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IMPROVING THE EFFICIENCY OF THE STRETCHING PROCESS OF ALUMINUM ALLOY PLATES

Yelda VELI[1], Marin PETRE[2], Alexandru M. MOREGA[3]

Aluminum alloys are subjected to controlled stretching operation. For non-heat-treated plates of 1xxx, 3xxx, 4xxx, and 5xxx aluminum series, the aim is to obtain flatness, and for heat-treated plates (2xxx, 6xxx, and 7xxx series alloys), to obtain the reduction of internal stresses induced by the solution heat treatment. The stretching operation supposes gripping both ends of the plate and pulling the plate in one direction. The initial normal efforts induced by the quenching process were obtained using the Deep-Hole Drilling method (DHD). The model was solved using finite element method (FEM) and the results were confirmed by industrial tests.

Keywords: aluminum alloy, efficiency, stretching, finite element method

1. Introduction

The quenching process generates residual stresses of tension and compression in the section of the plates due to heating at a high temperature during the solution heat treatment, near the lower limit of the melting intervals of aluminum alloys with structural hardening, and rapid cooling, by spraying with cold water on the upper and lower faces of the plates [1].

At the beginning of the quenching period, there is a cooling of the plate from the outside to the inside, which induces the contraction and hardening of the outer part of the plate before the inner part, which causes internal compression stresses. After a few seconds, the inside of the plate begins to cool and contract. This process of contraction is bounded by the already hardened outer layer of the plate, which will cause internal tensile stresses and will be stabilized by the external compressive stresses. The residual stresses induced by quenching are directly proportional to the thickness of the plates [2].

Usually, stretching and aging processes are necessary to reduce residual stresses after quenching. The controlled stretch stress relief process Reduction of

[1] Lecturer, Dept. of Electrical Machines, Materials and Drives, Faculty of Electrical Engineering, University POLITEHNICA of Bucharest, Romania, e-mail: yelda.veli@upb.ro

[2] Eng., Vimetco ALRO, Slatina, Romania, e-mail: mapetre@alro.ro

[3] Acad. Professor, “Gheorghe Mihoc – Caius Iacob” Institute of Statistical Mathematics and Applied Mathematics, Bucharest, Romanian Academy, and Dept. of Electrical Machines, Materials and Drives, Faculty of Electrical Engineering, University POLITEHNICA of Bucharest, Romania, e- mail: alexandru.morega@upb.ro

residual stresses induced by quenching is achieved by controlled stretching operation, which also has the role of obtaining a flat shape of the plate within the tolerances imposed by the specific standards.

The study of residual stresses is an important part of the design and manufacture of large aero-structures parts, which are obtained by various machining processes. The residual stresses are developed in aluminum alloy plates from different upstream manufacturing processes, such as skin-pass rolling, quenching, stretching, etc. [3]. The primary method for predicting residual stresses in aluminum plates is performed by numerical simulation [4]. The advantage of numerical simulations is given by the low costs that can be achieved by predicting and controlling the problems that could occur before processing. Using the ABAQUS program, the influence of the stretch ratio on stress relief for a thick 7075 aluminum plate was analyzed [5]. Using nonlinear regression, a model was developed for predicting residual stresses for 7075 aluminum alloy plates with thicknesses of 30, 40, and 50 mm [6].

An industrially applicable mathematical model of the residual stresses and the stretching process is still missing in the literature due to the complexity of the involved processes. The proof is the control of the residual stress of the aluminum alloy plates, which is one of the existing research problems in the aerospace industry [7]. In most of the published works in which the residual stresses resulting from the quenching process are modeled, the quenching process is also modeled, and implicitly the phase transformations that take place [8].

In the present work, the residual stresses resulting from the quenching process are considered input data for the finite element model. In this case, an important role is played by the method of determining the residual stresses. Currently, several methods are on the market for determining residual stresses, each with advantages and limitations. Residual stresses used here were determined after quenching by the deep hole drilling method (DHD) [9]. Results are compared for two numerical models.

2. Experimental setting

The industrial test was performed on 7075 aluminum alloy plates. The 7075 is often used in transport applications, especially aviation, due to its high specific strength. The plate was obtained from a cast slab with a chemical composition according to Table 1.

Table 1

Chemical composition of 7075 aluminum alloy slab (mass fraction, %)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other Elements		Al
								Each	Total	
0.14	0.21	1.49	0.06	2.52	0.18	5.72	0.03	≤ 0.05	≤ 0.15	89.64

Plates with dimensions 20 mm x 1670 mm x 9730 mm were obtained by hot rolling. To get the T651 temper, the plates were solution heat treated, quenched by water spraying, stretched, and artificially aged. Samples were taken before stretching to determine the residual stresses. Part of the experiment was performed on the special equipment in R&D Department. The stretching was achieved on the Danieli Fata Hunter 18 MN (Fig. 1).

Fig. 1. The independent equipment for the research of the residual stress removal process for the aluminum alloy plates with thicknesses lower than 20 mm.

The 3D representation and the main components of the equipment (Fig. 1) used in the industrial tests are presented in Fig. 2.

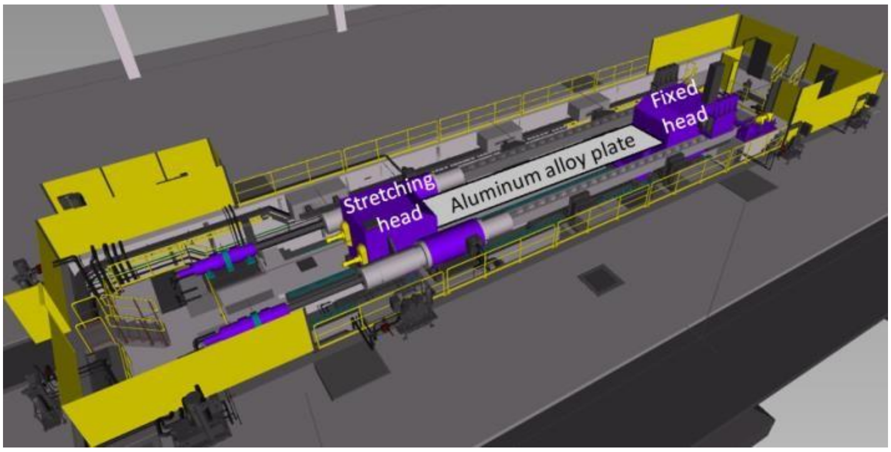

Fig. 2. The 3D representation and the main components of the independent equipment.

A unique measurement system of permanent elongation based on the incremental position encoders is used. The results are validated using measuring rulers/ tape rulers on each plate.

The stretcher consists of the following main parts:

- Stretching head – head connected to the quick-moving cylinder.
- Fixed head-head clamped to columns assembly.
- Stretching cylinders – plungers, quick-moving cylinders, specialized oil distributors.
- Columns assembly and additional system for shock absorption.
- Loading - unloading installation.

The main stretching parameters for the industrial test performed on the 7075 aluminum plate are presented in Fig. 3.

MAIN DATA			PROCESS DATA		
Equipment	18MN Plate Stretcher		Stretching Elongation Setup	2.10	%
Customer Name			Max Stretching Elongation	3.37	%
Entry Nominal Width	1670.0	mm	Final Stretching Elongation	2.97	%
Final Width	1645.7	mm	Setup Speed	9	mm/s
Entry Measured Thickness	20.58	mm	Max Stretching Force	8.1	MN
Exit Measured Thickness	20.22	mm	Max Stretching Pressure	78.3	bar
Entry Nominal Length	9730.0	mm	Initial Heads Distance	9513.6	mm
Final Length	10012.8	mm	Maximum Heads Distance	9842.0	mm
Weight	890.5	kg	Final Heads Distance	9805.9	mm
Alloy Code	7075		Clamping Begin DateTime	24/03/2021 23:05:09	
Temper Code	T651		Stretching Begin DateTime	24/03/2021 23:05:19	

Fig. 3. Report generated by the stretcher equipment for the 7075 alloy test plate.

According to the data from the generated report (Fig. 2), the maximum stretching force applied to the 7075-aluminum alloy plate(s) was 8.1 MN, for which a stretching maximum elongation of 3.37 %, for one aluminum alloy plate, and a final elongation of 2.97 % was obtained.

3. Mathematical model

The main idea for the mathematical model was to perform the numerical simulation of the stretching process for the 7075 aluminum alloy test plate and validate the results obtained from the industrial test for the stretching process of one and two plates, respectively. The efficacy improvement is outlined for the two-plate model.

Fig. 4 presents the significant positions before and after the stretching operation for two aluminum alloy plate models.

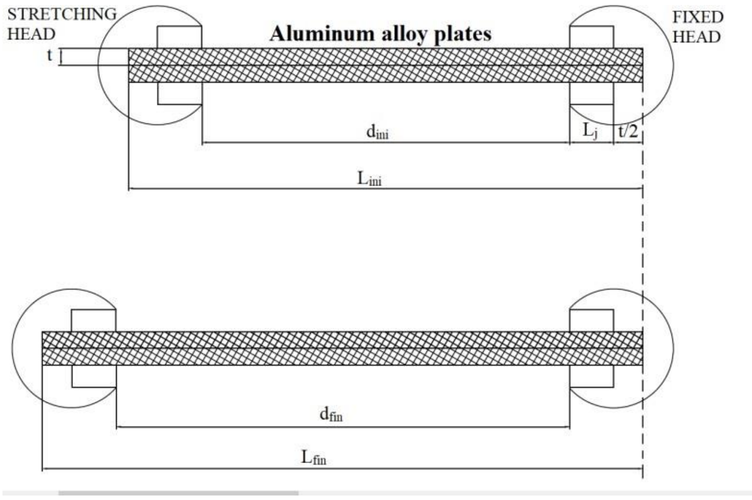

Fig. 4. Schematic drawing of two stretched aluminum alloy plates, where t – thickness of the plate, L_{ini} – initial length of the plate, d_{ini} – initial distance between jaws, L_j – length of the jaw; d_{fin} – final thickness between jaws, L_{fin} – final length of the plate.

The part of the plate subjected to stretching force doesn't correspond to the entire length but is smaller because it is the part d_{ini} between the jaws.

Since only the structural stresses that appear in the aluminum alloy plates during the stretching operation were studied, the geometric model used in the modeling of only the aluminum alloy plates and the fingerprints left by the jaws were represented (Fig. 5) for a single aluminum alloy plate model. The second model has two aluminum alloy plates, both with a total width of single aluminum alloy plates (20.58 mm, and 10.29 mm, respectively).

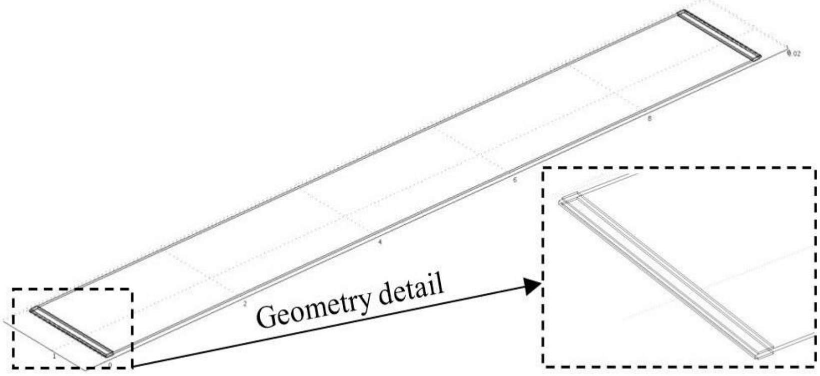

Fig. 5. One aluminum alloy plate and fingerprints left by the jaws - 3D representation used in the modeling – the units are in meters.

The mathematical model was implemented using COMSOL software, version 3.5a. It was assumed that the material represented by the aluminum alloy plate is elastic-perfectly plastic.

The total strain (ε) is the summation of the elastic strain (ε_e) and the plastic strain (ε_p):

$$\varepsilon = \varepsilon_e + \varepsilon_p \quad .(1)$$

The total strain in a material is linearly proportional to stress:

$$\sigma = E\varepsilon, \quad (2)$$

where *E* is the elastic modulus.

For the 7075 aluminum alloy plate, the longitudinal modulus of elasticity E [Pa] (Young's modulus) has the value of 75 GPa, and ν, the Poisson's ratio is 0.33.

Using the density calculation formula [10], a density of 2810 kg/m^3 was obtained for the 7075-aluminum alloy plate tested. For the yield stress level, the minimum value imposed in the standard [11] for 7075 aluminum alloy products, T651 temper, respectively 470 MPa was inserted in the model.

The discretization network for the two models, one and two aluminum alloy plates, respectively, is represented in Fig. 6 and is more refined on the surfaces where the jaw's fingerprints are in contact with the aluminum plates.

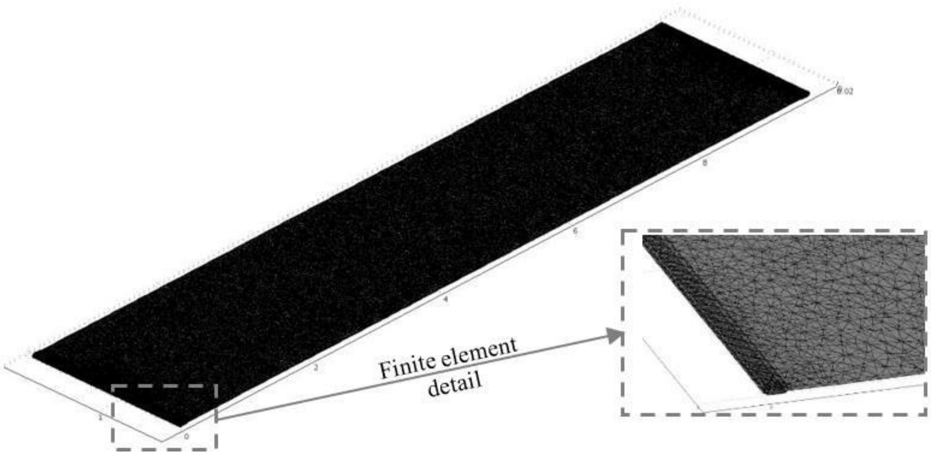

Fig.6. The discretization network used to implement the finite element method (FEM). The FEM network is unstructured (Delaunay) and is made up of approx. 1 million tetrahedral, Lagrange, and square elements for both models.

The novelty of the developed model is that the domain of the model includes the entire plate at the dimensions of the industrial test and includes the initial normal efforts (Fig. 3) of the plate induced by the quenching process for both models, the one aluminum plate and the two aluminum plates, respectively.

These residual stresses after the quenching process are graphically represented in Fig. 7.

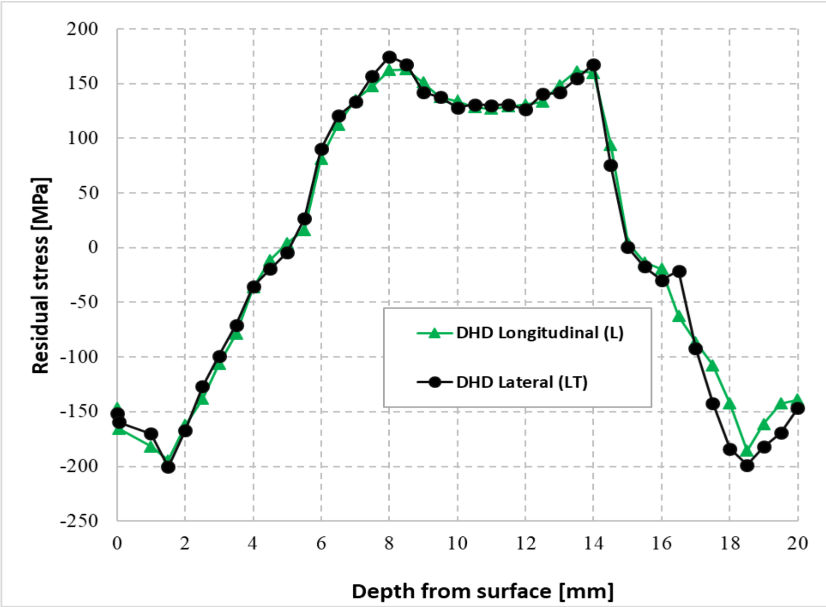

Fig. 7. Residual stresses of the 7075 aluminum alloy plate, after quenching.

These values were obtained using the Deep-Hole Drilling method (DHD) [9]. Longitudinal and transverse residual stresses were similar because this plate was quenched on equipment provided with distance control between the top nozzles and the surface of the plate during the quenching by mechanical displacement of the spray nozzles [12].

The boundary conditions are of the “free” type, except for the contact surface between the clamping head and the aluminum alloy plate, where a fixed condition was established, and for the contact surface between the stretching head and the aluminum alloy plate, a prescribed displacement condition in the direction of stretching by 282.8 mm, value resulting from the industrial test.

For the transient numerical simulation, an analytical function is implemented for the total load applied as a boundary condition at the contact surface between the stretching head and the aluminum alloy plate.

The force is divided by the area of the contact surface, and it is represented in Fig. 8, given the data validated by the industrial tests.

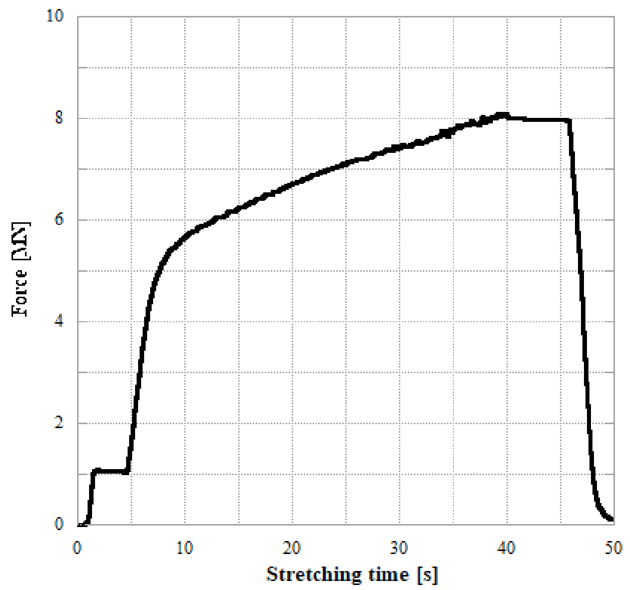

Fig. 8. The force applied as a boundary condition on the contact surface between the plates and thestretching head.

The mathematical model was solved numerically using the finite element method (FEM).

4. Results

The value obtained for the final length of the sheet (Fig. 9) after the stretching operation is influenced by the value imposed for the movement in the direction of stretching of the aluminum alloy sheet.

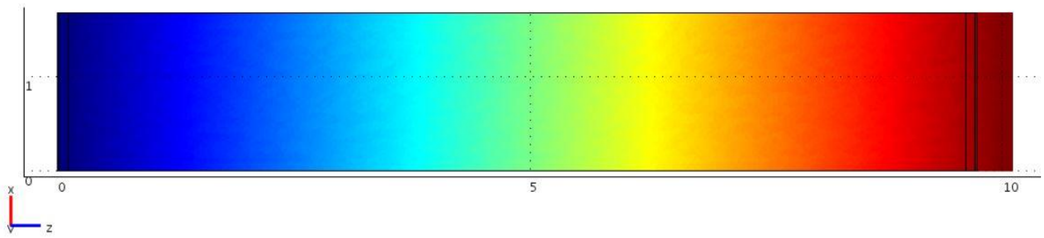

Fig. 9. The shape of the 7075 aluminum alloy sheet after the operation of stretching. Final elongation = 2.9 %. Maximum displacement is 282.86 mm, for one plate, and 302.68 mm for two plates, respectively.

The von Mises stresses required for traction in the *Oz* direction in Fig. 10 are influenced by the value imposed for the flow limit.

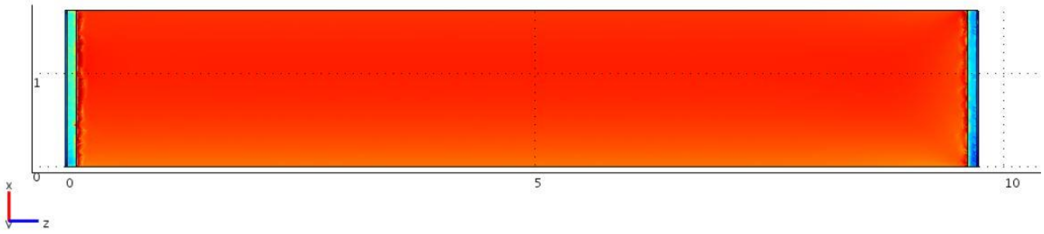

Fig. 10. Von Mises stresses for 7075 aluminum alloy sheets. Color is proportional to the local value of von Mises stresses - max. ~ 471 MPa.

The total tensile strength required to obtain a relative residual elongation of 2.9 % for both models, one plate and two aluminum alloy plates, respectively, is calculated for the contact surfaces between the tensile head and the aluminum alloy sheet; the value obtained is 7.58 MN for one plate, and for the two plate model, 7.49 MN, respectively.

The maximum force required for stretching was determined for different elongations (Table 2) and the data are represented in Fig. 11 and Fig. 12, respectively.

Table 2

Maximum tensile strength required to achieve different degrees of elongation of the 7075 alloy sheet, dimensions 9730 mm x 1670 mm x 20.58 mm (one plate), and 9730 mm x 1670 mm x 10.29 mm (two plates).

Final elongation [%]	Final sheet length - Initial sheet length [mm]	Maximum tensile strength [MN] – one plate	Maximum tensile strength [MN] – two plates
0.5%	0.048	3.78	5.05
1%	0.095	4.58	5.58
1.5%	0.143	5.41	6.13
2%	0.19	6.21	6.66
2.5%	0.238	7.04	7.21
3%	0.285	7.84	7.74
3.5%	0.333	8.68	8.30

The elongation analysis according to the maximum tensile force (Fig. 11) for the 7075 aluminum alloy sheet, with dimensions of 9730 mm x 1670 mm x 20.58 mm, indicates an increasing linear dependence: a tensile force of 8.68 MN produces a relative elongation of 3.5 %.

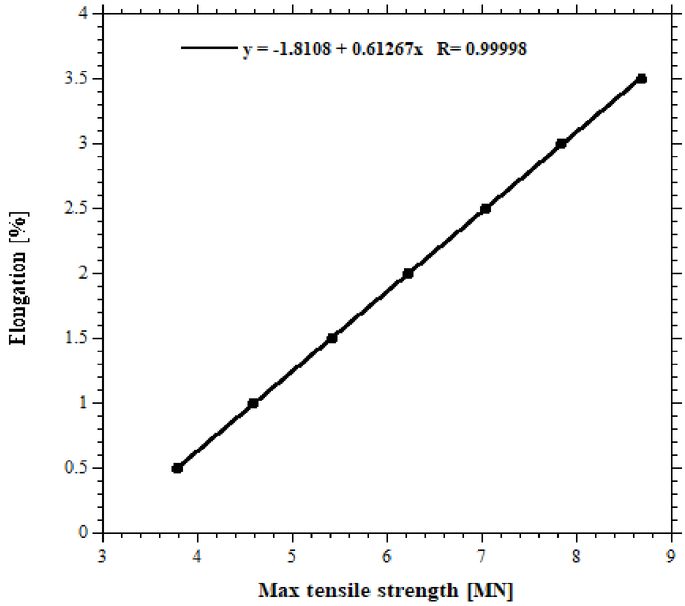

Fig. 11. Relative elongation as a function of tensile strength for 7075 alloy sheet dimensions 9730mm x 1670 mm x 20.58 mm, one aluminum plate, and the associated regression equation.

The relative elongation obtained is analytically represented by the regression equation:

$$Degree\_elongation = 0.61267 \cdot Maximum\_stretching\_force - 1.8108. \quad (3)$$

Fig. 12 presents the relative elongation as a function of the tensile strength for the model having two aluminum alloy plates fixed between the heads (Fig. 4), each plate having a width of 10.29 mm.

The relative elongation for the two-plate model is represented by the analytical regression equation:

$$Degree\_elongation = 0.92406 \cdot Maximum\_stretching\_force - 4.1608. \quad (4)$$

The relative elongation presents a linear dependency with the maximum tensile force for both models. Still, for the two aluminum alloy sheets, this dependency varies in a smaller range for the same given degree of elongation.

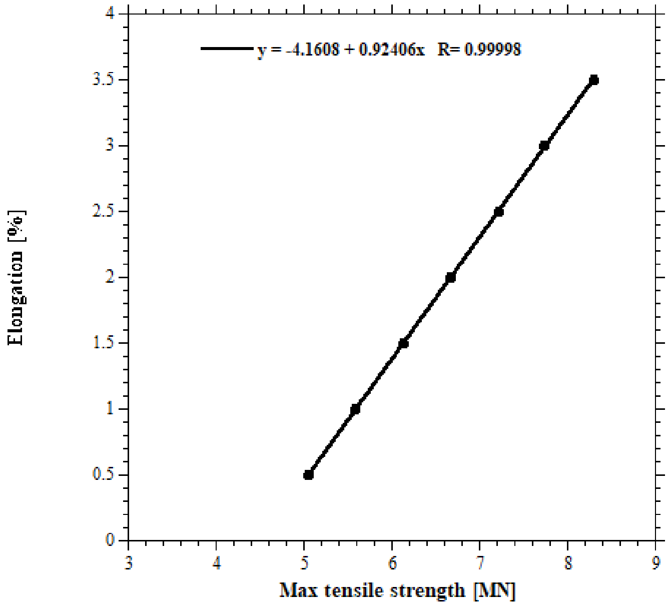

Fig. 12. Relative elongation as a function of tensile strength for 7075 alloy sheet dimensions 9730mm x 1670 mm x 10.29 mm, two aluminum plates, and the associated regression equation.

The maximum tensile strength, when considering the two aluminum alloy sheets model, reaches the desired value even when a slightly lower degree of elongation is imposed.

A value of approximately 7-8 MN is considered to be an optimal tensile strength value for stretching the aluminum sheets.

5. Conclusion

The developed model represents the entire sheet in the dimensions of the industrial test, including the state of normal initial sheet metal stresses induced by the solution and hardening process obtained experimentally by using the Deep-Hole Drilling (DHD) method and allows the implementation of mechanical loading (tensile stress) according to the test diagram.

For a 7075 aluminum alloy sheet measuring 9730 mm x 1670 mm x 20.58 mm, the maximum tensile strength and the relative tensile / elongation force regression equation were determined for different degrees. These data were determined also for two 7075 aluminum alloy sheets with dimensions of 9730 mm x 1670 mm x 10.29 mm each. The efficiency is reached by the two aluminum alloy sheet models for the same applied force.

The initial stresses were given by the industrial tests for each model as a sixth-degree polynomial equation. The results show an improvement in efficiency, mostly economically, by simultaneously performing the stretching operation for two or more plates, instead of a single plate.

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