DETERMINATION OF FORMING STRAIN RATIO OF SHEET METALS TO AUTOMOBILE APLICATIONS

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Abstract. *Most of the automobile industries in Brazil are seeking to localize their components in order to optimize their production costs. A great number of these components are made by stamping processes, and are considered as safety products, as life depends of its performance. One of the most common raw material normally used in the automobile industry is the ST4 LG (DIN 1624) that, in some cases, is imported from overseas. The main reason of this study was to verify the performance of the imported ST4 LG (DIN 1624) in comparison to the local raw material G4 RL (NBR 5007). It was made tests at the stress tensile machine to determine the anisotropy coefficient (Lankford R) and the work hardening coefficient n. Besides of this, the determination of the Forming Limit Diagrams (FLD's) was determined in order to compare and to verify the possibility to substitute the imported ST4 LG by the local G4 RL. It is possible to define that the Forming Limit Diagram is a empiric failed criterion where the maximum and minimum principal strain are evaluated for the verification of the deformation severity of the material that was submitted to a forming processes like, stretching, drawing and tensile stress. After proprieties R and n were identified and FLD determination was generated it was evaluated the similar local raw material that allow us to get results near to the imported raw material. As a result, we can say that the local raw material has enough characteristics to substitute the imported raw material. This was also confirmed in the practical experiences afterwards.*

Key-words. *Material Nationalization, Tensile Tests, Forming Limit Diagram.*

1. INTRODUCTION

Since 50's, period which the automobile industry was develop in Brazil with big companies like Volkswagen, Ford and General Motors, the Brazilian market characteristic has been focuses the international car assembly lines. This fact influences the production of the components to assembly the cars. A great number of these components are made outside Brazil. The Curitiba Industrial Park, established in São José dos Pinhais - PR, is a example of this situation.

The production cost, that involves transportation, high inventory level and the necessary logistic efforts to bring the pieces from overseas, is really high. Trying to decrease these costs, many automobile companies in Brazil are seeking to improve their localization program, manufacturing the components locally. The first step to get into this strategy is localizing the components raw material.

In the localization process, tests were necessary to analyze two material ranges; the original one, used in the normal production and its Brazilian alternative. Many of these tests were developed to study the sheet metals strain (Borsoi, 2000; CamSys, 2000; Usiminas). By the results of these tests is possible to compare and specify the similar local raw material in substitution to the imported one.

In last fifty years a lot of laboratory tests were developed to evaluate the sheet metals performance in industrial scale. Tensile tests (Schaeffer, 1999; Souza, 1974) and Nakajima drawability tests (Borsoi, 2000; CamSys, 2000; Usiminas) are among the main experiments used to study the sheet metal formability. The tensile tests results define the formability parameters and mechanical properties of the metal sheet, while Nakajima's tests define the forming limit diagram (FLD).

The elongation (E), ultimate tensile stress (UTS) and yield stress (YS) are some of the mechanical properties given by tensile tests. This test provide also the strain hardness exponent (n) and anisotropy coefficient (R). The strain hardness exponent define where the plastic region is formed, and the anisotropy coefficient define the capacity of the steel metal sheet to deform in different rolling direction. This formability parameters are very important to analyze the behavior of the steel during the stamping process (Askeland, 1996; Bresciani, 1991; Dieter, 1981; Lange, 1993).

Nakajima's method is one of the usual techniques to plot the forming limit diagrams (FLD's). The FLD's can be used to verify the similarity between two materials by the comparison of the diagrams strain distribution profile, that define the stamping material characteristics.

In the present work the imported St 4 LG (DIN 1624) sheet metal was analyzed. The local G4 RL (NBR 5007) was tested as a possibility to substitute the imported steel metal sheet. It was evaluated the performance of both specifications trough the formability parameters n and R, and trough the forming limit diagram.

2. EXPERIMENTAL WORK

2.1. PROPOSED TESTS

The proposed tests were divided in two parts. In the first part it was evaluated the mechanical properties and formability parameters by tensile tests. This part was called fundamental properties tests. The second part, called practice simulative tests, was the Nakajima's test, necessary to plot the forming limit diagrams.

Tensile test is an axis test method to strain standard specimens (Schaeffer, 1999; Souza, 1974). This test give the main characteristics of the material, like yield strain (YS), strain hardness exponent (n) and anisotropy coefficient (R) when the specimens are deformed until 18% of elongation. Other properties like maximum elongation (E) and ultimate tensile stress (UTS) are obtained from the sample failure. Tensile tests were carried out using machined samples as per ASTM E 8M, DIN 10002 and NBR 6673 specifications. The samples were tested along three directions, with the tensile axis being parallel (0º), diagonal (45º), and perpendicular (90º) to the rolling direction of the sheet (Fig. (1)). The influence of the rolling direction is analyzed by results to each specimen direction.

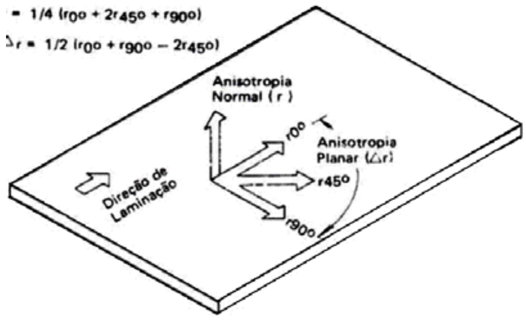

Figure 1. Tensile tests samples used in the experiments.

One of the most common methods to get the forming limit diagram (FLD) is the Nakajima test. Samples with different geometry are fixed in a die and formed by a spherical punch with 100 mm diameter.

The samples preparation is an important step in Nakajima test. This is justified because of the use of just one punch geometry. With a defined kind of punch, different samples geometry are responsible to get a good strain distribution profile during the tests. The strain distribution profile evaluates the forming process by stretching and drawing the material, and also comparing their characteristics. The right side of the X axis represents the stretching process of the sheet metal, while the left side represents the drawing process. Nakajima (Usiminas) considers 18 different samples geometry. Samples length are around 200 mm and width varies between 40 and 200 mm. A reduced number of blanks, with only 8 geometries (CamSys, 2000), can be used to compare the FLD's no affecting the results accuracy.

The 8 blanks used in the experiments are shown in Figure 2.

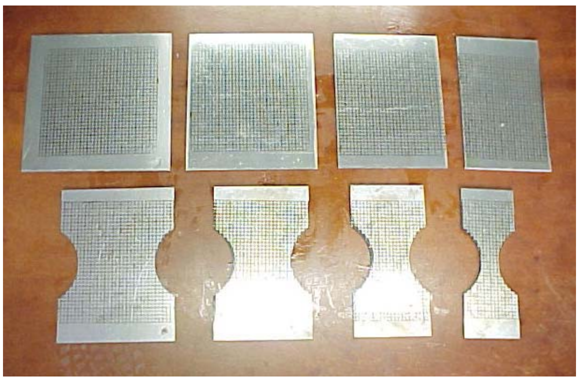

Figure 2. Models of blanks used in Nakajima's tests.

All samples shown above (Fig. (2)) were cut with 200 mm length. The width of samples 1, 2, 3 and 4 varied between 125 and 200 mm, while the width of samples 5, 6, 7 and 8 varied between 75 and 150 mm, always with differences of 25 mm. The last four samples however, have a circular engraving with 50 mm of radius. This engraving was to avoid failures in the region where the draw bed fix the sheet of small width on the die. Any failure at this point could reprove the experiment. This fact determine the strain distribution profile, i. e., if the stamping process is simulating stretching or deep drawing preferentially (Kumar, 2002).

The deformation of the material was measured using a grid marked in the samples. The circles with an initial diameter Do, became ellipses after sheet was stretched. The major and minor diameters of the ellipses, D1 and D2 respectively, were measured (Fig. (3)). With the D1 and D2 values, the true strain ε_1 and ε_2 were calculated by the following Equations (1), (2), (3) and (4):

$$e_1 = \frac{(D1 - Do)}{Do} \quad (1)$$

$$e_2 = \frac{(D2 - Do)}{Do} \quad (2)$$

$$\varepsilon_1 = Ln(e_1 + 1) \quad (3)$$

$$\varepsilon_2 = Ln(e_2 + 1) \quad (4)$$

where:

Do = initial diameter
D1 = major diameter of the ellipse
D2 = minor diameter of the ellipse
e_1 = major engineering strain
e_2 = minor engineering strain
ε_1 = major true strain
ε_2 = minor true strain

The ε_1 and ε_2 values were used to plot the forming limit diagram for both raw material (ST4 LG and G4 RL).

2.2. MATERIALS AND EQUIPMENTS

The table below (Tab. (1)) shows the standard values of the yield stress, ultimate tensile stress and elongation for both materials used in this work. It was used a 3 mm thickness sheet for both raw materials.

Table 1. Steels standard mechanical properties.

Properties	**Imported Steel St 4 LG DIN 1624**	**Brazilian Steel G4 RL NBR 5007**
YS (N/mm²)	Max. 225	Max. 235
UTS (N/mm²)	270 - 350	270 - 350
E (min. %) Thickness ≥ 3 mm	40	38
Bending	-	0E

The tensile tests was made in a 10 ton capacity EMIC testing machine. A maximum opening of 25 mm extensometer was used in the tests. The results of the experiments were calculated in a computer by Tesc 6.0 program, using a special test method developed by EMIC to get the mechanical and formability parameters according to the standards ASTM E 517 and ASTM E 646. The graphics Stress vs. Elongation were also obtained.

An 80 ton capacity servo-hydraulic machine was used for the Nakajima tests. The tooling in the experiments was made according to dimensions specified by Nakajima method. It was composed by a punch with 100 mm of diameter and a die, where the blank were fixed the samples during the punch-stretching. The test machine was still equipped with a manometer, to indicate the sheet metal strength, an eletro-optical scale to evaluate the height of the strain, a hydraulic valve to control the strain velocity, and a video camera. The video camera was positioned under the die in order to show the strain of the material during the test and indicate the instant of the failure. The accuracy of the tests depends of these equipments. It was possible to stop the movement of the punch just at the beginning of the failure.

A Jones & Lamson profile projector was used to obtain the major and minor diameters of the ellipses. Microsoft Excel was used to calculate the engineering strains (e_1 and e_2), the principal strains (ε_1 and ε_2) and to plot the forming limit diagram.

2.3. EXPERIMENTAL DEVELOPMENT

Initially it was identified the similar local raw material that had the standard characteristics like mechanical proprieties and chemical composition near to the imported one (Askeland, 1996; Bresciani, 1991; Dieter, 1981; Lange, 1993). G4 RL was then selected as a more similar raw material to start the tests.

The experimental evaluation started with tensile tests. It was prepared five samples in each rolling direction, 0º, 45º and 90º. The samples were deformed until 18% of elongation and than identified the results of yield stress (YS), strain hardening exponent (n) and anisotropy coefficient (R). Other three samples to each direction were machined in order to get the ultimate tensile stress (UTS) and elongation (E). The stress x strain graphic was plotted for every sample and for the eight-sample geometry shown in Fig. 2. The samples were deformed and the test was interrupted when the failure was detected. An important step after the drawing tests was the identification of the regions (ellipses) to measure and to evaluate the strain of the sheet metal. Three specific regions were measured; the opposite side of the failure, but in the same height of strain; the failure region and the region up and down to the failure.

The region in the opposite side of the failure was measured because the main aim of this work was to analyze the major strains supported by each material, and in this place the stretch is proportional to the failure, i.e., it is in the same height where the major force was applied. The failure region and the region up and down to the failure were measured to compare the strains with the opposite side of the failure. The major diameter of the ellipses, in the failure region, was obtained by adding the two separate parts of the broken ellipse.

The Equations (1), (2), (3) and (4) were included in this table, to calculate the engineering strains and true strains by the major and minor diameters of the ellipses. The forming limit curve was drawn taking the major strains points (ε_1) in Y axis. Three curves for each raw material were plotted, one for each region mentioned above.

3. RESULTS

In the Tab. (2) below we can find the results of the tensile. The values are an average of the five tested samples, where R_0, R_{45} and R_{90} are the anisotropy coefficient in the 0º, 45º and 90º directions respectively. The values of strain hardness exponent for the same directions are n_0, n_{45} and n_{90}. In the table are still the average values of yield stress, ultimate tensile stress and elongation.

Table 2. Tensile tests.

Properties	**Imported Steel St 4 LG**	**Brazilian Steel G4 RL**
$\mathbf{R_0}$	1.4351	1.1999
$\mathbf{R_{45}}$	1.1039	0.9032
$\mathbf{R_{90}}$	1.3940	1.2587
$\mathbf{R_m}$	1.2592	1.0663
$\mathbf{n_0}$	0.1787	0.2012
$\mathbf{n_{45}}$	0.1812	0.1844
$\mathbf{n_{90}}$	0.1844	0.1814
UTS (MPa)	308.2	305.8
YS (MPa)	202.4	193.9
E (%)	44.72	48.70
Bending	0E	0E

The Tesc 6.0 program were used to get the results of the tensile tests, were it was possible to get the Stress x Strain curves. These graphics are shown in the figure 3 and 4.

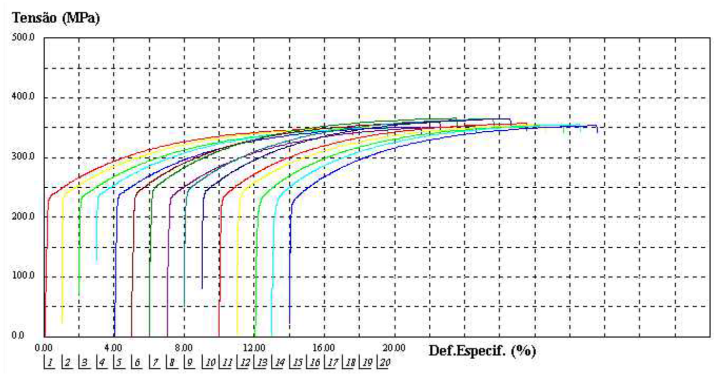

Figure 3. Stress x Strain curves for imported steel.

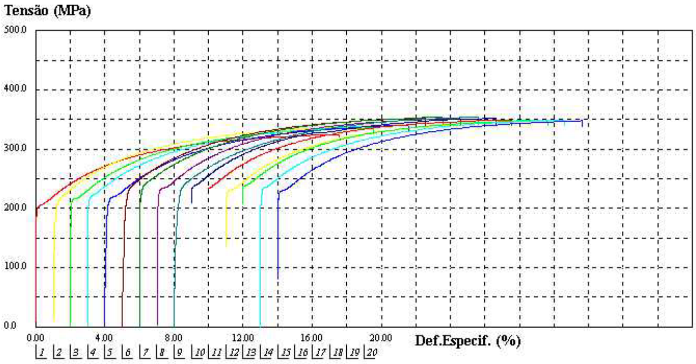

Figure 4. Stress x Strain curves for local steel.

In the next figure (5, 6 and 7) it is shown the forming limit curves (FLC) form Nakajima tests.

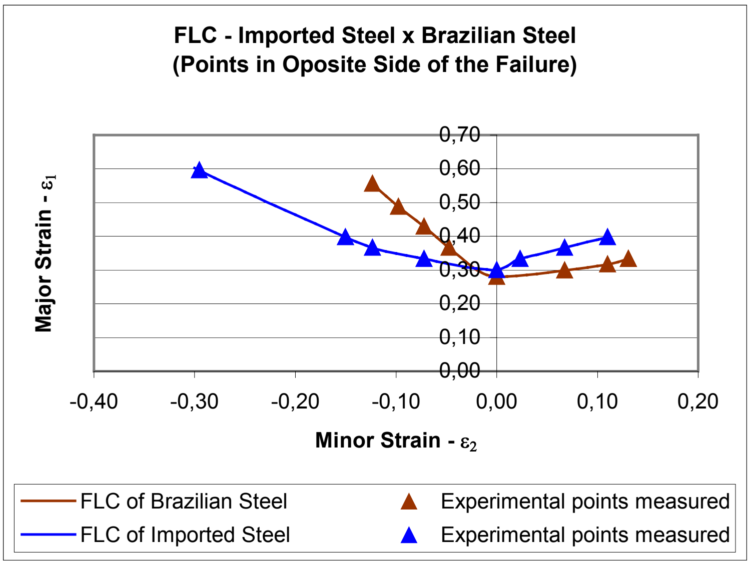

Figure 5. FLC for the region in the opposite side of the failure.

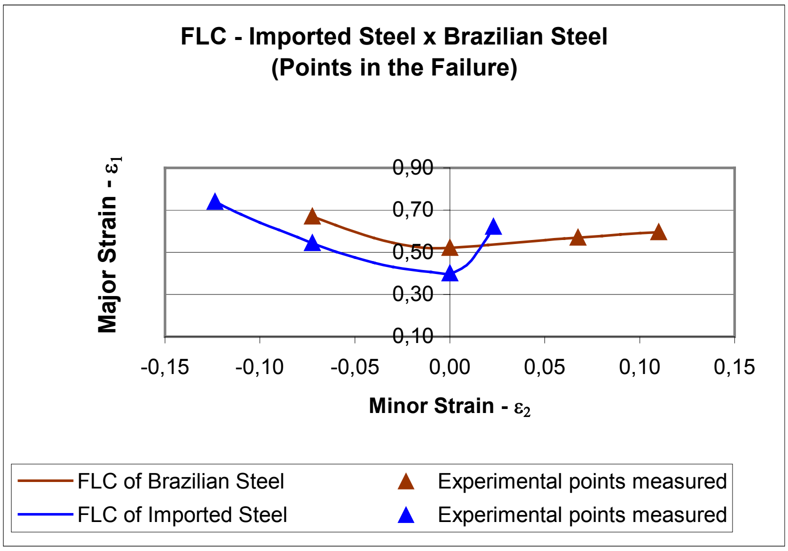

Figure 6. FLC for the points in the failure region.

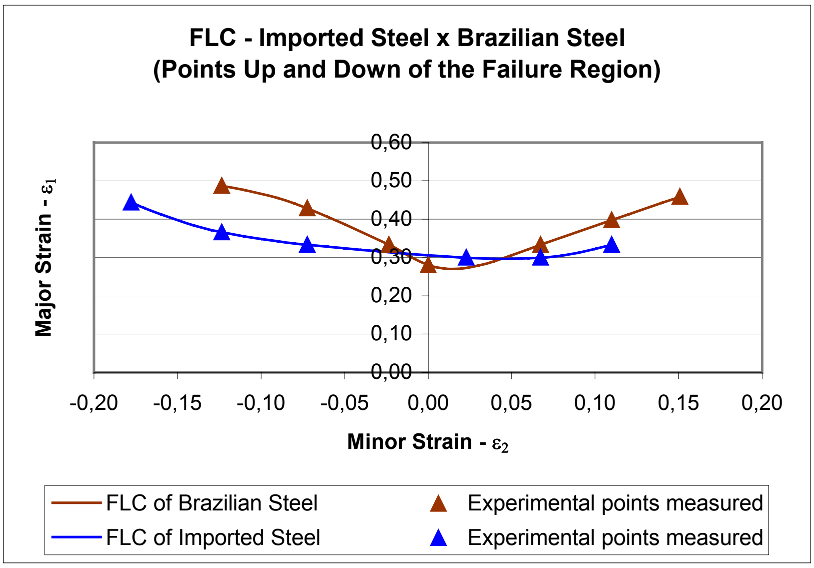

Figure 7. FLC for the up and down region of the failure.

The forming limit curve were plotted together (red curve for local steel and the blue curve for imported steel) to facilitate the comparison between the steels.

The minor strains (ε_2), calculated by the minor diameter of the ellipses, were represented in the X axis of the diagrams, while the major strains (ε_1), obtained from major diameter of the ellipses, were represented in the Y axis. An important characteristic of these graphics is that the major strains were always positive and the minor strains were positive and negative. This fact happened because the ellipses reached to its major axis a diameter major than the original circles diameter printed in the samples. The diameters of the minor axis were some times major and some times minor than the original circles diameter, what caused positive and negative strains respectively. The major strain represent the maximum limit that the material can support without failure, and the minor strain is distributed in positive and negative points, simulating the stretching and drawing stamping conditions respectively.

The stretching condition was represented in the right part of the curve, where the strains were positive. This was caused by the samples of 200, 175, 150 (models 1, 2 and 3) and, in part, by the sample with 125 mm (model 4) width. The width of the last sample, excepting the model 4, permitted that the draw bed held the blank in all parts around the punch (CamSys, 2000), getting a uniform (homogeneous) reduction of the sheet thickness according to Schaeffer, 1999. Otherwise, the sample with engraving caused the drawing stamping condition, which is characterized by a local (no uniform) reduction of the sheet thickness. This condition, represented in the left part of the graphics (negative strains), was caused due the specimens were not totally fixed by the draw bed during the experiments. The engraving part of the samples permitted that the material had enough capacity to be formed in this direction (Kumar, 2002).

4. DISCUSSION

The results of the yield stress, ultimate tensile stress and elongation obtained from tensile tests were close between imported and local steels. These values were in accordance to the material standard (DIN 1624 and NBR 5007), that determine a range of values for these properties. The results of the strain hardness exponent (n) were also close between the two steels, but with a variation to the 0º in the rolling direction. Anyway, this was not enough to reprove the local raw material as according to the tensile test standard a minimum of three samples are necessary for this evaluation and some of the samples could be scrapped.

A major distribution of the results was observed in the anisotropy coefficient (R). The results of this parameter for local steel were minor than the imported steel values. A minor value of R indicates a minor forming strain ratio of the sheet metal. This result is not enough to affect the condition for the local steel to substitute the imported material. However, some precautions are necessary before the tryout of the pieces, to avoid possible failures caused due the minor R of the Brazilian steel.

The Stress x Strain curves of the local steel show a defined yield point, while for the imported material such a point is not completely determined. This characteristics of indicates that the local steel is more ductile than the imported one. It is necessary to take some care about “spring back” effects in order to keep the dimensional tolerance. The forming limit curves (FLC) are the best way to evaluate the real potential of the local material to substitute the imported one. The local steel showed a higher curve in comparison to the imported curve in the drawing part of the graphics. Otherwise, for the stretching condition the imported curve was higher, in special in that points in the opposite side of the failure. A higher forming limit curve indicates a better forming strain ratio. In this case each material was higher in a specific part of the graphic that represent the drawing and stretching conditions of the stampings. In general, it is possible to say that the local steel is able to substitute the imported material, because there was not such a big difference between the curves.

5. CONCLUSIONS

The results show that the local raw material has good conditions to substitute the imported raw material. This was proved by the forming limit curves that permitted to see the real behavior of the sheet metals submitted to the stamping condition.

As a result we can say that, if the manufacturing process not exceed the forming limit curve of the imported steel, it will not exceed the forming limit of the local material, due the similar characteristics confirmed in the practical experiments.

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