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DAMAGE EVOLUTION EVALUATION IN DP600 STEEL ACCORDING SPEED VARIATION IN SHEET METAL FORMING

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Abstract. *The forming is intended to manufacture parts from flat plates. This process has as one of the biggest users in the automotive industry, where the existing competitiveness makes them look to reduction of time and costs. In recent decades the increased competition and the growing demand for safer cars, economical and less polluting demanded of automakers, steelmakers and scientific community investments in the research of new steels. The result of this research was the significant increase in the use of advanced high-strength steels in automobiles. The use of these steels allows working with thinner sheets, however the failures in these materials can be often reduced by the thickness. Thus, there is necessity to study the mechanism of formation and execution of ductile fracture in metallic materials. The numerical simulation of mathematical models that describe the failure mechanisms in ductile materials is common practice to investigate which failure criteria, in the literature, best represents the results obtained in experimental practice. Thus, the development of a computational model for simulation and evaluation of criteria for fracture simulation of Advanced High Strength Steels (AHSS) is proposed in this work. The methodology for finding the best operating condition used an optimization technique for obtaining the forming speed. The main results showed a significant improvement in stamping DP600 steel with variation in the stamping speed. Concluding that, for a specific stamping condition can be obtained the optimal operation time, by simulation, to achieve the best result of this forming.*

Keywords: *simulation, forming, damage, optimization*

1. INTRODUCTION

The forming is intended to manufacture parts from sheet metal. This process has as one of its largest users the automotive industry, where existing competitiveness makes them look for the reduction of time and costs.

In recent decades the increasing competition and the growing demand for safer, more economical and less polluting cars demanded of automakers, steel mills and scientific community investment in new steel research. The result of this research was the significant increase in the use of advanced high strength steels in cars.

The auto industry has promoted huge advances in metallurgy of steels evolution over the years. Just remember that the first cars had square format basically due to the inadequate formability of the sheet metal of ferritic-pearlitic steels at the time, a consequence not only of incipient metallurgical science of the time, as well as the limitations of industrial processes of refining and conformation (forming). However, the pressure of the automotive industry by reducing the price and improving the car project has forced the plants to evolve technologically to produce steel with high formability.

From the 1990s the new steels, who came to meet this need for better conformation, were encompassed in one family, designated as Advanced High Strength Steel (Advanced High Strength Steels - AHSS). Increasing the mechanical strength level obtained with these steels leads almost inevitably to a reduction of its total elongation, or its formability. However, the use of suitable microstructures can minimize the loss of ductility (Chemin Filho, 2011).

Given the economic necessity of the industries that work with sheet metal forming, especially the auto industry, to reduce the volumetric amount of steel in its products without losing strength, it is clear the need to expand the studies to seek new materials and new ways of forming accompanying the evolution of these materials.

1.1 Formulation of the problem

To describe the plastic deformation mechanism in steel and predict the appearance of damages and failures in these materials, have been studied various models since the 1960s.

However, there is no single model that can be considered as the forming that meets all situations for any material. This makes existing designs with restrictions are applied according to a measured characteristic or property, such as loss of strength, porosity onset, evolution of discontinuity, etc.

When failures are visible in a finished product it means that the choice of the shaping parameters did not occur adequately. The depth, conformation direction, the forming speed, lubrication and other tooling and processing parameters were evaluated correctly and not all together so that the final product had accordingly.

Besides the above mentioned parameters, the sheet forming speed can be determined for each case in order to optimize the operation.

The need for a thorough study about the models that describe the evolution of mechanisms of damage and the appearance of failure in the microstructure of metallic materials suffering forming, it shows suitable for the development of this study.

This happens because most of the works that seek developments in this field do through numerical simulation on sheet forming. However, simulation is used almost always a computer program that needs to be fed with information about the process, equipment and tooling, for example.

In addition to the characteristics of the process mentioned above, the experimental data to validate the models must always be present.

Experimental methods to determine the behavior of a single type of material, with respect to conformability, yield satisfactory results. However, the time spent is high. The numerical simulation can help get faster results with the same reliability of the test methods.

2. SHEET FORMING

Through the tensile test, according to Lorenz et al. (1998), you can determine the mechanical properties of sheet metal, such as obtaining the tensile strength, yield strength, uniform elongation percentage, degree of hardening and anisotropy ratio, which are influential parameters in performance materials during operations conformation.

According to the study made by Chemin Filho (2011), assays in laboratories seek to simulate the kind of forming the sheet will suffer on an industrial scale, can be classified according to the deformation so that aim to simulate a predominance of stretch tests, tests predominantly inlay, combined tests (stretching + deep drawing), tests that simulate the flanging and bending tests.

These tests used for lifting the mechanical properties of the material studied were used to characterize the material as part of this study and these properties were subsequently introduced simulation in the steel in question.

A good tool that has been used to relate the forming limit of the material, determined in laboratory scale with strain on an industrial scale is the Forming Limit Curve (FLC). This relationship allows us to conclude whether the material and the process are suitable for the manufacture of the part in question. The use of FLC is an important tool for the application development of a given product (Sampaio et al, 1998).

The survey Forming Limit Curve (FLC) is one of the steps important to know about the material behavior in the sheet forming. In determining the most common forming limit curve is to simulate the states since the condition of biaxial strain to uniaxial tensile stress condition through properly prepared specimens. In these specimens, print up networks of circles or squares, is tangential to each other or intertwining with strictly certain dimensions. The assay uses deep drawing Nakazima rectangular sheet which vary their width. These specimens are drawn knits that after forming will be measures to check the formability of the material.

3. ADVANCED HIGH STRENGTH STEEL

According to Asgari et al (2007) the main physical difference between the steels AHSS (Advanced High Strength Steel) and conventional is the microstructure. The AHSS steels are multiphase materials which may contain ferrite in microstructure, martensite, bainite and/or retained austenite as a function of alloying elements and the processing used, Andrade et al (2002).

As an example of these steels can cite the Dual Phase Steel - DP, Plasticity Steels Induced Deformation - TRIP, Complex Phase - CP, and Martensitic Steels - MART, (IISI, 2002).

It is possible to compare the mechanical strength and ductility characteristics of this new family of steels. The increased level of mechanical strength of the product leads almost inevitably to a reduction of its total extension, so formability. However, the use of suitable microstructures can minimize the loss of ductility at higher strength levels, Schröder (2004).

Specifically on the DP steels, one of the resources available to both maximize the ductility and strength of steels is the use of more complex microstructures than ferritic or ferritic-pearlitic normally present in public alloys low carbon.

This approach is based on the complex interactions that occur among various constituents present in the microstructure, which must also have significant variations in hardness between them. At the end of the 1970s came the first development in this direction, the so-called two-phase steel (dual phase) which, as its name implies, presents microstructure consists of a matrix with 80-85% of soft polygonal ferrite more 15-20 % hard martensite, Rashid (1977).

4. FRACTURE MECHANISM IN METAL MATERIALS

According to Moreira et al (2003), the amount of plastic deformation that the metal sheet can support before the occurrence of the localized necking is of great importance in forming sheets. Based on experimental measurements, the concept of Forming Limit Diagram (FLD) was first introduced by Keeler (1965) for positive values of the deformation of the lower main plane of the sheet. This concept was then extended by Goodwin (1968) and Woodthorpe et al (1969) of the deformation area between the uniaxial tension states and biaxial stretching. Since then numerous studies have been devoted to experimental determination and theoretical modeling of the boundary deformation in sheet.

FLD is set on the axes of the smaller and larger principal strain obtained in the sheet plane, according Moreira et al (2003). The curve drawn by linear deformation paths remains constant during the deformation process, is known as forming limit curve.

For Keeler (1968), the evaluation is a sheet metal may be formed without fail depends on the material properties, surface conditions, size and shape of the blank, lubrication of the press speed, press pressure plates, design punch and the die, and many other known and unknown factors.

The ASM Handbook (1993), as well as Wulpi (1999) classifies the fracture of the metal material into four main types: cellular, cleavage, or intergranular streaks.

Specifically on the ductile fracture, Wulpi (1999) defines this fracture condition highlighting its occurrence in shear deformation, which leads to the formation of wells in the most stressed regions. Also according to the author, these microcavities coalesce and interconnect, producing a fracture surface composed of alveoli or empty, corresponding to the alveolar fracture mode.

Regarding the macroscopic aspects of ductile fracture, specifically on cylindrical specimens, this type of fracture is called cup-cone because this has two regions: a central, corresponding to the cup and a truncated cone, with an approximate inclination of 45° around the periphery of the specimen. Regardless, however, the geometry of the specimen, a ductile fracture is characterized by having two regions: the central region, called fibrous region and another inclined approximately 45 degrees, called shear zone.

The ASM Handbook (1993) and Wulpi (1999) describe this similarly crack mechanism. According to the authors, the fracture starts at the center of the sample and, after the formation of the neck, the stress state becomes triaxial, such that the center of the smaller diameter section, you reach the maximum state both the longitudinal tension on the triaxial stress state. Thus, with increasing stress, the crack propagates stably, describing a zigzag path. Due to this aspect it is understood that is called the ductile fracture "shear fracture”, although this assertion is not strictly correct.

Something important to note is that recently published are focused primarily on the development of numerical models that simulate more accurately the time of onset and evolution of the fracture until the final break of high strength steels. The validation of numerical models used in many simulations printing processes finite element is made equivalent to the results obtained experimentally.

5. FAILURE AND DAMAGE

To predict fracture in metal forming studies present a study that brings together ductile fracture concepts associated with finite element. The concepts of ductile fracture, existing jobs are reviewed in this area. Experiments with specimens in different formats are investigated to validate the applicability of the methods under real conditions of stress and strain, next to those applicable in forming metallic materials.

They are presented implementation of the ductile fracture criterion in the finite element simulation and modeling by comparing the stress and strain between the experimental data and the values obtained by computer programming. However, not all fracture criteria have proven next to the experimental data values.

A comparison between the failure criteria existing in metal materials forming the theory is presented by Venugopal et al. (2003). Ten failure criteria were modeled for five different materials. The simulation based on the set of equations, respective to each criterion is compared with experimental results. The simulation performed by finite elements presents programming details such as: refining the mesh used in the simulation, chemical composition of the materials, mechanical properties and values of variables used in the equation of failure criteria. After the simulation and comparison with experimental data, Venugopal et al. (2003) present findings about the study criteria. In general, both the average and the deviation factor dispersion must be low to validate the simulation and consider certain criteria fails to be useful for predicting the occurrence and location of the damage.

None of the criteria showed better results in all simulations. However, depending on the geometry of the specimen or material, some criteria appear among the best ever, compared to the experimental data, with smaller differences than 2%.

Finally, Venugopal et al. (2003) present the conclusion that reports the failure criterion of theory based on the maximum principal stress, as best to find real data of damage to the material, compared to theories that depend on the energy of distortion.

6. METHODOLOGY SUGGESTED

The methodology presented in this paper aims to investigate computationally the failure mechanisms in steel DP600. Therefore, there is a need to develop a computer model to simulate the failure criteria.

As the base implementations of a computer code was developed using the ABAQUS software fed material data in question and configured to repeat the experimental data were developed to study Chemin Filho et al. (2013). The sheet settings, die and punch were the same used in that study, to obtain results that prove the validity of the model.

After this step and proof simulation model, remained the same initial conditions to obtain simulation results by varying the rate of deformation. This was possible by varying the forming speed. Since the amplitude of known conformation and taken as a fixed value, it was possible to vary the speed by varying the process time.

The value of the punch displacement amplitude in this simulation was set at 40 mm. Initially, embossing was used as a 4mm.s^{-1} for speed in steel DP600 for a sheet with the dimensions 200x200 mm and 1 mm thick. Fig. 1 shows the result of simulation for these conditions.

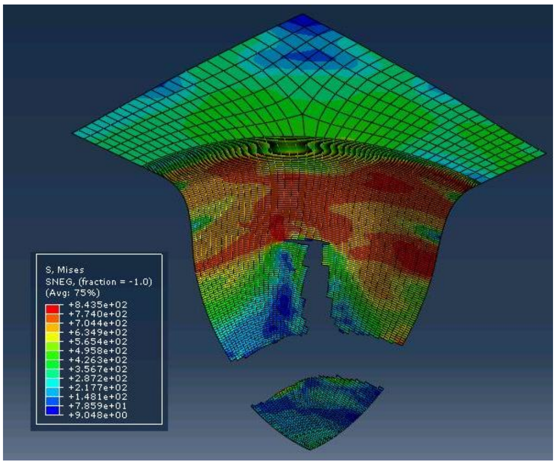

Figure 1. Simulation Results for speed 4 mm.s^{-1}

Given the unsatisfactory outcome for these conditions because the specimen in the simulation broke violently, it became clear the need to adjust the forming speed. Therefore, the goal for the moment was to use an optimization method that found the optimal speed for this forming process. This speed would be one that would lead to a satisfactory outcome of the process with the shortest time forming.

Thus, the process of searching the optimal speed for the forming was based on the nonlinear optimization methods. For both made if necessary reducing the search interval with the intent of generating the fewest iterations. This simple optimization method used the following reasoning:

1. Use the first simulation speed as a starting point;
2. Determination of the second point to create a range of interest (kickoff);
3. Analysis of the second point by checking the test piece in the simulation (break or not);
4. If the item 3 has not break, determination and simulation of intermediate or midpoint;
5. Analysis simulation to reduce the range of interest;
6. New reduced interval between two points, one with and one without break;
7. Simulation an intermediary or midpoint;
8. Simulation analysis to reduce the range of interest; (Same as item 5)
9. New reduced interval between two points, one with and one without break; (Same as item 6)
10. Simulation an intermediary or midpoint; (Same as item 7)
11. Repeat to obtain a shorter interval than or equal to 1% of the optimal speed process.

The selection of the second point to generate an interval was 1 mm.s^{-1} for the same displacement amplitude of 40 mm punch. Fig. 2 shows the simulation result for this condition.

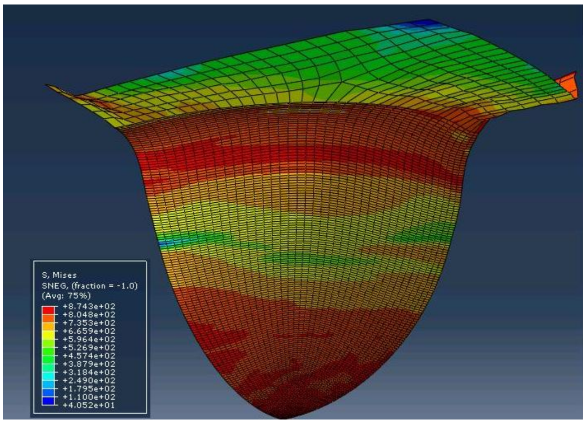

Figure 2. Simulation Results for speed 1 mm.s^{-1}

As the result of the simulation was no rupture, the next step was to determine an intermediate point to reduce the interval. The next points were chosen from: 3 mm.s^{-1}, 2 mm.s^{-1}, 1.5 mm.s^{-1}, 1.083 mm.s^{-1}, 1.125 mm.s^{-1}, 1.146 mm.s^{-1} and 1.135 mm.s^{-1}. When eliminating the range of interest and not with the remaining interval of interest between two points, which are points with one another without rupture.

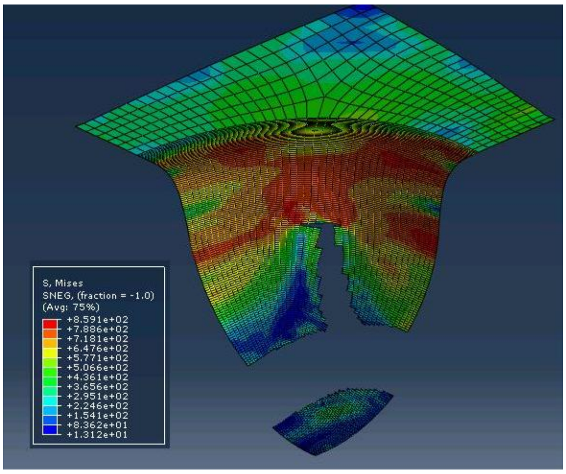

Figure 3. Simulation Results for speed 3 mm.s^{-1}

Fig. 3 and 4 show the simulation intermediate situations in which the sheet metal forming process is converging to an optimal forming for the configuration speed of this test piece at DP600 steel in this die.

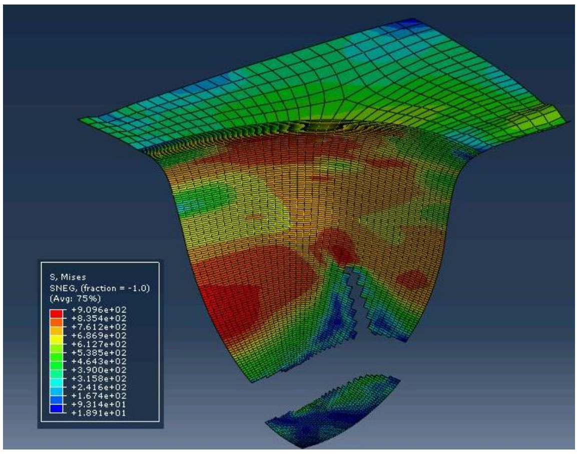

Figure 4. Simulation Results for speed 1.5 mm.s^{-1}

After nine iterations, the optimal simulation speed for this case study was the amount of 1.135 mm.s^{-1}, which is shown in Fig. 5. In view of the simulation immediately before the optimum value of speed was 1.146 mm .s^{-1} referring to Fig. 6, it is clear the numerical difference in speed, the precision of 1% was reached.

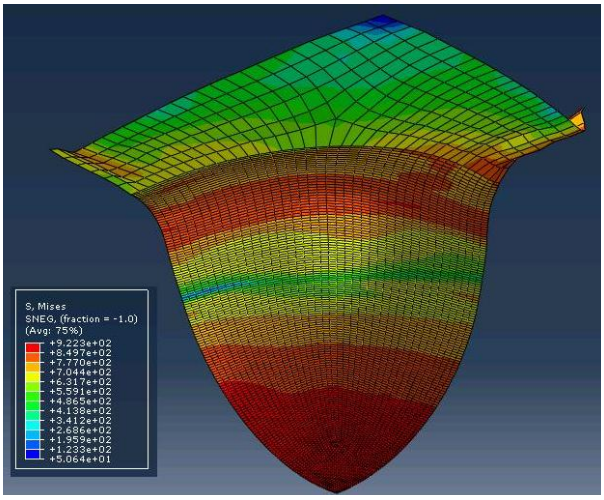

Figure 5. Simulation Results for speed 1.135 mm.s^{-1}

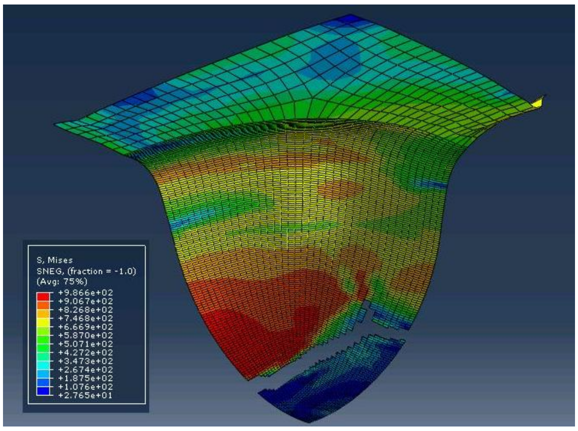

Figure 6. Simulation Results for speed 1.146 mm.s^{-1}

It's possible to check the difference in the outcome of the simulation conformation in terms of rupture of the specimens, between the speed of 4 mm.s^{-1} and 3 mm.s^{-1} Fig. 1 and 3, respectively, and the speed 1.146 in Fig. 6. It is clear that in Fig. 6 rupture occurs less intensity compared to Figs. 1 and 3 that show a specimen which broke more abruptly.

7. CONCLUSIONS

The result of the searches with metallic materials which provide a thickness reduction was significant increase in the use of advanced high strength steels in automobiles.

The use of these steels allows working with thinner sheets, however the appearance of failures in the material can be common by decreasing the thickness.

Further study of plastic deformation mechanism of AHSS was necessary, and growing especially in the last three decades, to make possible the forming of parts in steel accompanying the modernity of the current projects of metallurgical industrial area.

In the main failure criteria studied the forming rate appears as one of the very important factors. Thus, it justifies the study in question looking for a better result for the sheet metal forming process in AHSS sheet, particularly the DP600, through the pursuit of ideal speed processing.

The investigation of this parameter with the help of simulation and use of experimental data obtained in the previous study presented by Chemin Filho et al. (2013) is the proposal of the relevant work.

This study then suggests that with few steps of iterations in a short time compared to the experimental process settings, you can determine the optimal speed forming to a particular case. Therefore, it is necessary to feed a computer code with material parameters to be processed, as well as introduce the geometric characteristics of the die, punch and sheet.

The simulation proposed in this study is able to save time with the preparation of the process and helps to achieve better productivity levels, always with the attendance of quality requirements by the compliance of the final product.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

ANDRADE, S. L., TAISS, J. M., ROSA, L. K. **O aço no automóvel do futuro**. In: 57º Congresso da Associação Brasileira de Metalurgia e Materiais, 2002, São Paulo, *Anais*... São Paulo, Julho 2002.

ASGARI, S. A.; PEREIRA, M.; ROLFE, B. F.; DINGLE, M.; HODGSON, P. D., **Statistical analysis of finite element modeling in sheet metal forming and springback analysis**. *Journal Journal of Materials Processing Technology*, xxx (2007) xxx–xxx.

ASM INTERNATIONAL, ***Metals Handbook***, vol. 12 e 14., 9. ed., 1993.

CHEMIN FILHO, R. A. **Estudo da Fratura de Aços de Nova Gera ção DP600 Através da Variação de Pressão no Prensa-Chapas.** 2011. 148p. **Tese (Doutorado em Engenharia Mecânica) – Curso de Doutorado em Engenharia Mecânica,** Universidade Federal do Paraná, Curitiba, Brasil.

CHEMIN FILHO, R. A; TIGRINHO, L. M. V; BARRETO NETO, R.C; MARCONDES, P. V. P. **An Experimental Approach for Blankholder Force Determination for DP600 with Different Material Flow Strain Rates in the Flange During Stamping. Journal of Engineering Manufacture,** v. 227(3), p. 417-422, 2013.

GOODWIN, G. M**. Application os strain analyses to sheet metal forming problems in the press shop**. *Metall Italiana*, 60., p. 764-774, 1968.

IISI - International Iron and Steel Institute, ***UltraLight Steel Auto Body - Advanced Vehicle Concepts (ULSAB–AVC)*** **Overview Report (2002)**, disponível em: www.worldautosteel.org.

KEELER, S. P. **Determination of forming limits in automotive stampings**. *Sheet Met Ind*, 42., p. 683-691, 1965.

KEELER, S. P. **Understanding Sheet Metal Formability**. *Machinery*, 1968.

LORENZ, R.; GILAPA, G. M. **Avaliação da Conformabilidade de Chapas de Aço Plano**. In: Conferência Nacional de Conformação de Chapas, 1., 1998, Porto Alegre. *Anais*... Porto Alegre: UFRGS – Centro de Tecnologia, p. 141-150, 1998.

MOREIRA, L. P.; SAMPAIO, A. P.; FERRON, G.; LACERDA, A. C. **Análise numérica e experimentação da influência da espessura inicial das deformações limites em chapas**. In: CONFERÊNCIA NACIONAL DE CONFORMAÇÃO DE CHAPAS, 6., 2003, Porto Alegre. *Anais*... Porto Alegre: UFRGS – Centro de Tecnologia, p. 39-49, 2003.

RASHID, M. S. GM 980X – **Potential Applications and Review**. *International Automotive Engineering Congress and Exposition*. S.A.E. Technical Publication n° 770211. Detroit, 12 p., February-March 1977.

SAMPAIO, A. P.; MARTINS, C. A.; SOUZA, P. C. **Caracterização da Conformabilidade de Aço Livre de Intersticiais – IF – Produzido Via Recozimento em Caixa na Companhia Siderúrgica Nacional**. In: CONFERÊNCIA NACIONAL DE CONFORMAÇÃO DE CHAPAS, 1., 1998, Porto Alegre. *Anais*... Porto Alegre: UFRGS – Centro de Tecnologia, p. 89-100, 1998.

SCHRÖDER, T. **Ausgekochter Stahl für das Auto von morgen**. *Max Planck Forschung*, 3., p. 36-41, 2004.

VENUGOPAL RAO. A; RAMAKRISHNAN, N; KRISHNA KUMAR, R. **A Comparative Evaluetion of The Theoretical Failure Criteria for Workability in Cold Forging. Journal of Materials Processing Technology**, v. 142, p. 29-42, 2003.

WOODTHORPE, J.; PEARCE, R. **The Effect of r and n Upon the Fprming Limit Diagrams of Sheet Metal**. *Sheet Metal Industries.* p. 1061-1067, 1969.

WULPI, D. J. **Understanding How Components Fail**. 2.ed. USA: ASM International, 1999.