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ON THE FORMING AND FRACTURE LIMITS OF SHEET METALS

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Abstract

The forming and fracture limits of stainless steel and aluminum were studied. Hydraulic bulge testing was employed in the stretch forming experiments. Marciniak-type in-plane tests and tensile testing were carried out to study the limit strains in the deep drawing region. Both screen-printed and laser-marked grids were used to measure the surface strains. Scanning electron microscopy was employed to measure the thickness strains and to study the fracture surfaces.

Key words: forming limits, fracture, aluminum, stainless steel

1. INTRODUCTION

It became apparent in the late 1980s that most manufacturing processes in the future would first be simulated before industrial implementation. Sheet metal forming was one of the applications where this technology could be applied [7]. One of the issues was how to correctly model the plastic behavior of sheet materials, especially yielding and the associated plastic flow [2].

For accurate numerical simulations information is needed not only, on the initial yielding, but also on subsequent work-hardening and final localization of plastic flow and/or fracture.

Forming limits have been studied since the mid-1940s, when Gensamer and Lankford and coworkers [3,6] carried out their tests with steel and aluminum. As they demonstrated, various forming limits may be obtained in principal strain-based coordinates, depending on the measurement technique. The closer the measurement is made to the fracture or local neck, the higher is the limit strain. This is due to the diffuse necking. The so-called "zero grid size" or thickness measurement on the fractured sheet results in a downwardly sloping fracture limit curve, which has been independently confirmed by many authors since then [5]. Plastic load instability curves usually give values well below the measured forming limits as illustrated in figure 1, which is taken from the work of Slota and Spišák [9].

It may be noted that if an initial trough or weakness is assumed when calculating the limit strains, as proposed first by Marciniak and Kuczynski, even lower limit strains near the plane strain are obtained. Near equibiaxial stretching, on the other hand, the M-K analysis usually results in rather large limit strains. These become, however, much lower if the shape of the yield surface is elongated through plastic anisotropy or is modified by other means, e.g. based on experimental results, in such a way that the distance from equibiaxial stretching to the plane strain becomes shorter. Then the localization of straining in the trough takes place faster. The M-K analysis is only feasible when such troughs or local

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necks can be observed experimentally in stretch forming. However, many advanced high-strength steels often fail by fracture without any detectable local necking in stretch forming. Moreover, local necks in stretch forming are difficult to detect experimentally also in many other metals and alloys. Various standardized methods have been developed to reduce the scatter in measuring the limit strains. Two different techniques to eliminate the strain peak due to diffuse necking have been proposed in the new ISO standard prEN ISO 12004-2 [8].

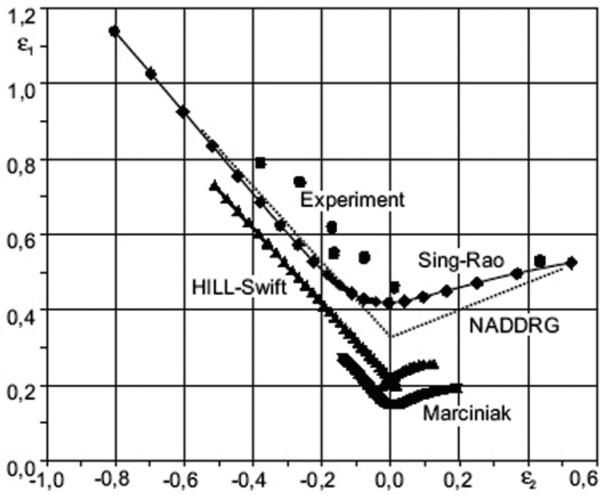

Fig 1. Forming limits curves for hot dip galvanized low-carbon steel DX 54D according to Slota and Spišák [9]. Usually the calculated necking limits are well below the experimental points, as shown in the figure.

Yet another method of determining the forming limits is to use stress-based coordinates instead of commonly used strain-based coordinates. A stress-based forming limit curve (SBFLC), such as first proposed by Arrieux, Bedrin and Boivin in 1982 [1], has since been claimed to be strain path independent by several authors [11]. Another method for determining the limit strains along curved strain paths would require integrating the effective limit strain along the strain path until the critical limit strain is reached. It may be noted that in the stress-based coordinates the differences between the various forming limits also become smaller due to the flattening of the stress strain curve at higher strains.

2. EXPERIMENTS

Experiments were carried out with various melts of AISI 304 type stainless steels and one experimental coil of AA 3104 type aluminum to study the forming and fracture limits. The yield and tensile strength values in the rolling direction for AA 3104 were 277 MPa and 298 MPa, respectively. For AISI 304 the values varied from $R_{p0.2}$ = 241 to 312MPa and R_m = 610 to 676 MPa depending on the composition of the melt. The total elongation of AA 3104 was 4.2 %, while for AISI 304 the values varied from 54.1 to 63.5 %.The experiments consisted of hydraulic bulge tests, deep drawing tests and tensile tests. Bulge tests were carried out with a circular die having a diameter of 100 mm and with two elliptic dies having major axes of 100/80 mm and 100/40 mm. A hydraulic 3 MN/2 MN deep drawing press was used to make Marciniak-type in-plane tests with the tools shown in figure 2. The punch diameter was 100 mm. For the strain measurements in the plane of the sheets, screen-printed and laser-marked square grids were used. They had sizes of 2 x 2 mm and 1 x 1 mm, respectively. Scanning electron microscopy (SEM) was employed to measure the thickness of the fractured samples.

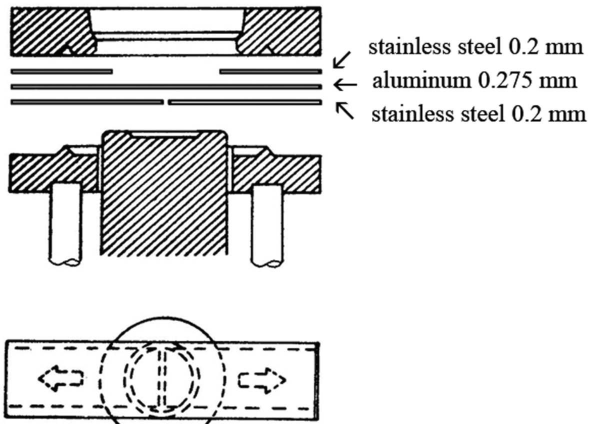

Fig. 2. In-plane stretching tools used for the experiments. For aluminum sheets two supporting AISI 304 sheets were used to prevent premature breakage near the die radius and to ensure uniform straining on top of the punch nose, as shown in the figure.

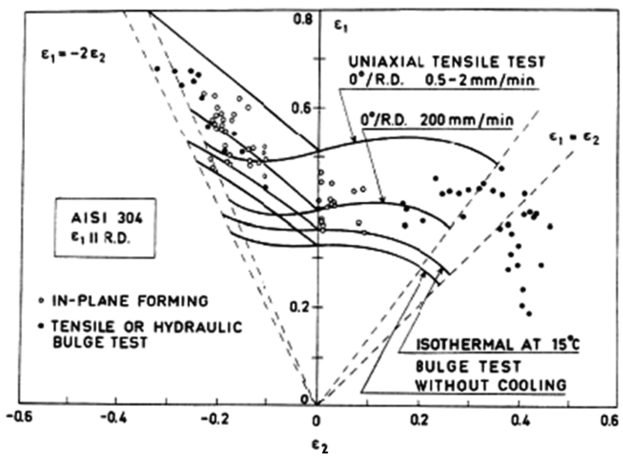

Fig. 3. Measured limit strains and calculated necking limit curves for the alloy AISI 304.

3. RESULTS

The measured limit strain curves and the calculated localized and diffuse necking limit curves for the AISI 304 stainless steel and aluminum alloy AA 3104 are shown in figure 3 and 4, respectively.

In stretch forming both the stainless steel and aluminum failed by ductile shearing without any visible local necking as illustrated in figure 5.

When a circular die was used the aluminum samples failed transverse to the rolling direction.

In Marciniak-type in-plane tests with the AA 3104 alloy, multiple necking was observed, as illustrated in figure 6.

In tensile testing, center cracking and subsequent local necking as well as local necking without previous center crack formation were both observed both in AA 3104 aluminum alloy and in AISI 304 stainless

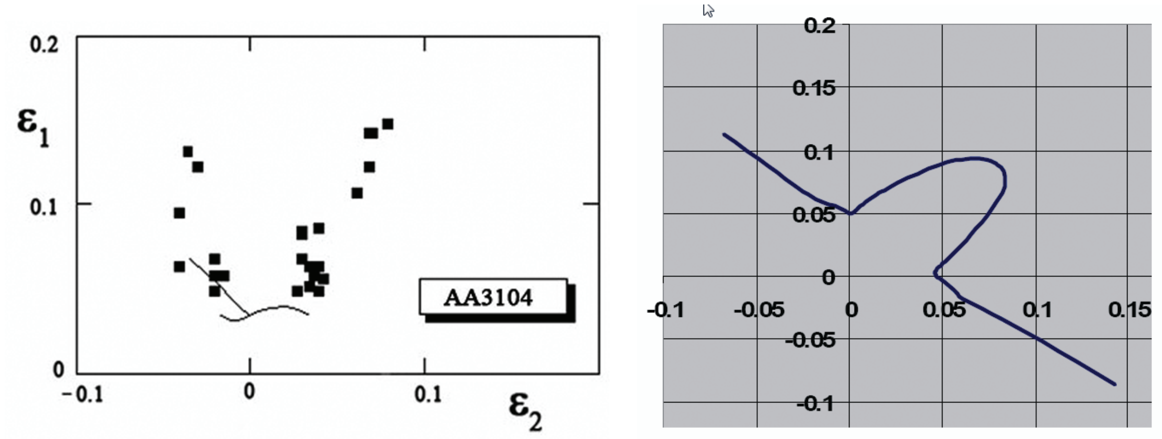

Fig. 4. Measured limit strains and calculated necking limit curves for the alloy AA 3104. Left figure shows limit strains measured from the screen-printed and laser-marked grids. Calculated diffuse and localized necking limits based on the Hollomon equation are also shown. The figure on the right shows calculated necking limits based on the Marciniak method [11]. Voce equation was used to describe the stress strain curve in this case.

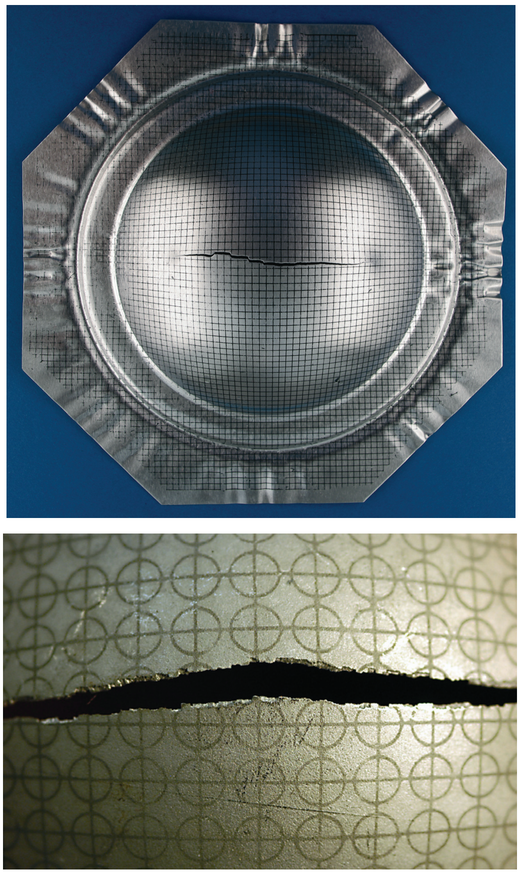

Fig. 5. Failures of aluminum (top) and austenitic stainless steel (bottom) in hydraulic bulging.

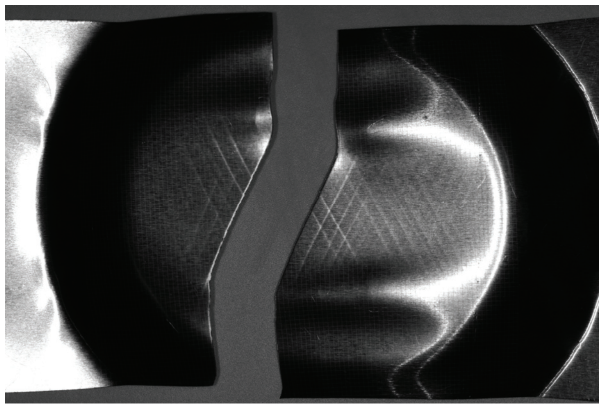

Fig. 6. An example of multiple necking in AA 3104 alloy in Marciniak tests.

steel. Examples of failed AA 3104 and AISI 304 tensile test specimens are shown in figures 7 and 8.

4. DISCUSSION

Although the forming limits of the AA 3104 were generally much lower than those of the AISI 304 stainless steel, they both failed in stretch forming by ductile shearing in the trough thickness direction without any visible local necking. The preferred failure direction for the AA 3104 alloy was transverse to the rolling direction as could be observed in the bulge tests with a circular die. This has been commonly observed in aluminum alloys and is contrary to the behavior of many steels.

both AA 3104 and AISI 304. However, no clear local necks were observed in the hydraulic bulging tests for either alloy.

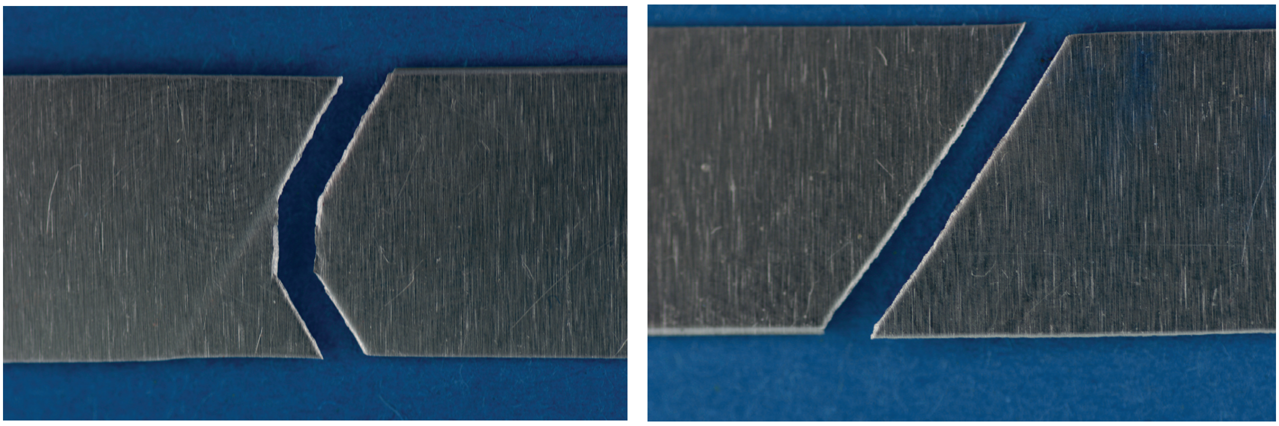

Fig. 7. Examples of failures of AA 3104 alloy in a tensile test. Both failures, including a center crack and subsequent necking (left) and necking without a preceding crack (right), were observed. The tensile test direction was transverse to the rolling direction in both cases.

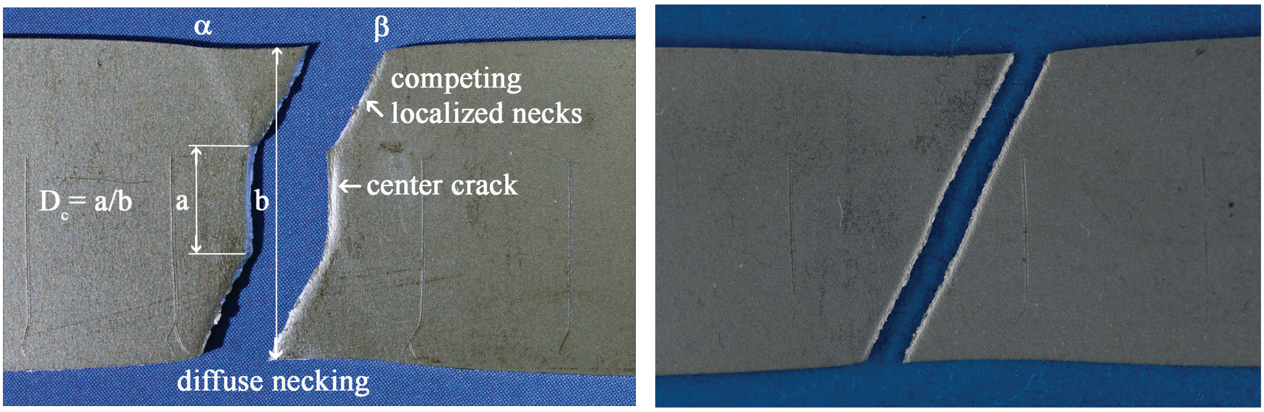

Fig. 8. Examples of failures of AISI 304 alloy in a tensile test. Both failures, including a center crack and subsequent necking (left) and necking without a preceding crack (right), were observed.

Multiple local necking in Marciniak-type tests has been reported previously in low-carbon steels [4]. Such behavior has been recently reported also in some FEM simulations, too. Such behavior indicates rather uniform straining at the bottom of the punch nose. The local necks are nearly parallel to each other and consist of two distinct set of characteristics.

There was considerable scatter in the limit strains measured for the AA 3104 alloy. Despite the relatively good accuracy of the laser-marked grid, the measured strain values varied greatly. The highest strain values near equibiaxial tension in figure 4 were measured from screen printed grids. Some qualitative support for the measurements may be obtained from an earlier work [10], where very low values below 0.05 were reported near the plane strain for an AA 3104 alloy. The Voce equation used to describe the stress strain curve in the Marcinak simulations describes better the strain hardening of

In tensile testing two failure modes, i.e. either central cracking and subsequent local necking or local necking without any preceding central cracking, could be observed in both the AISI 304 stainless steel and the AA 3104 alloy. The factors determining the type of the tensile failure are not well understood. The fracture mode may depend on the boundary conditions and the preparation of the tensile test specimen.

5. SUMMARY AND CONCLUSIONS

The formability of AISI 304 austenitic stainless steel and AA 3104 aluminum alloy was studied by carrying out hydraulic bulging, deep drawing and tensile tests. In stretch forming both materials failed by ductile shearing without any preceding necking. Multiple necking was observed in Marciniak-type deep drawing tests for the AA 3104 alloy. In tensile testing both central cracking and subsequent local necking as well as local necking without any preceding cracking could be observed in both stainless steel and aluminum.

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O OGRANICZENIACH ODKSZTAŁCENIA I PĘKANIA BLACH CIENKICH

Streszczenie

Badaniom poddane zostały ograniczenia możliwości odkształcania i pojawianie się pęknięć w blachach ze stali nierdzewnej i aluminium. Test hydraulicznego wybrzuszenia został przeprowadzony w procesie formowania z rozciąganiem. Test typu Marciniaka oraz testy rozciągania zostały przeprowadzone w celu zbadania granicznej odkształcalności. Siatka naniesiona metodą sitodruku i laserem została użyta do pomiaru odkształceń powierzchni próbki. Ponadto, użyto mikroskopu skaningowego do pomiaru odkształceń na grubości i badania powierzchni pęknięć.

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