ln\frac{a}{d_0},\ \varepsilon_w = \ln\frac{b}{d_0},\ \varepsilon_t = -\left(\varepsilon_l + \varepsilon_w\right) \qquad (1)$$

Where d_0 is the initial diameter of the grids, a,b are the larger and smaller diameters of the deformed grids, respectively. And ε_l , ε_w and ε_t are the true stains in longitudinal, traversal and out-of-plane strains, respectively.

4 HYDRODYNAMIC FORMING METHOD

The hydrodynamic forming method refers to using fluid pressure applied to the workpiece in a very short time. In this method, a large mass is dropped on a piston that is inside a cylinder filled with fluid (water or oil) and the sudden impact generates very high pressure inside the fluid. The pressure pulse is transferred through the medium fluid in all directions and finally reaches the specimen clamped with bolts to ensure no slipping occurs between the die and workpiece [16]. “Fig. 5” represents the schematic of the hydrodynamic forming method implemented in the present study. The main advantages of using the hydrodynamic forming method can be described as its resemblance to electrohydraulic forming method, both processes are categorized as non-contact forming methods. Thus, a rational forming improvement comparison of both Brass 260 and Al5182-O sheets by means of using moderate and high strain rates process could be stablished.

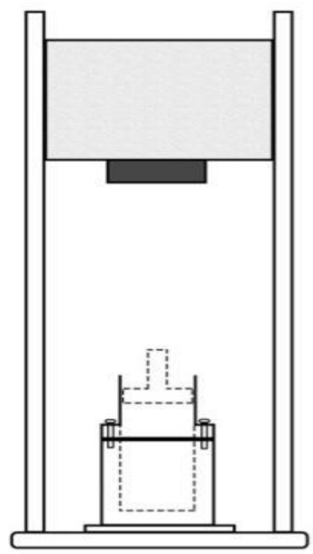


Fig. 5 Schematic of hydrodynamic equipment used as the moderate strain rate forming method.

The Nakazima test specimens prepared for quasi-static process would not yield desirable results in the hydrodynamic forming tests as the water can easily flow through the holes considered on the blanks to generate a different distribution of strain ratios. Accordingly, the blank configuration differs from the quasi-static test in the hydrodynamic testing. Maris et al. [8] utilized finite elements analysis in order to determine the initial shape of the blanks for generating different ratios of major to the minor strain in the necking area of the formed parts when they employed the electrohydraulic forming (EHF) process on the specimens. Since the water and solid interaction highly affects the forming process, as the water escapes from the large cut-outs considered in the initial blank, it is recommended to employ numerical models in order to save time and cost to finalize the shape of these cut-outs in the initial blank design. As such, the initial blanks are considered accordingly to [8]. "Fig. 7" " illustrates the configurations and dimensions of the initial blanks used in both the hydrodynamic and EHF processes.

As recommended in [8], the cut-outs were designed in such a way that any significant stress concentration could be avoided and the highest major strains would be generated at the center of the specimen where the necking might occur. The blanks used in the hydrodynamic and EHF processes have a nominal diameter of 120 mm and thickness of 1 mm. In this process, a 50.8 Kg mass is dropped from different altitudes so that the required necking emerges on every configuration of the specimens, for both materials.

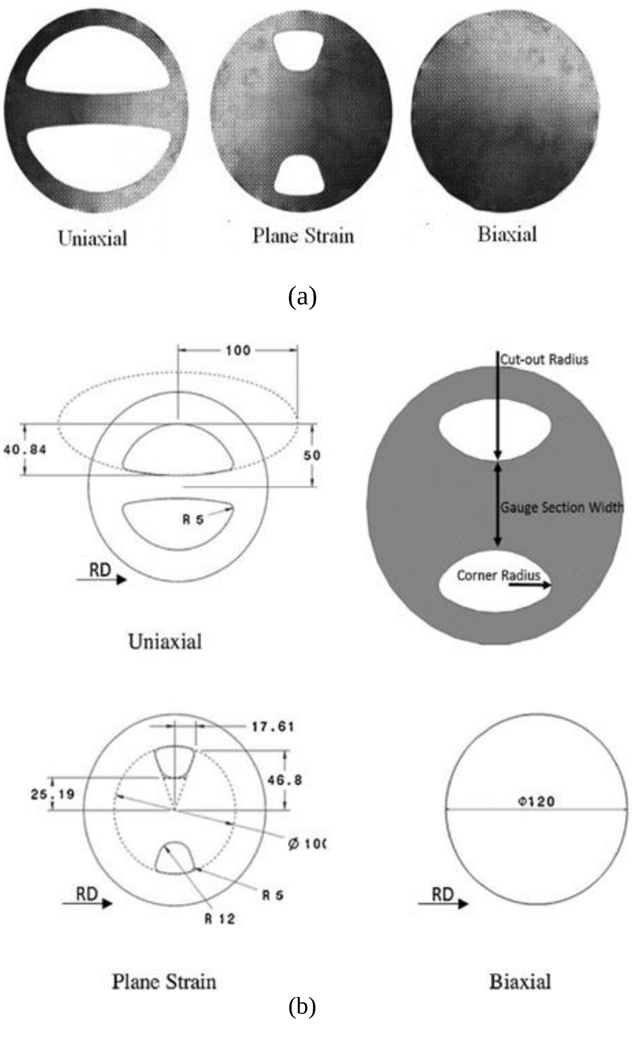


Fig. 6 (a): Different configurations and dimensions of initial blank to generate distinct major strains ratio (mm) [8] and (b): blanks' configuration of Brass 260 and Al5182-O sheets in hydrodynamic and EHF processes.

5 ELECTROHYDRAULIC FORMING PROCEDURE

In order to have a sensible comparison between the results of electrohydraulic forming method and hydrodynamic method, as described before, the same specimen configuration and dimensions as the hydrodynamic method are utilized here in the EHF process as well ("Fig. 6").

According to "Fig. 7", a hemispherical chamber was designed and two electrodes were embedded inside the chamber with coated high voltage resistant material to prevent any possible undesirable short circuit between die and electrodes. A high clarity copper wire with a diameter of 0.3 mm connects the electrodes. Not only does this wire usage facilitate the electrical discharge between two electrodes, but it also increases the repeatability of the process substantially. The chamber is filled with fresh water and the specimen is clamped with tightening the bolts to avoid the blank from any sudden draw-in. It also should be noted that the chamber water is changed after every electrical discharge since the properties of water changes and this phenomenon can have a negative impact on the repeatability of the process. Afterwards, the air is sucked out of the upper part of the chamber to avoid any possible counter force of the confined air.

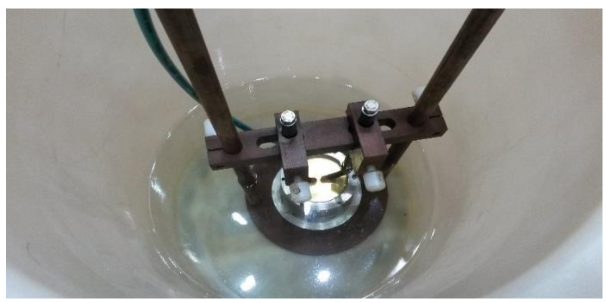


Fig. 7 The chamber used in the EHF.

The electrical discharge energy is calculated using the voltage and discharge current. "Fig. 8" shows the electrical facilities used for generating high voltage and charging the capacitor blocks. Electrohydraulic forming tests are performed on the specimens for every configuration in order to obtain the approximate voltage required for charging the capacitors so that the necking occurs in the formed part. The voltage can vary up to 50 KV that leads to charging the four capacitor blocks with 20 μF capacity each. Since the discharge energy plays a major role in the forming process of the sheet, it is essential to control it carefully. As mentioned earlier, if the electrical energy discharge in the water exceeds the certain value, the necking would not be achieved and the specimen will end with wrong fracture and the limiting strains. "Fig. 9" shows the electrohydraulic deformed specimen.

Fig. 8 Electrical equipment utilized in this study for generating high voltage and storing electrical energy

"Fig. 10" also shows the deformation modes of the EHF-formed parts, safe mode refers to the state that the electrical discharge energy was not high enough to result in necking or failure, split or failure mode emerged when the discharge energy exceeds the sustainable limit of the sheet material and finally, necked state is regarded as the state that the discharge energy is high enough to induce some necking in the critical area of the specimen.

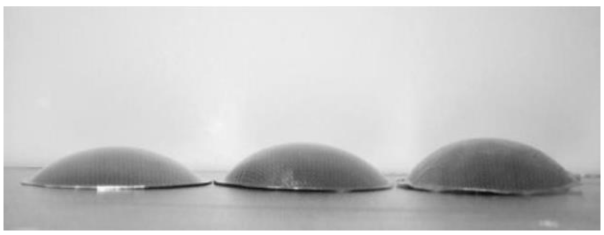


Fig. 9 Electrohydraulic deformed specimen.

As described in the literature, numerical analysis was extensively used to determine the necessary electrical discharge energy required to generate the necking state in the distinct configurations of the electrohydraulic forming process. The required energy is dependent on various parameters that significantly have an impact on the final shape and state of every experimental configuration. Nevertheless, the numerical analysis cannot include all practical issues exists in the electrohydraulic process.

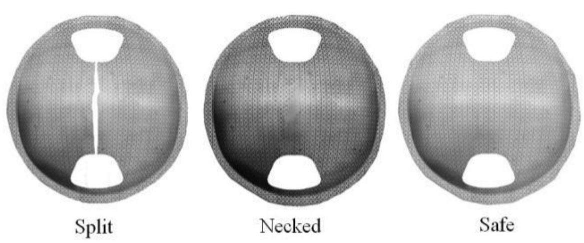


Fig. 10 Safe, necked and split (failure) modes of the EHF-formed parts.

Since the numerical calculations were not implemented in this study, an incremental trial scheme is employed to attain the required discharge energy for every configuration in the electrohydraulic forming process. "Fig. 11" represents the loading path for different configurations in electrohydraulic forming process for Brass. As it can be seen, the charge voltage and consequently, the electrical discharge energy increased in an incremental manner to achieve the desirable necking mode in every configuration for both materials. Afterward, the experiments repeated at least six times to ensure the repeatability and reliability of the tests and results.

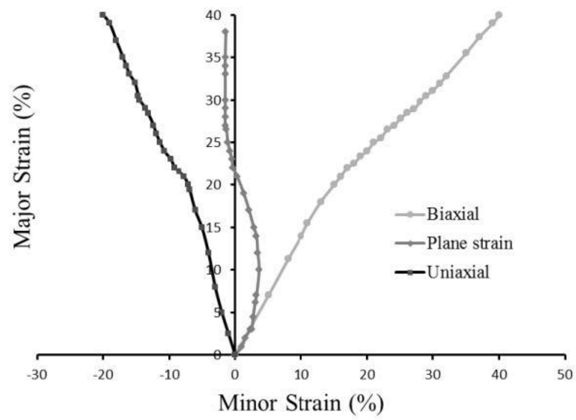


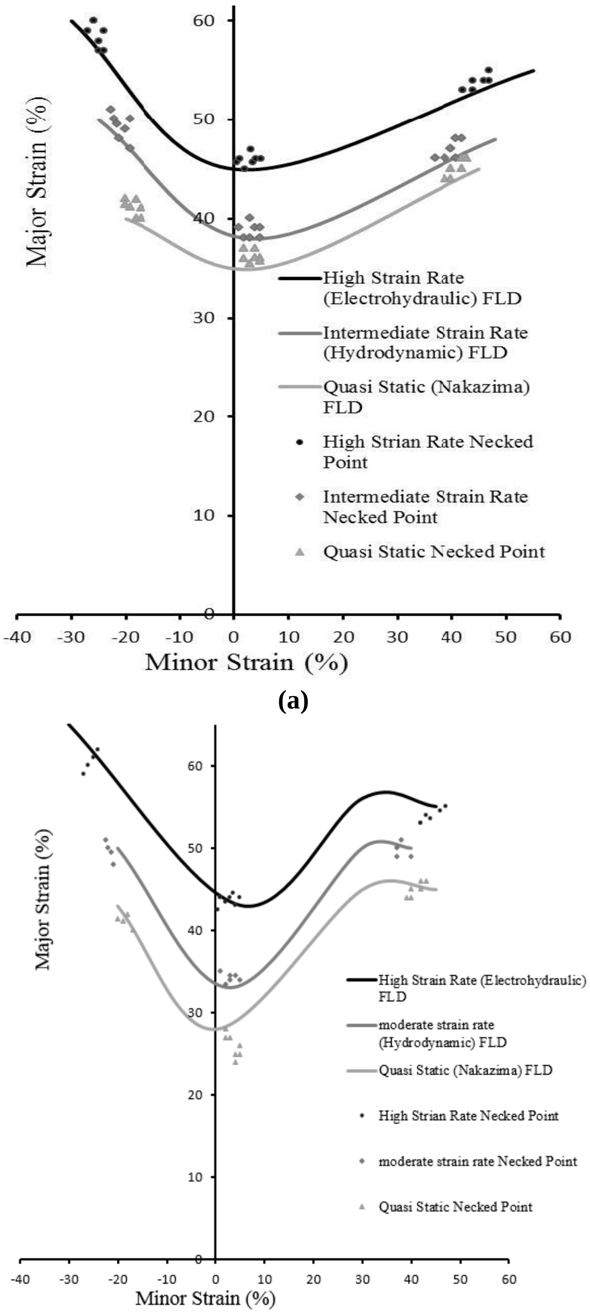
Fig. 11 The strain path of three distinct configurations in the EHF process with incremental increasing of the discharge voltage.

6 RESULTS AND DISCUSSION

Numerous experimental tests conducted on both Brass 260 and Al5182-O sheets to evaluate its FLD under different conditions by implementing the Nakazima test, the hydrodynamic forming method, and the electrohydraulic forming process. Some researchers [17-20] reported conflicting results on the formability improvement of some materials when utilizing high strain rates processes. Therefore, it is essential to investigate the formability improvement of materials more thoroughly. To obtain a reliable conclusion about this matter, the experimental tests, Nakazima, hydrodynamic and EHF tests were repeated several times to avoid some accidental results. "Fig. 12" represents the obtained forming limit diagram for Brass 260 and Al5182-O under different strain rate states. All the necking points are pinned on the major-minor plane to demonstrate critical condition that necking occurred on specimens.

According to "Fig. 12(a)", for an arbitrary necking minor strain value, the major limiting strain obtained from the hydrodynamic and EHF yields higher values than the corresponding one obtained from Nakazima quasi-static test.

It shows approximately 11% and 4% improvement in formability of Brass 260 when the hydrodynamic and EHF processes are employed, respectively. "Fig. 12(b)" demonstrates about 14% and 6% improvement in formability of Al51-82 using the hydrodynamic and EHF methods in comparison to Nakazima quasi-static test, respectively. As discussed by Balanethiram et al. [2], [3], the formability improvement is probably due to the inertia effects in stabilizing neck growth in the sheet material.



(b)

Fig. 12 The obtained FLDs from quasi-static and electrohydraulic forming methods for: (a): Brass 260 and (b): Al5182-O alloys.

7 CONCLUSION

In the present study, the formability of Brass 260 and Al5182-O sheets with 3% and 21% failure elongations were investigated through Nakazima quasi-static, hydrodynamic and electrohydraulic forming processes. The specimens were prepared in such a way that could generate the important and desirable strain states such as plane strain and biaxial strain states in all three experimental procedures. For a reasonable comparison between the obtained results of the hydrodynamic forming and electrohydraulic forming methods, configurations and dimensions of the specimens were taken as the same. The necking state was carefully observed and detected so that the results have consistency to be compared with each other. Regarding conflicting reports in the literature about formability improvement of materials using high strain forming processes, this study showed that the formability of Brass 260 and Al5182-O noticeably improved by 11% and 14% in comparison to quasi-static forming methods using electrohydraulic forming method, respectively. Furthermore, the formability of the Brass 260 and Al5182-O improved approximately by 4% and 6% employing moderate strain rate hydrodynamic forming process, respectively. Therefore, it is concluded that the electrohydraulic forming method has the advantage over both conventional quasi-static and the hydrodynamic forming methods and can increase the formability of materials categorized as low formability alloys (such as Brass 260) and ductile materials (such as Al5182-O). The present study shows the considerable effect of the strain rate on the behavior of materials that undergo plastic deformations during forming processes. As the deformation rate increases, both the materials can sustain the higher stresses in comparison to low strain rate deformations. The yield and ultimate tensile stress limits increase as the deformation takes place in higher strain rate states. Therefore, obtaining comprehensive knowledge of materials' performance under different conditions may result in higher efficiency product designs.

REFERENCES

[1] Bruno, E., High-Velocity Forming of Metals, American Society of Tool and Manufacturing Engineers, 1968.

[2] Balanethiram, V., Daehn,G. S., Enhanced Formability of Interstitial Free Iron at High Strain Rates, Scripta Metallurgica et Materialia, Vol. 27, No.12, 1992, pp. 1783-1788.

[3] Balanethiram, V., Daehn, G. S., Hyperplasticity: Increased Forming Limits at High Workpiece Velocity, Scripta Metallurgica et Materialia, Vol. 30, No. 4, 1994, pp. 515-520.

[4] Dariani, B., Liaghat, G., and Gerdooei, M., Experimental Investigation of Sheet Metal Formability Under Various Strain Rates, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 223, No. 6, 2009, pp. 703-712.

[5] A. Rohatgi, A., Stephens, E. V., Soulami, A., Davies, R. W., and Smith, M. T., Experimental Characterization of Sheet Metal Deformation During Electro-Hydraulic Forming, Journal of Materials Processing Technology, Vol. 211, No.11, 2011, pp. 1824-1833.

[6] Rohatgi, A., Soulami, A., Stephens, E. V., Davies, R. W., and Smith, M. T., An Investigation of Enhanced Formability in AA5182-O Al During High-Rate Free-Forming at Room-Temperature: Quantification of Deformation History, Journal of Materials Processing Technology, Vol. 214, No. 3, 2014, pp. 722-732.

[7] Gillard, A. J., Golovashchenko, S. F., and Mamutov, A. V., Effect of Quasi-Static prestrain on the Formability of Dual Phase Steels in Electrohydraulic Forming, Journal of Manufacturing Processes, Vol. 15, No. 2, 2013, pp. 201-218.

[8] Maris, C., Hassannejadasl, A., Green, D. E., Cheng, J., Golovashchenko, S. F., Gillard, A. J., and Liang, Y., Comparison of Quasi-Static and Electrohydraulic Free Forming Limits for DP600 and AA5182 Sheets, Journal of Materials Processing Technology, Vol. 235, No. 1, 2016, pp. 206-219.

[9] Cheng, J., Green, D. E., and Golovashchenko, S. F., Formability Enhancement of DP600 Steel Sheets in Electro-Hydraulic Die Forming, Journal of Materials Processing Technology, Vol. 244, No. 1, 2017, pp. 178-189.

[10] Hajializadeh, F., Mashhadi, M. M., Investigation and Numerical Analysis of Impulsive Hydroforming of Aluminum 6061-T6 Tube, Journal of Manufacturing Processes, Vol. 20, No. 1, 2015, pp. 257-273.

[11] Hassannejadasl, A., Green, D. E., Golovashchenko, S. F., Samei, J., and Maris, C., Numerical Modelling of Electrohydraulic Free-Forming and Die-Forming of DP590 Steel, Journal of Manufacturing Processes, Vol. 16, No. 3, 2014, pp. 391-404.

[12] Mamutov, A. V., Golovashchenko, S. F., Mamutov, V. S., and Bonnen, J. J., Modeling of Electrohydraulic Forming of Sheet Metal Parts, Journal of Materials Processing Technology, Vol. 219, No. 1, 2015, pp. 84-100.

[13] U. Standard, ASTM B36/B36M-08a, Standard Specification for Brass Plate, Sheet, Strip, and Rolled Bar, ASTM International, West Conshohocken, PA, 2003.

[14] E. ASTM, 8M. Standard Test Methods of Tension Testing of Metallic Materials [metric], Annual book of ASTM standards, Vol. 3, 2003.

[15] 12004-2:, Metallic Materials–Sheet and Strip–Determination of Forming-Limit Curves–Part 2: Determination of Forming-Limit Curves in the Laboratory, ISO, Vol. 1, 2008, pp. 1-27.

[16] Green, D. E., Black, K. C., A Visual Technique to Determine the Forming Limit for Sheet Materials, in, SAE Technical Paper, Vol.111, No.5, 2002.

[17] Golovashchenko, S. F., Material Formability and Coil Design in Electromagnetic Forming, Journal of Materials Engineering and Performance, Vol. 16, No. 3, 2007, pp. 314-320.

[18] Oliveira, D., Worswick, M., Finn, M., and Newman, D., Electromagnetic Forming of Aluminum Alloy Sheet: Free-Form and Cavity Fill Experiments and Model, Journal of Materials Processing Technology, Vol. 170, No. 1-2, 2005, pp. 350-362.

[19] Imbert, J., Winkler, S., Worswick, M., Oliveira, D., and Golovashchenko, S., The Effect of Tool–Sheet Interaction on Damage Evolution in Electromagnetic Forming of Aluminum Alloy Sheet, Journal of Engineering Materials and Technology, Vol. 127, No. 1, 2005, pp. 145-153.

[20] Golovashchenko, S. F., Gillard, A. J., and Mamutov, A. V., Formability of Dual Phase Steels in Electrohydraulic Forming, Journal of Materials Processing Technology, Vol. 213, No. 7, 2013, pp. 1191-1212.