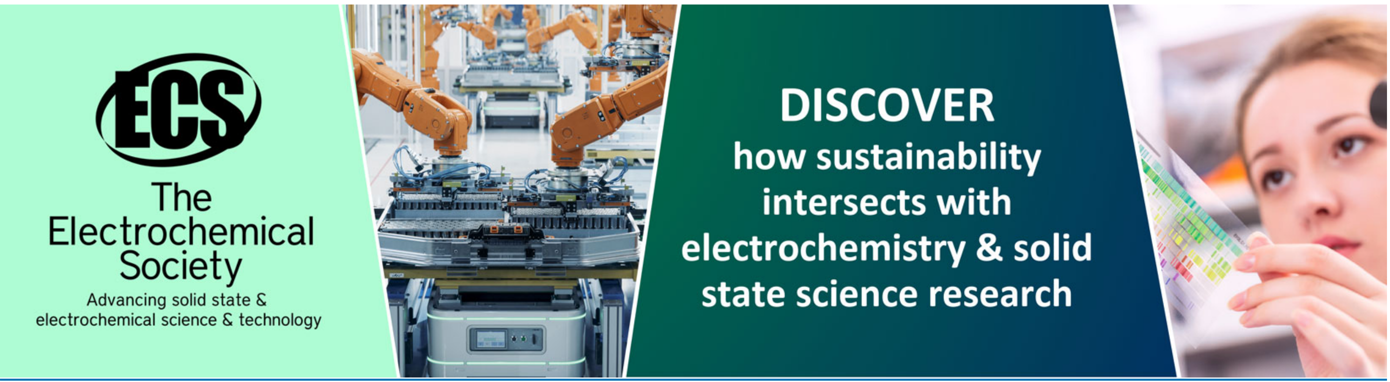
IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Development of novel forming limit curve testing method



Development of novel forming limit curve testing method

Z Deng[1*] and J P McGuire[1]

[1]Aleris North American Automotive Innovation Center, Madison Heights, MI 48071, USA

Email: Zhi.Deng@aleris.com

Abstract. A new concept of the forming limit curve testing method has been developed for evaluating sheet metal formability. This new method complies with the current ISO 12004-2 standard, and has been verified by the numerical analysis in terms of specimen deformation, strain path characterization and lubrication effect. It combines the advantages from both the standardized Marciniak and Nakajima tests, deforming the sheet metal materials under a complicated deformation mode following the linear strain path without using a carry blank. By comparing the simulation results with the experimental measurements, it is proven that this testing method works with the thinner and thicker sheet metals for a variety of blank geometries.

1. Introduction

The forming limit curve (FLC) has been widely used to characterize sheet metal formability. It is also an essential criterion in the automotive industry for designing stamping dies and processes to make failure-free products. The FLC developed by Keeler [1] and Goodwin [2] is a graphic representation of a series of the limit major and minor strain combinations associated with the onset of the through-thickness or localized necking under certain loading conditions. There are existing two standardized and well-known tests to experimentally measure the forming limit curves of sheet metals, namely the Marciniak test [3] and Nakajima test [4]. The Marciniak test uses a cylindrical flat-head punch to deform a sheet metal specimen. In this test, a carrier blank with a central hole cut is used to ensure the maximum plastic deformation generated in the central flat area of the specimen. With this testing setup, the major and minor strain limits can be measured under the linear strain path without the frictional effect. But the requirement of a carrier blank complicates the testing procedure and make it less popular. Compared to the Marciniak test, the Nakajima test is easier to conduct without using a carrier blank. The testing sample material is deformed with a hemispherical punch under a more complicated straining condition, which is more favorable to the real stamping applications. However, the forming limit curves measured from the Nakajima test have significant differences in strain limit values and FLC shape compared to the ones from the Marciniak test [5-7]. The major contributor to these differences is the strain path effect resulting from sheet curvature, contact pressure and frictional condition during the specimen deformation in the Nakajima test. It is found by many researchers [6, 8-10] that the forming limit curves measured under the nonlinear strain paths would lead to misinterpretation and errors in determining the strain limits, which is also a major concern in industrial applications of the FLC. As one of the efforts to solve the application problems associated with the FLCs measured with the Nakajima test, Min et al [6] proposed a mathematical procedure to compensate for the nonlinear strain path effect. Their work indicated that the FLCs measured from the Nakajima test are merged into the ones measured from the Marciniak test after compensation. Therefore, it is of great benefit to develop a new FLC testing method having the combined advantages from both the Marciniak and Nakajima tests.

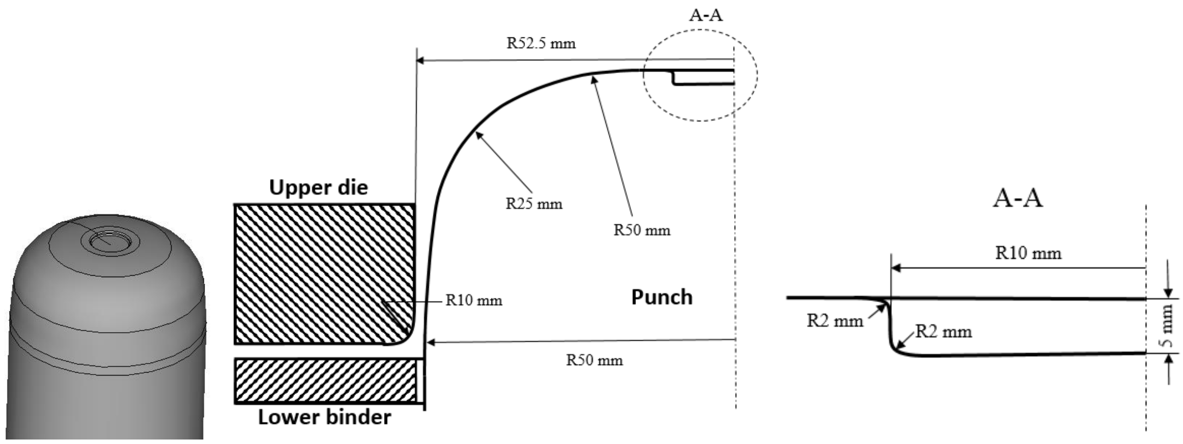
This paper presents a newly developed FLC testing method, aiming at keeping the simplicity of the Nakajima testing setup and the linear strain path inherent in the Marciniak test. In the new test, the specimen is stretched under a complicated deformation mode following the linear strain path. It does not require a carrier blank and also eliminates the frictional effect in the critical deformation area. By means of the numerical simulations, the testing tool geometry is optimized to ensure that the strain limits are achieved in the central area of a testing specimen, under the linear strain path, and are sensitive to the specimen geometries. This new concept was also validated with the experimentally measured FLCs of the 1.0 mm thick 5xxx and 1.7 mm thick 6xxx-T4 aluminum alloys in the virtual tryout.

2. Testing tool development

Both the Marciniak test and Nakajima test have been standardized for a long time, as detailed in the ISO 12004-2 [11] to experimentally measure the forming limit curves in the laboratory. The new testing tool development is based on this widely accepted ISO standard. The main focus of the new development is to modify the punch geometry in order to create a unique deformation condition for the FLC testing. Except the modified punch geometry, all of the other testing conditions and requirements are remained the same as described in the ISO 12004-2.

2.1 Punch geometry

The criteria for developing the new punch geometry are: (1) to ensure the maximum plastic deformation occurring in the central region of a testing specimen; (2) to generate the linear strain path in the measuring area of the interest; (3) to eliminate the frictional effect and (4) to produce the major and minor strain values being sensitive to the changes in specimen width. After numerous trials, the punch geometry has been optimized to meet all of the above-mentioned criteria and is illustrated in Figure 1.



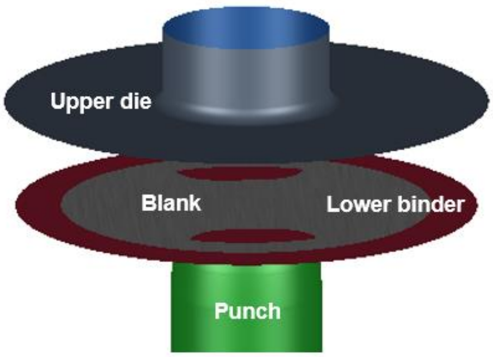
(a) (b) (c)

Figure 1. (a) The developed punch geometry, (b) its dimensions and (c) the local details on the top.

It is seen from Figure 1 that the newly developed tooling adapts the standard tooling setup, clearance between the upper die and the punch, and the punch diameter. However, the new punch geometry is not a simply modification of the existing punch geometry used in the Marciniak test and Nakajima test. It has a unique sectional profile, starting with a flat head on the top, transferring to a bigger curvature and eventually merging to the standard punch radius with a smaller curvature. This unique punch sectional profile creates a complicated strain condition, centralizes the maximum specimen deformation staying on the top of the punch, and maintains a sufficient stretching on a specimen over the entire testing process. In the new development, a circular cut-off is applied to the top area of the punch which eliminates the direct contact between the testing material and the punch. This feature provides great advantages of frictionless effect over the standard Nakajima test, and also of linear strain path without a carrier blank over the standard Marciniak test.

2.2 Numerical analysis

Numerous numerical analysis has been conducted to validate this new concept, as usually done for real stamping engineering. The analysis was carried out in AutoForm^plus R7, using three node triangle elements with 11 layers, adaptively tangential refinement and modified "Final Validation Accuracy" settings. The testing speed as stated in the ISO 12004-2 standard was adapted. For controlling simulation time step, the maximum tool and material displacement was defined as 0.2 mm in all the simulations. The analysis was focus on aluminum alloys at the thinner and thicker gages. As demonstrated earlier [12], the BBC 2005 yield criterion and the combined Swift/Hockett-Sherby strain-hardening model are the best choice to describe the aluminum material behavior and thus solely used for the current validation. Figure 2 shows the tooling setup adopted in AutoForm simulations. The blank geometry used in simulations is illustrated in Figure 3, where the width "W" of the specimen varies from 50 mm to 245 mm and the outer boundary of the specimen is 245 mm in diameter.



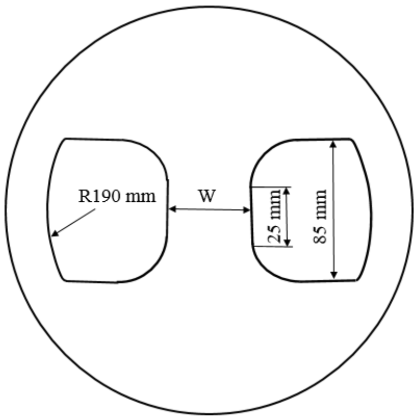
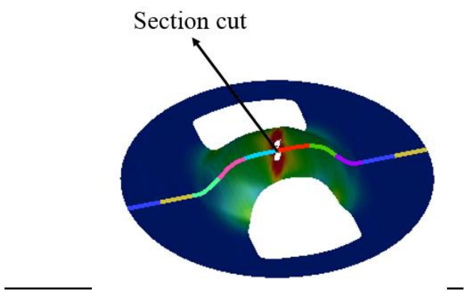


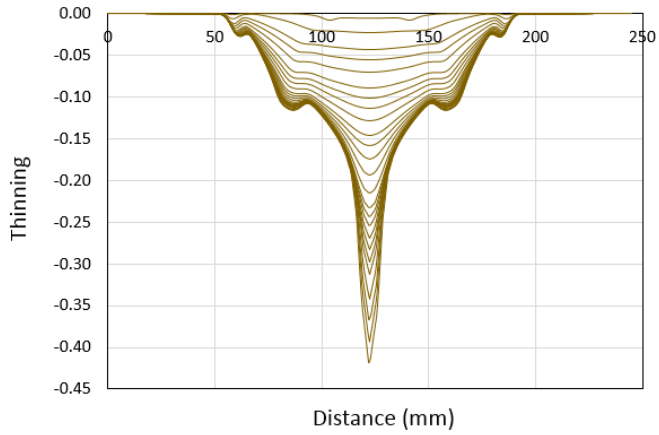
Figure 2. Tooling setup in simulations. **Figure 3.** Testing specimen geometry used in simulations.

2.3 Plastic deformation on specimen

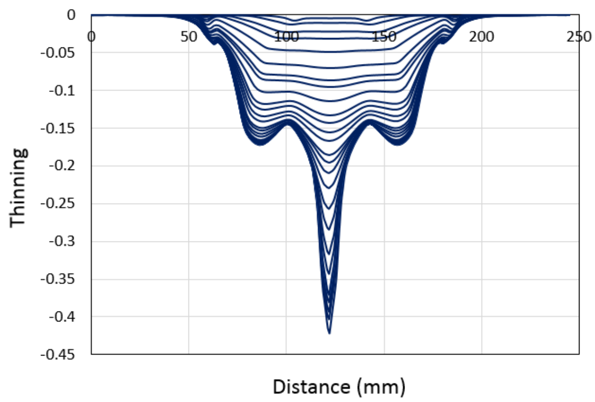
By means of the newly developed testing method, the maximum plastic deformation can be generated in the central region of a specimen where the material undergoes in-plane stretching deformation and is entirely frictionless. This way would ensure the onset of the through-thickness or localized necking captured in that region by the Digital Image Correlation (DIC) system. In order to demonstrate this characteristics, Figure 4 shows the thinning development along the central sections of the specimens over the testing process, as examples for the 1.0 mm thick 5xxx aluminum alloy at the specimen widths of 70 mm, 100 mm and 135 mm respectively. The previous Nakajima tests proved that the measured strain limits from these specimens are at the tension-compression, near plane strain and biaxial stretching states. It is clear from Figure 4 (b), (c) and (d) that with the punch geometry developed, the specimens are able to be stretched under a uniform in-plane strain condition in the central regions. After the deformation on the specimen accumulates to a certain amount, the maximum plastic deformation initiates in the centre of the specimen at when the through-thickness or localized necking starts. This phenomenon looks similar to what observed in the Marciniak tests. It would be concluded from this fact that the new testing method is able to reproduce the similar deformation condition as in the standard Marciniak test without using a carrier blank.



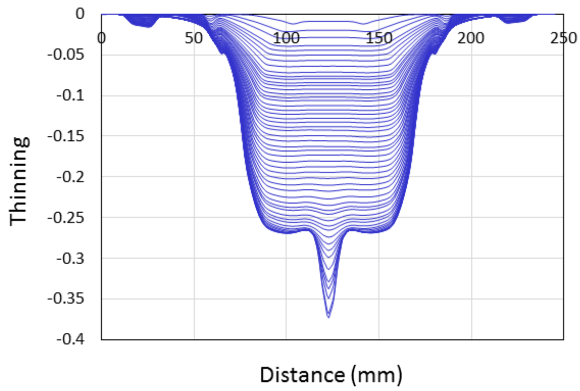
(a)



(b)



(c)



(d)

Figure 4. (a) Location of the section cut, (b) thinning development for the 70 mm wide specimen, (c) thinning development for the 100 mm and (d) thinning development for the 135 mm wide specimen of the 1.0 mm 5xxx aluminum alloy.

2.4 Influence of lubrication

For both the Marciniak test and Nakajima test, lubrication applied to the interface between the a specimen or a carrier blank and the punch is necessary. This is especially important for the Nakajima test, where the inherent friction at the interface of a specimen in direct contact with the hemispherical punch has a considerable effect on strain distribution, strain path and ultimately the shape of the FLC [13]. In order to gain a basic understanding on the new FLC testing method, the numerical analyses have been completed for different lubrication conditions. Figure 5 compares the thinning development along the central sections of the specimens (as shown in Figure 4 (a)) over the testing process under the friction coefficients of 0.01 and 0.05 for the 6xxx-T4 aluminum alloy at the 1.7 mm thickness. Under the well lubricated condition, the material stretching is easily concentrated in the central region of the specimen where there is no direct contact between the specimen and the punch. Therefore, the through-thickness or localized necking is initially developed. Under the less lubricated condition, the uniform strain distribution can still be developed at the lower plastic deformation level. After the plastic deformation of the specimen reaches a certain amount, the material stretching is localized in the punch radius area where the onset of the through-thickness necking occurs. Apparently, the strain limits measured under this lubricated condition would be greatly different compared to the ones measured under the well lubricated condition. It is recommended that minimizing the frictional effect is necessary for the newly developed FLC test, as usually done for the standard Nakajima test.

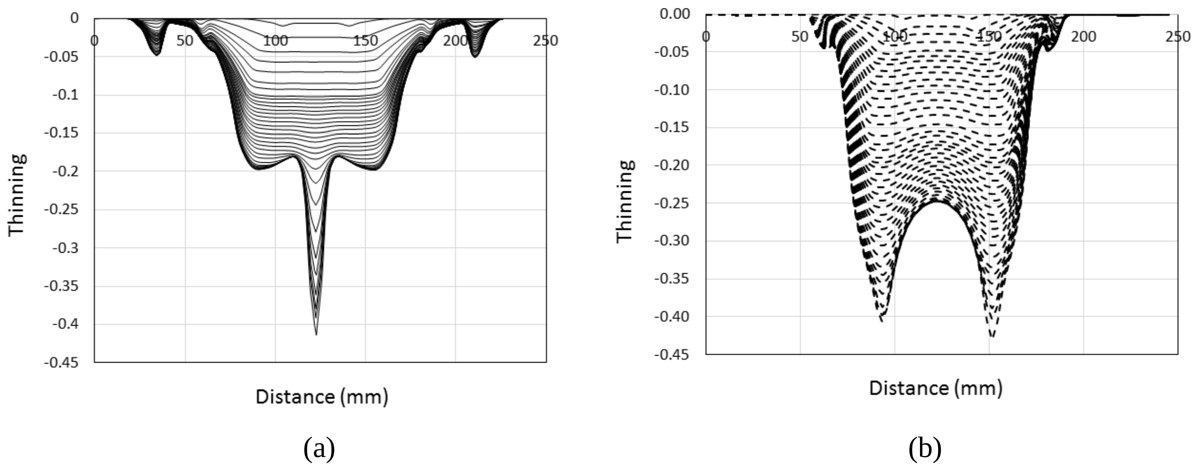


Figure 5. Thinning development for the 125 mm wide 6xxx-T4 aluminum alloy specimen at the 1.7 mm thickness under (a) friction coefficient 0.01 and (b) friction coefficient 0.05.

3. Validation with the measured forming limit curves

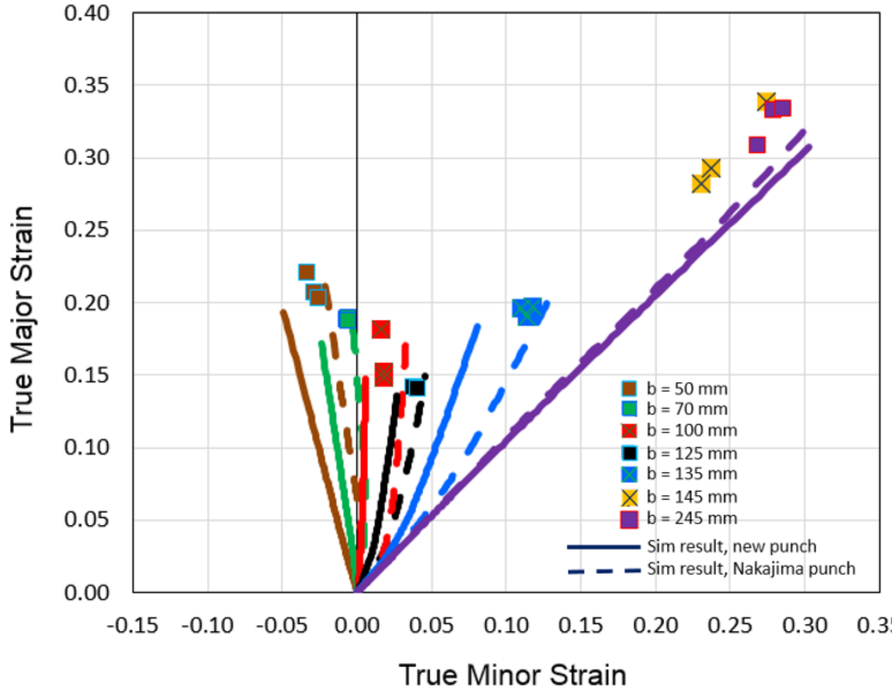
The new FLC testing method has been further validated with the experimentally measured forming limits by using the Nakajima tests. The main purpose of this comparative study is to characterize the strain path and strain limit variations from the different widths of the specimens. The 1.0 mm 5xxx and 1.7 mm 6xxx-T4 aluminum alloys were targeted, which demonstrates the feasibility of the new testing method for thinner and thicker sheet metal materials.

3.1 Nakajima tests

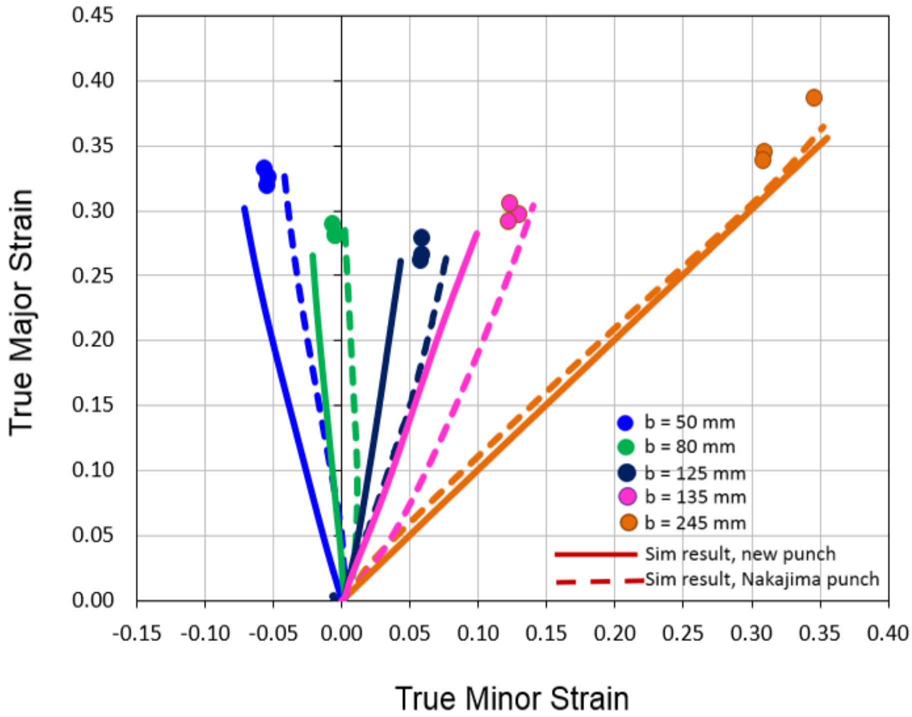
The standard Nakajima test was carried out to experimentally measure the forming limits for the above-mentioned aluminum alloys, following the ISO 12004-2 standard [11]. The specimen geometry used for testing is shown in Figure 3, with the specimen width varying from 50 mm to 245 mm. At least 5 strain paths were measured to construct the forming limit curves. For each of the specimen widths, three tests were repeated. In the testing, seven layers of lubricants were applied as described in the ISO 12004-2 standard [11]. The DIC system was used during all the testing to record the deformation history of the specimens. Based on the DIC history data, the onset of the through-thickness or localized necking of a specimen was determined by using the ISO method.

3.2 Virtual tryout

For the purpose of verifying the new concept, the simulative strain path trajectories leading to the forming limits from using the newly developed tooling and the standard Nakajima tooling are compared with the experimental forming limit points measured by means of the Nakajima tests. The simulations with AutoForm software has been detailed in Section 2.2. The comparisons between the simulation results and the experimental measurements for the above-mentioned two aluminum alloys were depicted in Figure 6 (a) and (b) respectively. In Figure 6, the points are the experimental forming limits measured in the standard Nakajima test with the punch diameter of 100.0 mm. The solid lines represent the simulative stain path trajectories with the newly developed tooling, and the dashed lines are the simulative strain path trajectories with the standard Nakajima tooling.



(a)



(b)

Figure 6. Comparison of the simulative strain path trajectories and the measured strain limits at different strain paths (a) 1.0 mm 5xxx aluminum alloy and (b) 1.7 mm 6xxx-T4 aluminum alloy.

It is evident from Figure 6 (a) and (b) that the simulation results with the standard Nakajima punch are in good agreement with the measurements for the cases studied at both the thinner and thicker gages. For each of the cases, the nonlinear strain paths leading to the measured forming limits are reproduced which are similar to what were observed in other researches [6, 7]. In contrast to those nonlinear strain paths with the Nakajima punch, the linear strain paths are generated with the new punch for all the cases. These linear strain paths are very close to the ones reported by Junying Min et al. [6] and Christian Leppin [7] in the traditional Marciniak tests of the MP980 steel and 6xxx aluminum alloys. Even though no carrier blank is used with the new punch, the linear strain paths leading to the forming limits can still be reproduced. As demonstrated by Junying Min et al. [6], the standard Marciniak and Nakajima tests produce essentially identical forming limit curves after correcting for the effects of curvature, nonlinear strain path and contact pressure. Actually, the correction shifts the FLCs measured from the Nakajima test to merge with the FLCs measured from the Marciniak test with the reduced major strain values and the minor strains moving to the left-hand side. This correction effect is reproduced by the newly developed punch geometry as shown in Figure 6 (a) and (b), except the equal-biaxial case where the specimen is deformed under the perfect biaxial stretching condition in the simulations.

4. Conclusions

The new punch geometry was developed to incorporated with the current ISO 12004-2 standard for the forming limit curve testing. The new testing method has been validated via the numerical analysis in terms of strain distribution and strain path produced on the specimens and by the experimental measurements. It is planned to further validate this new testing method with the real tooling and to compare with the measurements from the standard Marciniak and Nakajima tests.

References

[1] Keeler SP and Backhofen WA, 1964, *ASM Trans Quart* **56** p 25
[2] Goodwin GM, 1968, *SAE Tech Report*, **680093**
[3] Marciniak Z and Kuczynski K 1967 *Int. J. of Mech Sci* **9** p 609
[4] Nakazima K, Kikuma T and Hasuka K, 1968 *Yawata Tech Report* **264** 8517
[5] Abspoel M, Atzema EH, Droog JM, Khandeparkar T, Scholting ME, Schouten FJ and Vegter H, 2011, *in: Proc. of IDDRG* (Bilboa)
[6] Min JY, Stoughton TB, Carsley JE and Lin JP 2016 *Int. J. of Mech Sci* **117** p 115
[7] Leppin C, Li J and Daniel D, 2008, *Proc. of the 7th Int. Conf. and Workshop on Numerical Simulation of 3D Sheet Metal Forming Processes* (Interlaken) vol A p 217
[8] Bergström Y and Ölund S 1982 *Mater Sci Eng* **56** p 47
[9] Graf A and Hosford WF 1993 *Metall Trans* A **24** p 2497
[10] Gaber C, Jocham D, Weiss HA, Böttcher O and Volk W 2016 *Int. J. Mater Form* p 1 0
[11] International Organization for Standardization, 2008, *ISO 12004-2*, **2008(E)**
[12] Deng Z and Hennig R, 2017, *J. of Phys.: Conf. Ser.* **896** 012025
[13] Zhang L, Min JY, Carsley JE, Stoughton TB and Lin JP 2017 *Int. J. of Mech Sci* **133** p 217