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Construction of Forming Limit Diagrams for AA 5754 and AA 2024 Aluminium Alloys

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Forming of sheet metals in desired shape is restricted by localized necking and fracture in sheet forming operations. In order to attain a successful forming process, forming analysis must be done. Forming analysis is accomplished with a help of computer models which have been developed to predict material behavior in forming operations. To use these models to simulate a real manufacturing process, experimental data are required. Generally, these data are obtained from tensile tests and forming limit diagrams (FLDs). FLDs offer a useful tool in sheet metal forming analysis.

In this study FLDs of AA 5754-O and AA 2024-T4 materials were constructed. Nakazima test, a kind of out of plane forming experiments, is used to obtain the FLDs. The forming limits of materials is found from grids, created by serigraphy method on the samples, which were formed until tearing and necking, by using a special automatic strain measurement software ASAME.

In order to obtain the most accurate FLD, accuracy of creating grid and measuring of the strains were found. Repeatability of determining limit strains was also found. Consequently the grids could be created with 0.28% accuracy and 0.8% repeatability. Repeatability of the measuring system was found to be 0.26% strain. The limit strains were determined with 2% repeatability.

Keywords: *AA 5754, AA2024, Forming Limit Diagram, FLD, FEM*

1. Introduction

AA 5754 aluminium alloys are generally used in automotive industry and AA 2024 aluminium alloys are generally used in aerospace industry with a view to reducing weight. Boogaard [1] found that 10 % reduction in a vehicle weight will improve fuel efficiency by 5.5 %. Formability of an aluminium sheet under normal processing conditions is typically lower than that of mild steel. That is why aluminium molding process is more critical.

Before forming of sheet metals, the process is modeled and analyzed on a computer by using finite element method thereby providing possibility of predicting possible fractures, wrinkles or springback problems in the metals. It is possible to get rid of these problems by making modifications on process parameters, part geometries or on material. Therefore, the number of trial and error method is minimized and hence enabling savings in terms of time and costs. In order to make analysis with a finite elements (FE) program it is necessary that the materials are defined to the program. For this the yield curve of the materials must be defined in the program. With this information, the analysis is conducted and strain values for every point on a part are calculated. To predict whether the obtained strain values will cause fracture or necking upon material, it is also necessary to define FLD which give details on how far the material can be strained.

FLD determines limit strain values in sheet metals up to which the material can sustain necking or fracture. This limit is expressed in terms of combination of the major ε_1 and minor ε_2 principal strains formed on the sheet by using FLD's [2]. The FLD which determines limit strain values where damages occur in sheet materials is the most effective tool in determining formability.

The FLD's can be obtained both theoretically and experimentally. In experimental studies, the ε_1 and ε_2 strains which construct the forming limit curve on FLD can be calculated by measuring the grids (circular or square patterns marked on a sheet) on fractured areas after forming the sheet metal. Efforts were made to obtain a wide interval FLD on different moulds and specimens by using different geometric, dimensional and frictional conditions to change strain ratios ($\varepsilon_2/\varepsilon_1$). Many researchers have developed different experimental methods based on the shapes and sizes of the moulds and specimens used in the tests. The tests are generally, classified into two, plane and out of plane formability tests. Hemispherical punches are used in out-of-plane tests. In this field the first research was started by Keeler and Backhofen [3]. They used grids that are initially circular and later become elliptical under various lubricating conditions and punch geometries and found minimum principle strains corresponding to maximum principle strain at the time of fracture after a two axis straining (ε_1>0, ε_2>0). In this test only right hand side of the FLD can be obtained. After Keeler Goodwin used different mechanical tests in 1968 and obtained a curve for a tension /compression area (ε_1>0, ε_2<0) [4]. Both Keeler and Goodwin curves give strain values, ε_1 and ε_2 at the moment of material fracture. This is still known as Forming Limit Diagram (FLD). In the Hasek [5] test, only one type of hemispherical punch is used. However, to get rid of the wrinkling and to achieve various strain paths on the right and left hand side of the FLD, notches are cut at different radii on circular specimens. In Nakazima test [6] specimens with different widths are formed until fracture with a hemispherical punch and a circular female die. By varying the specimen widths and lubrication conditions, the right and left hand sides of the FLD are found. The Nakazima test is the most widely used out-of-plane formability test. On other hand, generally cylindrical punches are used for plane formability tests. In Marciniak test, the most applied among plane tests, instead of a direct impact, a sheet is deformed with a cylindrical punch by using a center holed washer until it gets fractured. Different strain paths are formed by changing specimen and washer geometries [7]. Although the friction is not effective on experiments, this test is difficult to perform because of preparing the specimens and washers. Holmberg et al [8] developed another planar test that is carried out on a tensile testing device and used to determine the FLD quickly and simply. But in this test, only left of the FLD could be obtained by changing specimen dimensions.

Due to the fact that, creating FLD's experimentally is a tedious and time consuming task that needs special equipment. Several studies have been conducted on forming FLD's by calculating limit strains on metals and thereby a number of theoretical models have been developed, so far. In a study by Banabic et al [9] the researchers summarized the models used to predict FLDs. The Hill's local necking and the Swift's distributed necking, Marciniak and Kuczynski method and ductile fracture criteria are the most used among these models. None of the theoretical models can offer reliable prediction of FLD for all materials and at each side of the FLD. That is why it is necessary to obtain FLD's experimentally.

In this study, Nakazima test was used to obtain FLDs for AA 5754-O and AA 2024-T4 materials. Repeatability of measurement system and that of the limit strains were obtained.

2. Experimental study

The process of obtaining the FLD involves three steps. First of all circular or square grids are formed on specimens with certain shape or size in order to measure the degree of deformations on these specimens. Then the sheet with grids is deformed until necking or fracture appears. Finally, deformations along minor and major principle axes on areas near affected area are measured and then principle strains ε_1 and ε_2 are calculated. Then these values are marked on the FLD thereby the forming limit curve was constructed. To obtain a wide range forming limit curve the specimen widths are varied and then different strain paths and values are found.

2.1 Gridding

The grids formed on a sheet surface should exhibit resistances against deformation and operating processes like friction and lubrication. Besides this, at high accuracies, the grids should possess high resolutions and the method needs to be economic. When these features are considered the most appropriate among the gridding methods is serigraph Ozturk et al (2009). In this study, 2.5 mm size square grids were used to form by serigraphy method.

2.2 Forming process

The FLD's were constructed with the application of Nakazima test. The specimens used in the tests have widths of 25, 50, 75, 100, 125, 150, 175, 200 mm and thickness of 1 mm. A sample specimen is shown in Fig.1. In this figure the specimen width is designated with "w". The shape of the specimens with width sizes of 25mm to 100 mm are as in the figure below. Other specimens were 200 mm long, rectangular in shape and with widths of 125, 150, 175, and 200 mm. The 200 mm wide specimens were also tested by using different lubricants so higher strain ratios were obtained. The specimens were made of AA 5754-O and AA 2024-T4 materials. Their yield curves are given in Fig. 2.

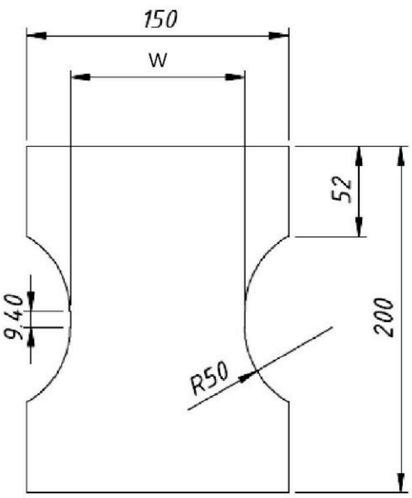


Fig. 1 Non rectangular Nakazima test specimen

The specimens were formed on a double acting MTS brand press by using the Nakazima test equipment shown in Fig. 3. The press which can be controlled both manually and numerically has 70 ton punch and 80 ton blank holder force capacities and can operate at a punch speed of 10~1000 mm/min. On top of that the blank holder force, punch speed and position control can be made on the test device. The test device possessed sensing feature which enables it to determine whether necking or fracture takes place and terminates the process. Nakazima test is all about blowing up a sheet by 100 mm diameter hemispherical punch up to necking or fracture after attaching the sheet on a draw bead with a certain size in such a way that the sheet will not slide. The punch speed chosen in this study was 25 mm/min. In order to obtain different strain paths for the specimens with 200 mm widths, two different lubricant were used between the punch and the sheet. In the first, a 0.3 mm thick polyethylene film was used, whereas the second lubricant was SAE 10 mineral oil which was used along with this solid lubrication. Whenever the sheet started to undergo necking or fracture, the tests were stopped and efforts to catch a limit strain were made. In 95% of Al 5754 test specimens necking was achieved whereas in the other specimens fracture took place.

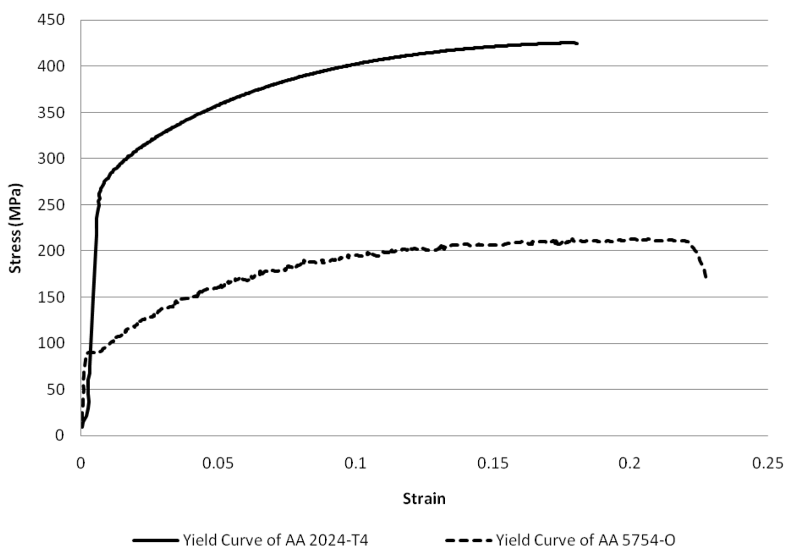


Fig. 2 The yield curves of the AA 5754-O and AA 2024-T4 materials

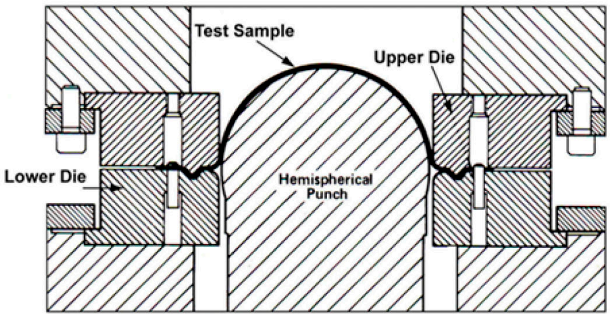


Fig. 3 Nakazima test setup (Ozturk and Lee, 2005)

As for Al 2024 specimens, only fracture took place and necking could not be obtained due to the fact that the material is brittle. In all the tests three successful repeats were conducted

2.3 Measurement of grids and construction of forming limit diagrams

In order to find limit strains on the dome shaped specimen in this study, measurements were taken on two specimen areas. As seen in Fig. 4, one of the areas has undergone either necking or fracture while the other is opposite to the necking or fracture area. An area large enough to contain necking or fracture and another area with the same size on the opposite were measured. Strain values adjacent to the fracture were assumed to be deficient or have undergone necking while the rest was taken as safe strain values. The purpose of measuring adjacent sides of the fractures or necking is to obtain details of the incipient necking and those of safe forming limit. The strain values in this area are known as necking, incipient necking and safe strain values. The FLD was obtained by passing the forming limit

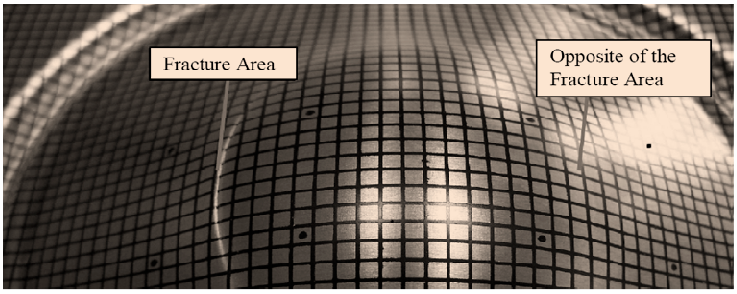


Fig. 4 Fracture and opposite of the fracture area

curve below the strain values at incipient necking and above safe strain values. ASAME automatic grid measuring program was used to measure the grids. In this program, deformations of grids pressed on a sheet metal are measured through photographs and thereby major and minor strains are calculated. Then points corresponding to these values are marked on FLD.

3. Results and Discussion

3.1 Repeatability

In this study, repeatability of gridding, grid measurement system, computation of limit strain values and formation of FLD were determined in order to achieve a reliable FLD.

The grids accuracy and their repeatability were previously found in a study conducted by Ozturk et al (2009) to be, respectively, 0.28% and 0.8% for 95% of reliability. According to ASTM E2218-02 standard which deals with construction of the FLDs, grid accuracy should be at least 1%.

To determine the accuracies of these measurement systems, an undeformed flat sheet was measured, as it is assumed that the actual strains on the flat sheet are zero. Therefore, the deviation of the measured values from zero determines the accuracy of the measurement system. The average accuracy for major strain values for the measurement system at 95% reliability was found to be 0.10 ± 0,16 whereas that for minor strain values was 0,38 ± 0,13. The ASTM E2218-02 standard specifies that the FLC accuracy be ± % 2.5 and within range of strain values. Repeatability of the measurements obtained with different cameras and at different ambient are given in Table 1. As for

Table1 Effects of Camera and environment on repeatability of measuring strains

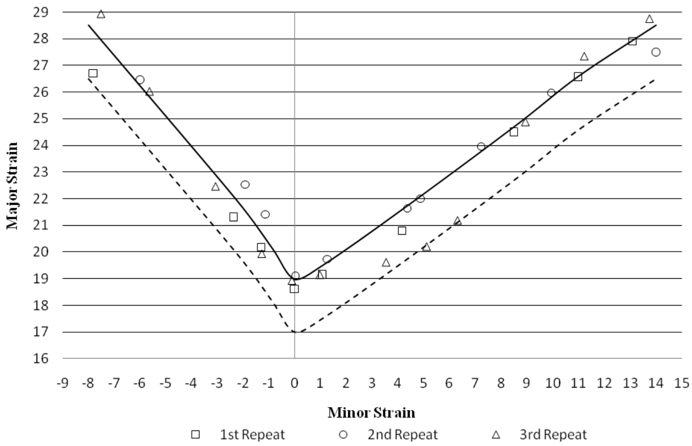
Camera used	Ambient	Repeatability (% strain)
Kodak (taken by the authors with amateur camera)	On Florescent light	2.24
	At a shade on open air	1.49
	Closed wide area with light reflection at different angles	1
	Closed wide area with indirect sunlight	0.66
Nikon (With Professional photographer and SLR camera)	At studio under shadow sunlight difference	0.25
Canon (with professional SLR camera and the authors)	At Office under daylight	0.26

repeatability, three measurements were repeated over same area on same specimen where the average of twice the standard deviations of grid strain values at points of intersection was calculated with 95% reliability. For all the measurements made with SLR professional camera at closed wide area and under indirect day light that is the best results on effects of camera and ambient on repeatability were obtained by authors.

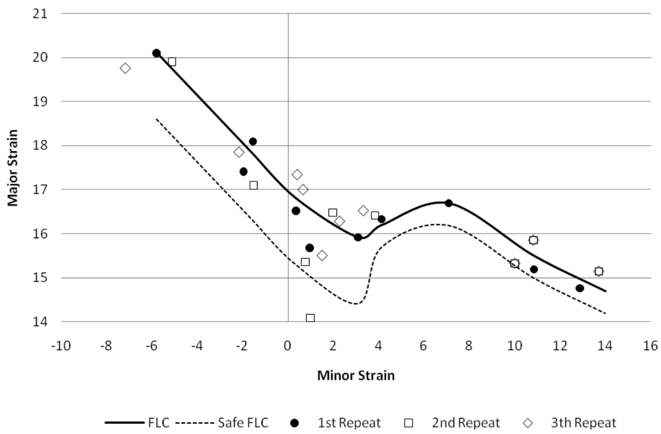
Repeatability for finding limit strains up to necking was found on an experimental study where limit strains for 4 different specimens with same widths were found by with a reliability of 95%. It was found that limit strains repeatability for major strains was 2% while that for minor strains was 0.7%

3.2 Forming limit diagrams

In Fig. 5a and b, limit strain values with FLC and safe FLC for AA 5754-O and AA 2024-T4 materials are respectively shown where 3 test repetitions were made on specimens with different widths and along rolling direction. Safe FLC was drawn by offsetting FLC in such a way that the safe FLC will pass below all limit strain values. This offset value was taken as indication of



(a)



(b)

Fig. 5 FLDs of a) AA 5754-O and b) AA 2024-T4 obtained FLD's repeatability whose strain values were 2% for AA 5754-O and 1.5% for AA2024. The graphs show that the FLC that belong to AA 5754 material is higher than that of AA 2024. It can hence be said here that, formability of AA 5754 material is higher as compared to AA 2024.

4. Conclusions

In this study, formabilities of Al 5754-O and Al 2024-T4 materials were investigated for the materials were well defined on simulation programs in order to improve molding performance. Formability was determined by obtaining forming limit diagram experimentally. In order to obtain a reliable FLD, accuracies and repeatability of the grids and the grid measurement system were found. While the accuracy and repeatability of the grids were respectively 0.28% and 0.8% the accuracy and repeatability of the grid measurement system were respectively obtained as strains at 0.38% and 0.26%. Limit strains were found to have a repeatability of 2%. As these values are below the 2.5% specified in the ASTM E2218-02 standard, it can be said that the FLDs obtained are reliable.

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