Forming Limits in Sheet Metal Forming for Non-Proportional Loading Conditions – Experimental and Theoretical Approach

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Abstract. The influence of strain paths (loading history) on material formability is well known in sheet forming processes. Sophisticated experimental methods are used to determine the entire shape of strain paths of forming limits for aluminum AA6016-T4 alloy. Forming limits for sheet metal in as-received condition as well as for different pre-deformation are presented. A theoretical approach based on Arrieux’s intrinsic Forming Limit Stress Curve (FLSC) concept is employed to numerically predict the influence of loading history on forming severity. The detailed experimental strain paths are used in the theoretical study instead of any linear or bilinear simplified loading histories to demonstrate the predictive quality of forming limits in the state of stress.

Keywords: non-proportional loading, formability, strain path, pre-deformation, FLSC.

INTRODUCTION

Experimental Forming Limit Curves (FLC) are commonly used to judge forming severity of drawn parts. An FLC represents the material formability in the state of strain and depends on its forming history. The severe influence of changes in the strain paths in the position and shape of the FLC is shown in e.g. references [1-3]. Consequently, the applicability of classical experimental FLCs is considerably reduced [4], due to the fact that they are only valid for forming processes having almost the same forming history as given in punch tests used for FLC determination. It is unlikely that these specific strain paths which result from sheet forming with a simple tooling geometry (e.g. flat [5] or hemispherical [6] punch) coincide with strain paths, originating from industrial deep drawing processes with complex tool geometries and/or multi-step operations [7]. Hence, each point of a drawn part is subject to a different strain path and therefore each point requires its own unique forming limit strains.

Defining the forming limits for all possible strain path shapes with experiments is not only tedious but simply impossible. Thus scientists address this issue using different theoretical approaches to predict forming limits numerically (e.g. refs. [8 -10]). Most of these classical models assume constant linear strain paths (= proportional loading) for the prediction of sheet material failure due to thinning, which ultimately leads to a split in the sheet. More recently developed failure prediction approaches (e.g. ref. [11]) and the method used in this study [12] are formulated to account for non-linear strain paths during the deformation of sheet metals.

The experimental analysis given in this article outlines the mechanical properties of the investigated AA6016-T4 alloy first and then gives a short overview concerning the experimental setup and the strain measurement system used for this study. Detailed FLC data and its corresponding measured shape of strain paths are presented. Furthermore, the effect of changing strain path during FLC determination is explored experimentally. Therefore, the influence of pre-deformation on the formability on the aluminum alloy is shown. In the theoretical analysis of this work, stress-based forming limits are calculated. The
Forming Limit Stress Curve (short FLSC) for AA6016-T4 is defined using a strain-stress transformation concept, which is based on Arrieux’s formulation [12]. The predictive quality of the FLSC approach is investigated. Therefore a comparison between theoretical and experimental forming limits for pre-deformed aluminum sheet is made. Finally, the results of this work and the experience made using the FLSC approach to predict forming limits are summarized.

EXPERIMENTAL ANALYSIS

The experimental analysis presented in this work was carried out at the Chair of Manufacturing Technology (University of Erlangen-Nuremberg). The aim of these experiments is to investigate the influence of forming history (= shape of strain path) on material formability. Hence emphasis is put on characterizing experimentally the entire strain paths during the determination of forming limits under various loading conditions.

Material properties

The sheet material of this experimental study is the precipitation hardenable aluminum alloy AA6016-T4 with a sheet thickness t₀ = 1.15mm. The mechanical properties of AA6016-T4 are determined in tensile tests according to DIN EN 10002. The tensile specimens are cut with the tensile axes parallel to the rolling direction (0° orientation; RD) and parallel to transverse direction (90° orientation; TD). Additional tensile specimens are oriented 45° to rolling direction. At least three specimens are tested for each of these three orientations. The results of tensile tests oriented parallel to rolling direction and the averaged Lankford parameter rₘ = (r₀ + 2r₄₅ + r₉₀)/4 are listed in Table 1.

### Table 1. Material characteristics of AA6016 –T4

<table>
<thead>
<tr>
<th>Tensile Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength [MPa]</td>
<td>93.32±4.15</td>
</tr>
<tr>
<td>Tensile Strength [MPa]</td>
<td>201.63±4.23</td>
</tr>
<tr>
<td>Uniform Elongation [%]</td>
<td>21.61±2.8</td>
</tr>
<tr>
<td>Work Hardening Exponent [-]</td>
<td>0.245±0.003</td>
</tr>
</tbody>
</table>

Experimental Setup

A hydraulic testing machine with a hemispherical punch (98 mm punch diameter) is employed to strain differently shaped sheet specimens with a chosen punch velocity of 1.5 mm/s. The scheme of this Nakazima testing setup is shown and described in detail in [13, 14]. The optical deformation measurement system ARAMIS (GOM company) used allows to record and analyze the strain distribution during the entire forming process. Executions of tests as well as the analysis of strain distribution and the definition of onset of necking are done according to [14, 15].

Experiments for Sheets in As-Received Condition

To determine the Forming Limit Curve of AA6016-T4 in as-received condition, six different specimen geometries are used. These notched blank geometries are so-called Hasek specimens [16] with a diameter of 170 mm. The orientation of the notches is always parallel to the rolling direction. Thus, the axis of major true strain ϕ₁ is aligned with the rolling direction and the axes of minor true strain with the transverse direction. Several specimens are tested for each of the six geometries. All forming limit strains determined according to [15] for sheets in as-received condition and one entire strain path for each specimen geometry are presented in Fig. 1.

**Figure 1**: Measured shapes of strain paths for six different specimen geometries to determine forming limit strains for AA6016-T4 (sheet material in as-received condition). The forming limits obtained are marked by black filled circles. The directions of strain paths with strain ratios $\beta = d\phi_2/d\phi_1$ for uniaxial straining ($\beta = -0.5$), for in-plane plane strain straining ($\beta = 0$) and balanced biaxial straining ($\beta = 1$) are represented by solid arrows.

Figure 1 shows that forming limits measured for almost uniaxial loading conditions ($\phi_1 \approx -2\phi_2$ at the onset of necking; path a₀) are slightly lower than the
sustainable strain values for biaxial loading, where the limit major strain $\phi^*_1$ and limit minor strain $\phi^*_2$ are almost equal (i.e. $\phi^*_1 \approx \phi^*_2$; path $f_0$). The formability of AA6016-T4 decreases, when the limit minor strain $\phi^*_2$ converges towards unity. Additionally, it is observed that the shape of strain paths vary distinctly. The curvature of forming path labeled (a0) in Fig. 1 indicates that almost proportional straining remains for loading conditions similar to uniaxial loading until the forming limit is reached. It is of particular interest that strain paths of specimens which tend at their ends almost towards in-plane plane strain condition (i.e. strain path parallel to the ordinate, see Fig. 1, paths c0, d0 and e0), the shape of the strain path changes from an almost linear path (e.g. path a0) to gradually curved paths. Furthermore, the strain paths ending closest to the ordinate (path c0 and d0) do not exhibit in-plane plane strain condition (i.e. $\beta'=0$; $\beta' = \frac{d\phi^*_1}{d\phi^*_2}$) as frequently taken for granted. The forming limit of path c0 ends with a ratio $\beta'$ which is nearly zero and represents the minimum of limit strains observed. This measured shape of strain path c0 may explain, why the minimum of forming limits is often found to the right (i.e. within the positive minor strain region $\phi < \phi_1 > 0$) of what is considered to be in-plane plane strain in proportional loading (i.e. intersection of FLC with y-axis).

Experiments for Sheets in Various Pre-strained Conditions

In this section, the effect of abrupt changing strain path during straining on formability is explored. Therefore, sheets of AA6016-T4 are pre-strained in uniaxial and biaxial tension to several strain levels. Then, different notched specimens cut from the pre-strained sheets are further strained using a hemispherical punch to obtain the forming limits for selected combination of pre-strain path and level. Further details of the experimental procedure of testing sheets in pre-strained conditions are reported in [17]. In the interest of brevity only experimental forming limits for uniaxially pre-strained sheets are discussed subsequently.

Experimental Forming Limits for Uniaxially Pre-strained Sheets

Specimens with two levels of uniaxial pre-strain ($\phi_1 \approx -2\phi_2$) are tested. In case U1, the major true strain at the end of pre-strain $\phi_{pre} = 0.1$ and in case U2, $\phi_{pre} = 0.2$, respectively. In both cases (U1 and U2), the tension axes in prestrain and the axes of the larger principal strain (i.e. $\phi_1$) during Nakazima testing is always aligned with the rolling direction (RD). Two different geometries of specimens are employed (geometry causing strain path d0 and f0, see Fig. 1). The forming limits for uniaxially pre-strained sheets and one strain path for each specimen geometry and level of pre-strain tested, are given in Fig. 2.

**Figure 2:** Experimental forming limits and their strain paths (open circles) observed for uniaxially pre-strained sheets (case U1, $\phi_{pre} = 0.1$ and case U2, $\phi_{pre} = 0.2$) of AA6016-T4. Geometries tested for strain paths ending almost in in-plane plane strain (paths d) and biaxial strain conditions (paths f). The forming limits for the same forming histories for sheets in as-received condition are depicted as a reference (filled circles).

Figure 2 shows that uniaxial pre-strain shifts the sustainable strain values for almost in-plane plane strain testing (paths d) as well as for biaxial testing (paths f) in comparison to corresponding forming limits obtained for as-received sheets (ends of path d0 and f0). Greater uniaxial pre-strains (e.g. case U2) raise the forming limits further. It is worth noting that the shape of the strain paths for the same specimen geometries evolve similar, no matter whether the specimens are uniaxially pre-strained (e.g. d0 and d0, Fig. 2) or in as-received condition (path d0).

THEORETICAL ANALYSIS

This chapter discusses the incorporation of gradual as well as abrupt path changes into the theoretical prediction of forming limits. A comparison between numerical and experimental results is given.
Calculation Method

The calculation method for this theoretical study is derived from the Forming Limit Stress Curve concept (short FLSC) of Arrieux [12]. His failure criterion assesses material formability based on associative plasticity and the loading history (strain path) that the sheet is subjected to during forming. This FLSC-concept was further developed, the applicability broadened and its advantages highlighted by Stoughton (e.g. [18, 19]). Theoretical considerations and the characteristics of Arrieux’s approach (e.g. stability condition) in comparison to other classical methods to determine numerically forming limits in sheet forming ([8, 9, 20]) are outlined in [21]. In contrast to this previous work of the authors [21] and other studies [22], the entire experimentally determined shape of strain paths is considered, instead of any simplified linear and bilinear strain paths to calculate the FLSC. This intrinsic Forming Limit Stress Curve is calculated using the high-exponent (non-quadratic) yield function introduced by Hosford [23], assuming planar stress, planar isotropy and a principal coordinate system. For these assumptions, the yield criterion has the form:

\[ \sigma^v = \frac{1}{r_v + 1} \left( |\sigma_x| + |\sigma_y| + r_v (|\sigma_x| - |\sigma_y|) \right) \]  

(1)

It is recommended to use \( M = 8 \) with face-centered cubic crystal structures, like the Al-alloy considered in this work [24]. A numerical solution for the determination of \( d\sigma \) is employed in the simulation. The stress-strain behavior of AA6016-T4 is modeled using a Voce type saturation hardening law (isotropic hardening) of the following form:

\[ \sigma = S (1 - Ae^{-\beta}) \]  

(2)

The three coefficients (S, A, B) of Voce empirical work hardening law are determined using the experimental data of the flow curve for uniaxial straining parallel to RD. The coefficients found are \( S = 255.4, A = 0.624 \) and \( B = 12.29 \).

Calculated Forming Limit Stress Curve

The Forming Limit Stress Curve (FLSC) represents limits of sheet formability in the state of stress [22]. Six experimentally determined strain paths (paths \( a_0 \) to \( f_0 \), see Fig. 1) and their forming limit strains of sheets in as-received condition are used to calculate forming limit stresses for AA6016-T4. The FLSC for this alloy is formed linking the six pairs of calculated limit stresses (see black filled squares in Fig. 3) with straight lines. The FLSC is extended, using two more states of limit stresses, labeled \( L_1 \) and \( L_2 \). \( L_1 \) represents limit stresses for the limit strain ratio \( \beta^* = -0.5 \) (uniaxial straining) and \( L_2 \) represents \( \beta^* = 1 \) (balanced biaxial straining). Additionally, the initial yield surface is displayed in Fig. 3. The contorted shape of the stress paths indicates the changes in loading condition during the Nakazima formability tests with different notched specimens.

Predictive Quality of FLSC Approach

The predictive quality of the theoretical FLSC approach is investigated. Therefore, the FLSC determined for AA6016-T4 based on six experimental strain paths and their forming limits determined for sheets in as-received condition is defined to predict forming limit strains considering abrupt and gradual path changes. The strain paths assumed in this validation are identical with the experimentally determined paths for sheets in pre-strained conditions of this study (i.e. \( d_{i(0)} \) and \( f_{i(0)} \)). Thus, numerical predictions can be compared with experimental data.

First, the strain paths are transformed into stress paths and their individual intersection with the FLSC are assessed. The calculated representation of four uniaxially pre-deformed forming histories in the state of stress is given in Fig. 4. Additionally, the located
Figure 4: Four calculated stress paths ($\sigma_{U1}$, $\sigma_{U2}$, $\sigma_{U1}$ and $\sigma_{U2}$) for uniaxially pre-deformed sheets (case $U1$, $\varphi_{U1} = 0.1$; case $U2$, $\varphi_{U2} = 0.2$). The open squares I, II and III represent the intersection of the stress paths with the FLSC (black dashed line) and hence mark the material formability for these forming histories. The yield surfaces after prestrain for cases $U1$ and $U2$ are displayed as dotted gray curves. The path segments $R-S_1$, $R-S_2$, $P-Q_1$ and $P-Q_2$ (black dotted lines) sketch the change of loading (elastic!) due to the abrupt change of strain paths at the level of pre-strain.

Figure 5: Transformation of calculated forming limit stresses into forming limits in the state of strain (black filled squares). The assumed forming histories (path $d_{U1}$, $d_{U2}$, $f_{U1}$ and $f_{U2}$) with an abrupt change of strain path after uniaxial pre-strain of $U1$ ($\varphi_{U1} = 0.1$) or of $U2$ ($\varphi_{U2} = 0.2$) and their experimental forming limits (open circles) are depicted as a reference.

Excellent agreement is obtained between computed and experimental forming limits for strain paths $d_{U1}$, $d_{U2}$, $f_{U1}$ and $f_{U2}$. The predicted limit strains coincide with the scatter plots of corresponding test data. A discrepancy is observed for the prediction of the forming limit for strain path $d_{U2}$. It is assumed that the reason for this deviation is twofold: On one hand transient hardening effects could influence the material formability, especially for elevated pre-strains, followed by in-plane plane strain condition, as examined and reported for similar forming histories and similar sheet material in [25]. On the other hand, the FLSC approach applied account for isotropic hardening only and this causes limitations, which are discussed in depths in [21].

**SUMMARY**

The influence of the forming history on material formability is experimentally investigated. Therefore, entire strain paths and the forming limits are determined for sheet metal AA6016-T4, which is subjected to Nakazima testing in as-received condition and in various pre-strained conditions. It is observed that the shape of the strain paths vary distinctly from a

Points of intersection on the FLSC (open squares, labeled I, II and III) are shown.
straight to a curved shape for different specimen geometries of as-received material. The minimum of formability is found to be in the positive minor strain region, with a strain path which finally tends towards in-plane plane strain. Additionally, the effect of selected pre-strains on the formability is shown. In the theoretical part of this study, the FLSC for AA6016-T4 is calculated, using the curved shape of strain paths and their forming limits of sheet in as-received condition. The predictive quality of Arrieux’s FLSC approach is examined. The forming limits for different forming histories with abrupt as well as gradual change in the strain paths are predicted. Excellent agreement between the theoretical and experimental results is obtained. A small deviation is observed for a strain path, which consists of elevated uniaxial pre-strain and continues with in-plane plane strain. It is concluded that transient hardening effects could explain this result, considering that the theoretical FLSC approach, assumes isotropic hardening only.

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REFERENCES