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Development of Nakazima Test Simulation Tool for Forming Limit Diagram Generation of Aluminium Alloys

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ABSTRACT

In sheet metal forming processes, plastic instability may occur, leading to defective products. In order to manufacture defect free products, the prediction of the forming limits of sheet metals is a very important issue. In this study, FLD's are predicted by simulating Nakazima test using finite element software Pam-Stamp 2G. For this purpose Finite Element Model (FEM) for Nakazima test is established. Then the credibility of Nakazima test simulation tool is established.

***Keywords**: Stretch forming, Forming Limit Diagram, Nakazima test*

INRODUCTION

Sheet metal forming is the process of converting flat sheet of metal into a part of desired shape without fracture or excessive localized thinning. The application of sheet metal forming includes automotive industry, aerospace industry, household equipment's and many more. Forming Limit Diagram (FLD) is used during the design stage of any new sheet metal component for tooling shape & optimizing variables. It is nothing but a combination of major & minor strain. The Forming Limit Diagram (FLD) is a widely used concept to represent the formability of thin metallic sheets. To control the operation of sheet metal forming without failure, a diagram is used in which the safe, critical and failure forming regions are shown. This diagram is known as the Forming Limit Diagram (FLD) or the Forming Limit Curve (FLC). In sheet metal industry and studies, it is widely used and considered as one of the important tool to determine the formability of sheet metals. Every sheet metal has its own forming limit diagram which determines its formability, strain limit and forming regions.

Forming limit diagram is a representation of the critical combination of the two principal surface strains major and minor above which localized necking instability is observed, illustrated in Fig 1. For varying strain ratios, from pure shear to equibiaxial tension, the forming limit curve is plotted. When the strain ratio is positive, in other words where minor strain is positive, it means stretching is observed. In case of negative strain ratio, in other words negative minor strain, one can conclude that drawing is observed. It should also be noticed that the strains plotted are true strains.

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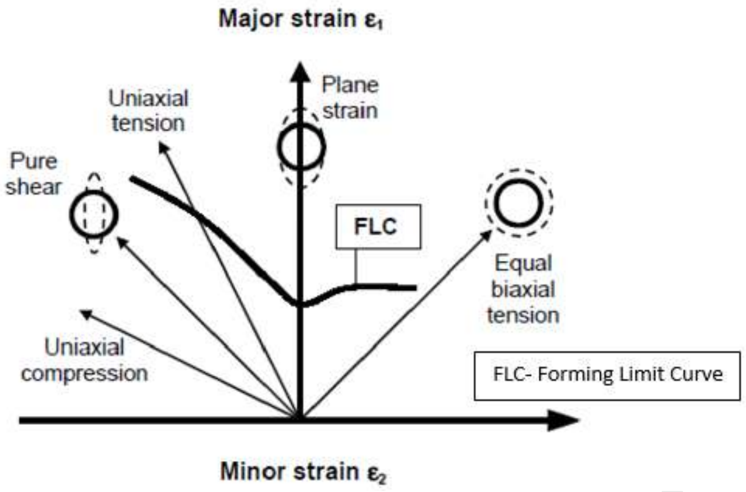

Figure 1:Forming Limit Diagram

In order to analyse the sheet metal instabilities and construct the FLD, various experimental and approaches exist.

Uniaxial tensile test, hydraulic bulge test, punch stretching test, Keeler test, Hecker test, Marciniak test, Nakazima test are some of the experimental procedures. In uniaxial tension test, the frictional effects are eliminated and only the negative range of FLD ($\varepsilon_2 < 0$) can be obtained. The hydraulic bulge test is performed to determine only the positive range of FLD ($\varepsilon_2 > 0$) by changing the shape of the elliptical dies to obtain different strain paths. The frictional effects are also eliminated in this test. Next, punch stretching test can be used to obtain the FLD. In this test the specimen is clamped between a die and a blank holder and stretched by a hemispherical or elliptical punch. Different strain paths are obtained by varying the specimen geometries. Keeler test consist the use of punches of different radius to obtain different stress states to obtain the positive ($\varepsilon_2 > 0$) range of FLDs. The main disadvantage of the test is the need for high amount of experimental work. By varying the friction regime, using the same die and specimen geometries the positive range of FLD can be obtained by Hecker test. Then, in Marciniak test a hollow punch is used. There is an intermediate part which has a circular hole is placed between the work piece and the punch. The aim is to obtain the tearing at the planar bottom section of the cup, otherwise cracks occurs between the cylindrical wall and the bottom. Complex geometries of punches and dies are required and there is a limitation for the positive range of the FLD. By using different specimen geometries and intermediate parts full range of FLD can be obtained. Finally, Nakazima test can be used to obtain the full range of FLD. By drawing the specimens with hemispherical punch and a circular die for varying widths, different strain paths can be obtained.

From all of the above tests, Nakazima test seems to be the most powerful and advantageous test because the tools used for the test is simple, the geometries of the specimens are not complex and full range of the FLD can be determined. Today, it is widely used in industry and sheet metal testing laboratories in order to evaluate the forming limits of the sheet metals.

MODELING OF NAKAZIMA TEST SIMULATION TOOL

For a FE simulation, the analysis process starts with the modeling of the required tools, then meshing them appropriately.

In general, to create geometries of the tools, a 3D modeling software like ProEngineer, Ideas, Catia, Solidworks etc. is used. After constructing the models of each tool in the 3-D software, each model is saved with an appropriate file format as IGES, VDA, STL etc. which the FEA software can read. Some FE software's are not very efficient and user-friendly in the pre-processing or post-processing phases.

Therefore, instead of trying to use only one FE software to achieve pre-processing, solution and post-processing stages, different software's can be used to progress faster and more efficient. Today, several software's are available that are specialized for only pre-processing, solving and post-processing stages. After, deciding which software to use, the models are opened and meshed in the FE software. Then, the analysis is done.

In this study, the geometries of the tools and blank are modeled in a well-known commercial software Catia. In Catia, the geometries of the tools are drawn in 2-D then converted to 3-D by rotation. For blank, the geometry is drawn in 2-D.

Now, the required tools (punch, die, blank holder) and blank are ready to be imported in Pam-Stamp.

In Pam-Stamp, the meshes are imported first and the positions of the tools are adjusted for the stamping process. The distance between the punch, blank holder and die with respect to the blank are half of the thickness of the blank in the vertical direction such that the blank holder and the punch are located above the blank whereas die is placed below the blank as shown in Fig 2.

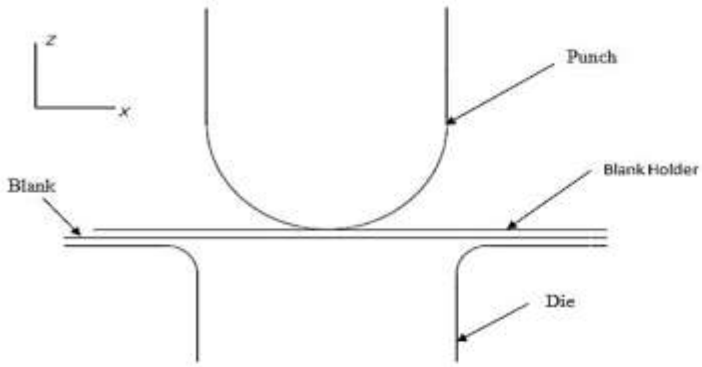

Figure 2: Initial Tool Positions

After meshing, the initial and boundary conditions of the tools, the process parameters are defined. First, the blank is defined as the deformable body whereas the other tools are rigid bodies. Then the material is assigned to the blank. Pam-Stamp has various materials in its database. However, new user-defined materials can be added to the database. In current study, new materials were defined. The material property values, plastic law and hardening curve were defined.

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HILL 48 MATERIAL LAW

The HILL 48 criterion coupled to an isotropic hardening law is the most commonly used criterion. The data of this law are easy to obtain and it is used for standard steels and aluminium.

$$\sigma_{\text{HILL48}} = \sqrt{\frac{1}{2}\left(H(\sigma_{11}-\sigma_{22})^2 + F(\sigma_{22}-\sigma_{33})^2 + G(\sigma_{33}-\sigma_{11})^2 + 2N\sigma_{12}^2\right)}$$

F, G and N are Hill's coefficients and the need for coefficients depends on anisotropic type option:

- **Orthotropic**: The anisotropy in three directions is taken into account so three values r_0, r_{45}, r_{90} are needed.
- **Normal**: Only the anisotropy through the thickness is taken into account, so only one average value 'r' independent of the direction is needed.
- **Isotropic**: There is no anisotropy so there is no need for Lankford's coefficient.

MATERIAL HARDENING LAW

Hollomon prolongation: The program is used to simulate the Hollomon's law coefficients ($\sigma=K\varepsilon^n$) on the interval ($10< \varepsilon <20\%$) and extend the curve up to $\varepsilon = 100\%$ using Hollomon's law. R_e (Yield stress) is defined in the hardening curve definition.

The other process parameters, such as coefficient of friction, punch velocity, blank holder force are defined. Furthermore, mesh refinement option exists in the software. Finally, the start-stop criteria and contents of the output file are determined and pre-processing stage is completed.

After finishing the analysis, post-processing modules of Pam-Stamp are used. For all elements and nodes, the stress, strain values can be evaluated for each deformation step. Finally, critical and safe zones of the deformable tool are evaluated and the success of the process is discussed.

FE SIMULATIONS

This study is aimed to find out how the predicted limit strains in the FE models are related to the one developed by experiments. In this study, commercial dynamic-explicit FE code PAM-Stamp has been used. The geometries of the tools are shown in Fig 3.

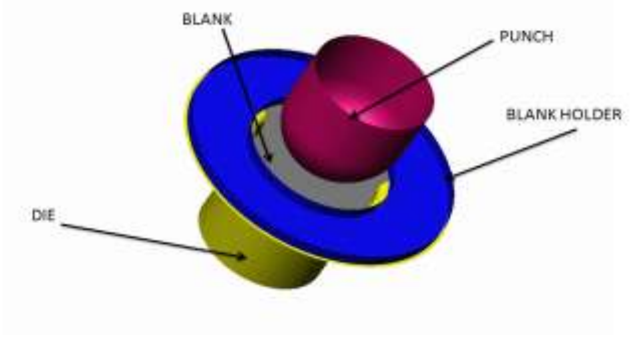

Figure 3: Nakazima Tools

In the present study, for all of the analysis of the specimens of AA2024-O, the geometries of punch, die and blank holder are the same. The determination of FLDs are standardized as ISO 12004-2, "Determination of Forming Limit Curves in the Laboratory". The parameters of the Nakazima test are shown in Table 1.

Table 1: Process Parameters

PROCESS PARAMETERS	
Hemispherical punch radius:	50mm
Die profile radius:	5mm
Die inner radius:	105mm
Blank material	AA 2024
Blank holder force:	100 kN
Friction coefficient:	0.08
Element type:	4 Node Rectangular And 3 Node Triangular Elements
Element size of blank:	3mm

For the finite element models, punch, die and blank holder are considered as the rigid tools whereas blank is the only deformable tool. In meshing the geometries, 4 node rectangular and three node triangular elements are used with a maximal element size of 3mm. Additional mesh refinement is used in order to trace the elemental stresses and strains.

ANALYSIS OF AA2024-0

The thickness of the aluminium AA2024-0 sheet simulated is 0.6 mm. The chemical composition and the material properties are given in Table 2 and Table 3, respectively.

Table 2: Chemical Composition of AA2024-O

COMPONENT	wt%
Al	90.7 - 94.7
Cr	Max 0.1
Cu	3.8 - 4.9
Fe	Max 0.5
Mg	1.2 - 1.8
Mn	0.3 - 0.9
Si	Max 0.5
Ti	Max 0.15
Zn	Max 0.25

Table 3: Material Properties of AA2024-O

YS (Mpa)	UTS (MPa)	Elastic Modulus (Mpa)	Poisson Ratio	R0	R45	R90	K (MPa)	n	ρ (kg/mm^3)
72	121	73100	0.33	0.65	0.83	0.6	326.8	0.226	2.73e^{-6}

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Totally, 7 different specimens are tested from uniaxial tension to biaxial tension states. The geometries of the specimens are shown in Fig 4.

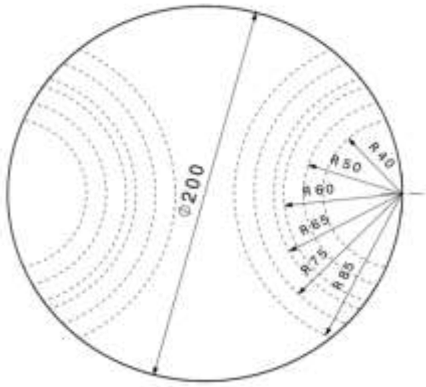

Figure 4: Nakazima Geometry of Aluminium

The deformed states of all geometries are shown in Fig 5.

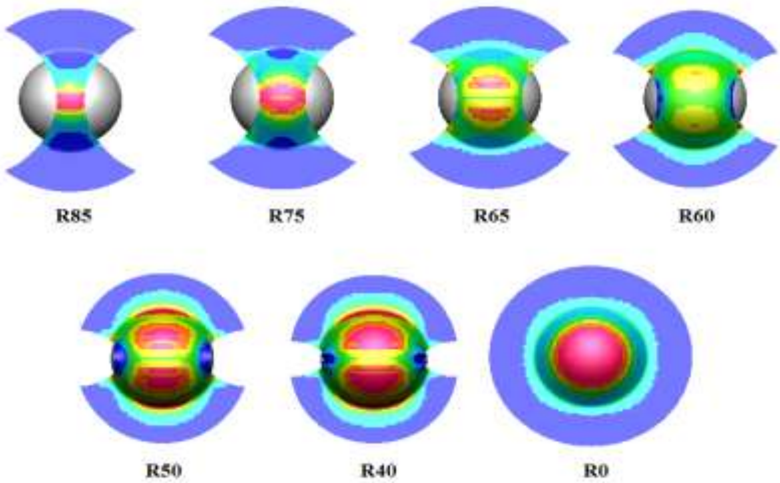

Figure 5: Deformed States of the AA2024-O Specimens

The deformation of the specimens are carried out for all seven specimens till the specimens undergo necking and the major and minor strain values are taken from mesh elements near the critically necked region. The deformed geometry of the sheet specimen R85 is shown in fig 6 and the major and minor strain values taken from mesh elements near the critically necked region are shown in fig 7.

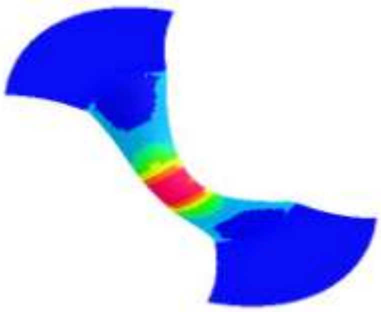

Figure 6: Deformed Geometry of R85

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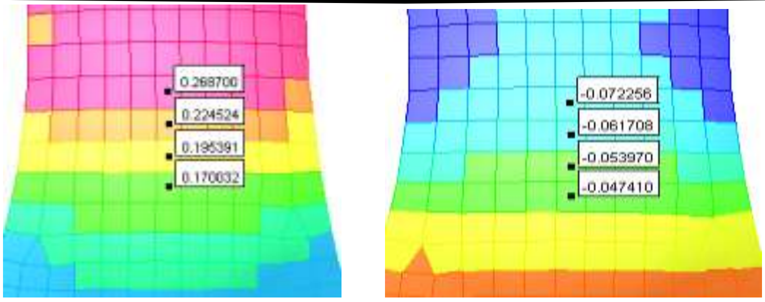

Figure 7: (a) major strain value (b) minor strain value

RESULT DISCUSSION

The values of major and minor strains obtained from both experimental [1] and simulation are shown in table 4.

Table 4: Experimental and FEM Results

SPECIMEN	EXPERIMENTAL VALUES		SIMULATION RESULTS	
DIMENSION(mm)	MINOR STRAIN	MAJOR STRAIN	MINOR STRAIN	MAJOR STRAIN
R 85	-0.0462	0.23125	-0.0617	0.2245
R 75	-0.0198	0.225	-0.038	0.2238
R 65	-0.0033	0.2125	-0.0060	0.2277
R 60	0.0132	0.1812	0.0072	0.1885
R 50	0.02	0.1687	0.0122	0.1767
R 40	0.0632	0.22	0.0542	0.2222
R 0	0.18	0.2305	0.1718	0.2319

The experimental and simulated values of major and minor strains are plotted to find out the accuracy of the FEM results. Fig 8 shows the experimentally and FEM plotted graph.

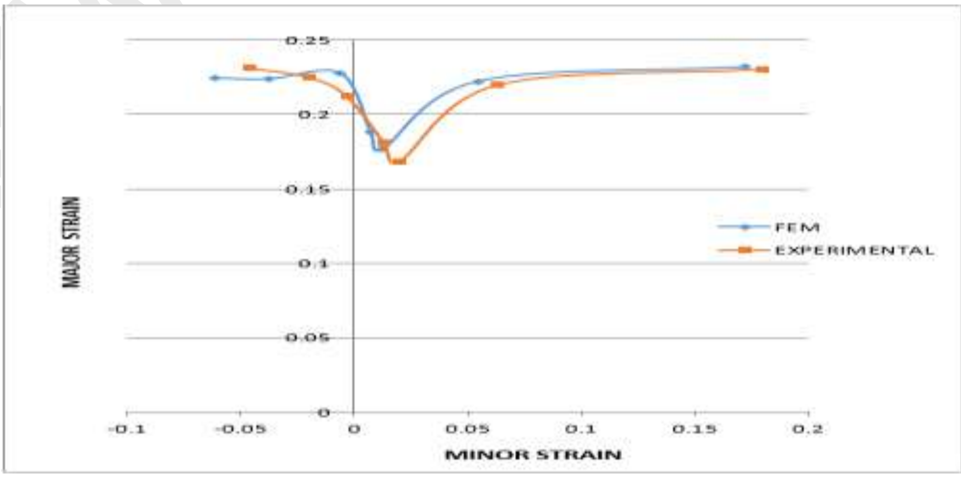

Figure 8: FLC generated by experiment and FEM

Good agreement has been obtained between the experimental and FEM generated FLCs. Thus the Nakazima test simulation tool is validated for the generation of FLD.

CONCLUSION

Forming limit prediction is a very important issue that should be analyzed in detail in order to produce higher quality products in sheet metal forming processes. Especially in drawing and stretching operations, extensive knowledge of the deformation characteristics and the forming limits of a material are necessary to determine the best forming technique and the most suitable material to manufacture a higher quality product.

Today, trial and error methods are being used to optimise the manufacturing parameters of sheet metal parts. This procedure results in increase of production time, material and tools which results in increase of product costs. Therefore, several researches and studies are being carried out in this field to overcome these difficulties and disadvantages.

In this work, Nakazima testing method for the determination of FLD is simulated using FE based sheet metal forming software Pam-Stamp 2G. The Nakazima test was simulated to find out the Forming Limit Diagram of AA2024-O aluminium alloy sheet metal. The obtained FLD was compared with the experimentally found FLDs and the credibility of the Nakazima test simulation tool is established. Thus the obtained Nakazima test simulation tool can be used for predicting the FLD of other 2000 series Aluminium Alloys.

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