Development of a Nakazima formability test methodology for high temperature applications on titanium alloys sheet metal

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Abstract: Forming Limit Curves (FLCs) in applications of hard-to-form materials results essential to optimise the complex forming processes involved. The need of applying high temperature in most of these applications increases the importance of FLCs for cost-effective procedure designs. Nevertheless, either a lack of knowledge is detected relative to this field in literature, or the experimental methods proposed to obtain FLCs result complex to be executed. In the present work, an easy-to-use methodology based on the traditional Nakazima test is proposed and the research has been applied to different titanium alloys. For that, a heated Nakazima device was developed and some new geometry for test samples was proposed. The results agree with those obtained by other authors in similar conditions, what validates the approach developed herein.

Keywords: Forming Limit Curve, Titanium alloys, Nakazima test, High Temperature.

1. Introduction

Forming Limit Curves (FLCs) are one of the main tools in the field of sheet metal forming, due to their simplicity of use and wide range of application. Their determination is usually done by means of several specific tests as the Nakazima, hydraulic-gas bulge and Marziniak tests [1,2]. These tests are focused on triggering a deformation to sheet metal under different strain states. To promote those, several sample geometries must be defined. The hydraulic-gas bulge test consists of applying force against the sheet by means of a fluid-gas under pressure [3]. Despite the uniform distribution of the force on the surface of the sample, this test requires a complex facility, especially if high temperature must be applied. Marziniak and Nakazima tests produce the sheet metal deformation by a mechanical punch. The difference between them is the geometry of the punch used, that is, flat in Marziniak’s and hemispherical in Nakazima’s. Although Marziniak test is broadly applied for sheet metal characterization, it presents the drawback of being necessary to guarantee the frictionless condition to avoid the failure on the punch edge [1]. These limitations suggest to most researchers to select the Nakazima procedure and so that it has been widely used on traditional deep drawing quality or easy-to-form materials.

Nevertheless, alloys with poor formability, like titanium alloys, should be heat assistant-processed and, consequently, their characterization should be obtained under the same conditions. Different solutions were proposed to characterize the formability at high temperature. Gao et al. [4] studied the forming limit of AA2060-T83 at 300 to 450°C by integrating the test assembly into a furnace. Junjia et
al. [5] evaluated the formability up to 900°C of 22MNB5 steel using a Nakazima device having electrical heating elements. Batalha and Button [6] heated a sheet metal in a furnace before testing, and transferred it to a press for testing. This simplified the test set-up at the expense of poor test temperature monitoring. Induction heating is widely used, although it is difficult to establish the test temperature. However, the induction loop should be removed or disconnected prior to the test, which makes it difficult to achieve a constant and homogeneous test temperature. To avoid the temperature drop, Wang et al. [7] added a secondary heating system using cartridge heaters inside the punch. Kotkunde et al. [8] and Mahalle et al. [9] used this solution in combination with a water-cooling temperature control system. Thus, this permitted the FLC of the Ti6Al4V alloy at 400°C and IN718 alloy up to 700°C were obtained. Ma et al. [10] pointed out the improvement in the Nakazima test performance with a non-uniform temperature distribution in the sheet, which made the fracture to occur in an appropriate zone. They found as well that the limit strain was only dependent of the final temperature. In subsequent work, Ma et al. [11] introduced temperature variation in the Marziniak-Kuczynski model to predict sheet metal failure in non-isothermal stamping conditions.

From the works analysed, it seems clear that temperature control is of vital importance for all the elements involved in any test device developed and that the definition of FLCs under high temperature situations has been little addressed. In addition, in the recent time, cutting edge heat assistant-forming processes applied to titanium alloys are wakening a great interest and it is essential to develop a procedure for a technological test, like Nakazima, to be used at high temperature. In this work, it is presented an extension of the Nakazima device that permits tests up to 750°C to be carried out. The methodology was executed over two different titanium alloys, Ti62 or pure titanium grade 2 (UNS R50400) and Ti6Al4V (UNS R56400) alloy and the results obtained allow us to establish its validation.

2. Description of a high temperature Nakazima device

A new heat assisted Nakazima device was designed and built that allows temperatures up to 750°C to be reached under controlled conditions. The device consisted of three main parts: a fixed lower die, an upper die or blankholder and a 80-mm hemispherical punch, as shown in figure 1. The bottom die and the blankholder was fixed to the lower and the intermediate plates, respectively, of a guiding frame that was actioned by a hydraulic system. The maximum clamping force that can be applied was 30 kN. The punch was joint to the highest plate of the guiding system and can slide freely. The whole guiding device was located between the platforms of a universal test machine IBERTEST UIB 200kN AN, (S.A.E. Ibertest, Madrid, Spain) that actions the punch directly.

Special drawbeads were designed to clamp the sheet avoiding the breaking of the sheet in this area. This is essential in hard-to-form materials like Ti6Al4V alloy. In figure 2(b), a detail of the drawbeads designed can be appreciated.
To obtain a uniform distribution of temperature during the tests, two independent electric resistance heating zones were defined, one for each die, that were suitably insulated to optimize the thermal efficiency. Temperature control was carried out by means of two main K-thermocouples connected to PID-controllers that were located in the central area of the hot chamber of both dies. The split of the heating and control system in two areas lead to obtain a robust temperature management of the main elements involved. In figure 2, a detail of the heating system is depicted.

However, the high thermal inertia and construction characteristics of the punch would make it difficult to reach the requirements of tests temperature. This means that during the tests the temperature of the sheet would substantially change [12]. Thus, it was necessary to control the punch temperature, and, for that, a third thermocouple was introduced into it. This allowed us to control the punch had reached a suitable temperature, close to the test target, to start the test avoiding a relevant temperature drop of the sheet. Finally, the real temperature of the sheet was registered by a fourth thermocouple in contact with it at the bottom side as shown in figure 2.

![Figure 2. The heating control elements in the developed Nakazima device.](image)

2.1. Test Methodology

Sheet metal samples of Ticp2 and Ti6Al4V alloys with a thickness of 0.8 mm were machined according to different proposed geometries inspired in literature or standards to achieve the failure of the sheet under plane-strain, near-biaxial and uniaxial-tensile conditions. The mechanical properties for both materials, obtained in a previous work [13], are collected in table 1.

|            | Temp. (°C) | \(\sigma_{0.2}\) (MPa) | Strain hardening, n | Strength coef., K (MPa) | Normal anisotropy, \(r_n\) | Planar anisotropy, \(\Delta r\) |
|------------|------------|-------------------------|---------------------|-------------------------|-----------------------------|-------------------------------|
| Ti6Al4V    | 25         | 1017                    | 0.041               | 1255                    | 1.97                        | -1.70                         |
|            | 450        | 565                     | 0.065               | 848                     | 1.55                        | -0.98                         |
| Ticp2      | 25         | 368                     | 0.135               | 368                     | 5.78                        | -0.44                         |
|            | 450        | 100                     | 0.183               | 100                     | 4.59                        | 0.11                          |

To measure the failure final strain after each test, an electrolytic marked was carried out by means of an Ostling EU-Classic 300 (Ostling Inc, Solingen, Germany). Two different grid patterns were tried with 1 and 2 mm-diameter circles, respectively [14]. However, 1mm-circles were left due to their low resolution that led to a significant measuring error. By a trial-error procedure, the marking parameters, voltage and time, were set up to optimize the contrast of the grid. A solution of HNO₃ and glycol was employed as electrolyte. To reduce the surface oxidation during the tests at high temperature, the bottom side of the sheet was covered with a fine layer of boron nitride powder. The sheet face in contact with
the punch was covered with MoS$_2$ or h-BN depending on the temperature [13], to reduce friction and eliminate the tangential stresses involved, which could lead to a strain-state far away from the desired one [1,15].

Once the system (specially the punch) was preheated to the target temperature, the sheet sample was put between the dies, applying the clamping force through the blankholder. Around 10 minutes were necessary to reach a homogeneous temperature of the sheet. Temperature configuration must be slightly higher than the target one for compensating the unavoidable heating losses through the system, as shown in Table 2. As it can be seen, the thermal behaviour of all device elements was similar for the whole testing temperature range, which ensured a uniformity in the procedure under any test condition. The oscillation in the temperature of the sheet during the test did not exceed 20ºC in any case, which shows the great thermal stability of the developed device. Finally, the punch velocity during the test was 10 mm/min.

| Target Temp. (°C) | PID Temp. (°C) | Sheet Temp. (°C) | Punch Temp. (°C) | Sheet Temp. Variation (°C) |
|-------------------|----------------|-----------------|-----------------|--------------------------|
| 300               | 305            | 301             | 276             | 9.5                      |
| 450               | 475            | 446             | 406             | 16.8                     |
| 600               | 625            | 585             | 525             | 13.5                     |
| 750               | 775            | 721             | 646             | 15                       |

2.2. Measuring of the limit strain

The constructional and operational characteristics of the device to operate at high temperature made the use of Digital Image Correlation (DIC) systems for strain measurement very difficult. Therefore, despite its lower accuracy and discrete measurement, the traditional method of marking and measuring a regular circular pattern was used. The change of the marked circles after the test was measured by a stereoscopic microscopy. From the images obtained, all points of each deformed circle were fitted to an ellipse to obtain the value of the mayor and minor axes and work out the principal strains.

![Figure 3. Inverse parabola fitting according to ISO standard for the Ti6Al4V uniaxial tension at 25°C.](image-url)

To determine the limit strain, the procedure described in ISO 12004-2:2008 [14] was carried out. Thus, deformations were measured in points along a straight line perpendicular to the fracture one and then, fitted to an inverse parabola. Therefore, the value of the fracture limit strain was evaluated as can be seen in figure 3. The accuracy of this method depends on the number of points measured in the neighbourhood of the fracture, i.e., it is highly dependent on the size of the grid used [2]. Nevertheless, this method is a good approximation when DIC systems cannot be applied.
3. Results and discussion

3.1. Discussion on the sample design

Samples designed as ISO 12004-2 proposes were suitable for the uniaxial and biaxial tensile states as the failure appeared in the dome area in all cases. However, under plane strain condition, great difficulties were found to promote a correct failure of the sheet due to the mechanical characteristics of each material and the maximum force possibility of the machine used. To overcome those limitations, a new proper sample designs were developed and proven. Properly, the low plasticity of the Ti6Al4V alloy promoted the frequent breakage of the material in the drawbead-clamping area, regardless of the specimen shape and size, as can be seen in figure 4(a) to figure 4(d). The use of samples with an outer complete ring solved this problem and a severe mark on the sheet for drawbeads was not necessary, figure 4(e) and figure 4(f). Different states of deformation were achieved by machining tailor made hollows on each side of the specimen axis, figure 4 to figure 6. Particularly, in figure 4(e) to figure 4(f) although a better performance with the solution indicated was achieved, the position of the hollows respect with the maximum stress area of the sample is very important to avoid the cracking propagation outwards, figure 6(b).

![Figure 4. Sample geometries discarded for evaluation of the forming limit curves, FLC, of Ti6Al4V alloy at room temperature. Yellow lines designate the failure location.](image)

The drawbeads designed for Ti6Al4V implies a limited holding capacity for certain specimens and materials, as it was the case of Ticp2. Although Ticp2 presents high plasticity and no problems relative to hard-to-form materials were expected, its high drawability involved high deformations in the process and the mechanical action on the blankholder made difficult to hold the sheet. Thus, an auxiliar holding system had to be used. The high drawability is justified by a great Lankford index-value of this material. The high anisotropy promoted a severe stress gradient in the sample, figure 5(e), that finally provoked the breakage out of the dome area. Effectively, the central area of the sample was deformed under plane strain condition involving higher plastic work than the outer area submitted to unbalanced tension according to Hill-48 criterion [16]. Thus, a more traditional sample was tested with good results, as shown in figure 6(e). This last design, together the uniaxial and biaxial ones allowed us to work with three valid areas to build the FLC of Ticp2 at any temperature, figure 6(d) to figure 6(f).
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Figure 5 Types of samples discarded for the evaluation of the FLCs of Ticp2 alloy. (a) Insufficient clamping force with the result of drawing. (b), (c) and (d) depict failure in wrong areas under an unbalanced tension. (e) distortion of the yield loci due to a high anisotropy according to Hill-48 criterion.

Figure 6. Samples validated for Nakazima test. Application at 450 ºC. (a) Ti6Al4V uniaxial tension. (b) Ti6Al4V plane strain. (c) Ti6Al4V biaxial tension. (d) Ticp2 uniaxial tension. (e) Ticp2 plane strain. (f) Ticp2 biaxial tension.

3.2. Forming Limit Curves
From the samples tested, the strains in the close fracture area were measured and represented in a typical $\varepsilon_1$- $\varepsilon_2$ diagram, figure 7. According to the ISO procedure afore indicated, the FLCs were drawn from three strain-state areas, what are enough to quantify the influence of the temperature in formability. Moreover, the strain measurements of discrete points classified according to the traditional procedure proposed by Hecker, which classifies the marked deformed ellipses into acceptable, necked and fractured [2], were also represented. At the results viewpoint, for Ti6Al4V, the ISO criterion may be considered some conservative as the corresponding curves are long distanced from the fracture points.
in some cases. The temperature increase resulted in an average formability improvement of about 13% for Ti6Al4V, with the largest increase (close to 18.7%) occurring in the plane strain ($\varepsilon_2 = 0$) area. These results agree with those existing in literature for similar condition [17]. For the case of Ticp2 the increase in formability due to temperature was around 25%. However, despite the use of lubricant, it was not possible to obtain points close to the biaxial state due to the higher friction coefficient of this material [13, 18], so the formability analysis could only be obtained for the second quadrant ($\varepsilon_2$ negative values).

Figure 7. FLCs corresponding to (a) Ti6Al4V at 25ºC. (b) Ti6Al4V at 450ºC. (c) Ticp2 at 25ºC. (d) Ticp2 at 450ºC.

4. Conclusions
A Nakazima testing device was developed which, together with the specific samples designed, led the authors to solve the researching problems existing in this field for the alloys proposed. The device allowed to obtain a high thermal stability, with a deviation of less than 20ºC in the sheet, during the test at any temperature. Thus, the results obtained in preliminary tests demonstrated the capability of the developed methodology to obtain the FLC of the titanium alloys in a wide range of temperature conditions (25ºC to 750ºC).

Particularly, tests were carried out at 25 and 450ºC for Ticp2 and Ti6Al4V alloys to validate the test approach proposed. A careful analysis of the shape and dimensions of the samples was performed to optimize the success of the tests. For plane strain condition, that constitutes the most complex state, complete disks with machined hollows conducted to evaluate the Ti6Al4V formability. FLCs for the materials and temperatures involved here were represented according to ISO and Hecker criteria. The evaluation of the formability improvement with the temperature was very sensitive and an average improvement of 13% and 25% was obtained for Ti6Al4V and Ticp2, respectively.

Future work must be plan forward achieving more strain paths and reduction of the friction punch-sheet existing that can distort the biaxial strain path.
Acknowledgements
This research was funded by the Regional Research Plan’s financial support promoted by the Government of Castilla-La Mancha and FEDER funds: project PREJCCM2016/13.

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