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# Numerical simulation of the Super Plastic Forming Process Of the EFA – 2000 Under Carriage Door

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## ABSTRACT

The present work summarises the preliminary results of a numerical simulation of the Super Plastic Forming Process on the EF2000 Under Carriage Door. The simulation is performed using the MSC Marc code.

The final goal is the acquisition of the methodology, the validation of the results by a numerical-experimental correlation of the thickness distribution, and the verification of the new capabilities of Marc2000 in relation to the optimization of pressure-time cycle and to the remeshing.

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## INTRODUCTION

The more and more frequent utilisation, especially for aeronautical purposes, of the process of Super Plastic Forming (S.P.F.) has determined the necessity in developing very useful tools of numerical simulation. Those tools have to be able to give the designer the capability to evaluate - in an accurate way and in advance with respect to the production phases - the critical points of the part to be formed and the strategies to produce optimized parts. Thanks to those tools, besides, a reduction of the test and of the production global cycle can be possible, with the consequent decrease of the global prices.

In this work the results obtained by choosing the MSC/Marc as tool for the numerical simulation of the S.P.F. are shown. It has been decided to apply the Marc code to a concrete problem of the Alenia Aerospazio-Divisione Aeronautica company, i. e. the superplastic forming of the Under Carriage Door on the EF2000 aircraft. For this door, in fact, the thickness numerical readings are available, what enables to realize a numerical-experimental correlation; the good agreement of the thickness numerical-experimental correlation will demonstrate the validity of the code MSC/Marc as a numerical tool of S.P.F. simulation.

In this work a study about the possibility of a simulation of the friction between the die and the plate to be formed has been performed. Then the new Marc capabilities were examined; particularly, the one of generating numerically an optimised loading curve for the S.P.F. process has been analysed, as well as to realise auto-adaptive meshes, corresponding to the critical zones.

## THE S.P.F. PROCESS

The S.P.F. is a process, used especially in the aeronautic word, able to produce very complex shaped and integrated structures, generally lighter and stronger than the assemblies they replace. The process is based on the superplasticity, that is a particular state achieved by various kind of materials – metals, alloys, ceramic materials- in specific temperature and pressure conditions, in which they show a plastic-viscous behaviour. In this state the material is able to undergo high deformations (for some materials even strains of 1000% are tolerable) without necking. To achieve this state, it is necessary that the following conditions occur same time:

- grains' little dimensions (1÷10 μm)
- forming temperature higher than 50% fusion temperature
- low deformation velocity
- strain rate sensitivity factor at least equal to 0.3

The S.P.F. requires a temperature lower than the annealing temperature, so that the produced objects are dimensionally stable and free of residual stresses.

## S.P.F. NUMERIC SIMULATION FOR EF2000 U/C DOOR

To realize the superplastic forming of a part whose material grain dimension are opportune, heated dies and presses are used in order to achieve the right value of pressure, temperature and strain rate. The Marc code is able to simulate numerically this process, through a F.E.M. model of the initial plate to be formed and of the dies, known the loading curve used in the real process.

In the next figures, the numerical models - of the die for the EF2000 Under Carriage Door and of the initial plate- have been represented. Notice how from the same plate at the end of the process both the door and a "test" article – able to evaluate the goodness of the process - will be formed.

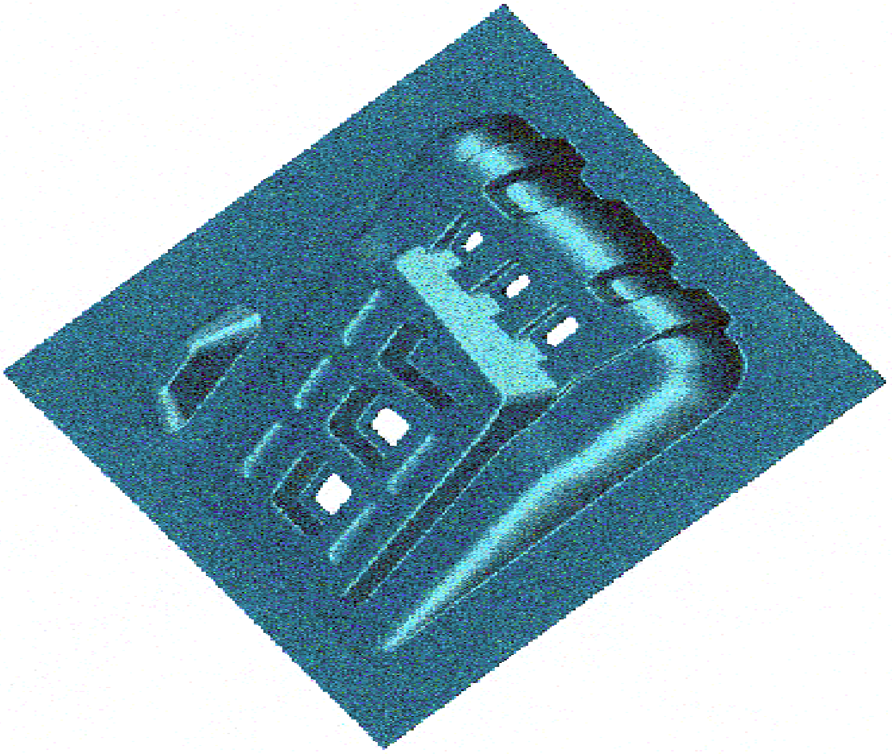


*Fig. 1: F.E. model of the die for EF2000 U/C Door*

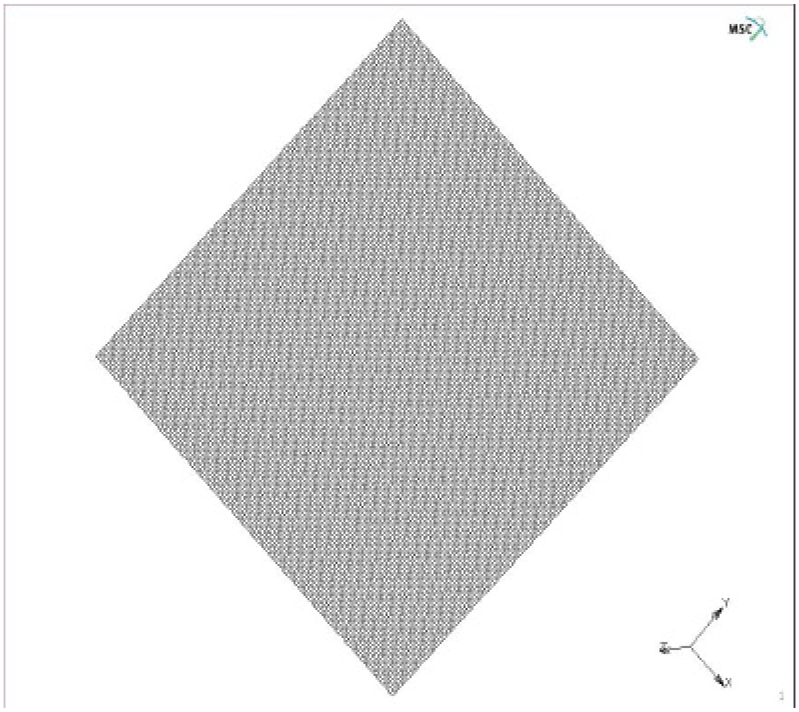


*Fig. 2: F.E. model of the initial plate to be formed*

The initial plate to be formed is made by 7075 Aluminium. The initial thickness of 2.5 mm. It has been obtained by the insufflation of pressurised air on the upper and on the lower part of plate, at a temperature of 485±10°C and by maintaining a controlled strain rate (target strain rate=$4*10^{-4}$ $sec^{-1}$)
Immediately the problem of characterising the material of the plate emerged. The Marc code is able to define different constitutive laws for the material; in our case, for the kind of the process to be

simulated, it has been chosen to describe the material like isotropic and with a rigid-plastic law. The relative equation ( the "power law") is:

$$s_Y = A\times(e_0 + e)^m + B\times\dot{e}^n$$

In our case the first part, related to the hardening of the material, is negligible with respect to the second one, so that we can write:

$$s_Y = B\times\dot{e}^n$$

in which B and n (sensitivity strain rate, i.e. is the slope of flow stress versus strain-rate curve) are unknown. To find the values of those parameters, a bibliographic research has been performed, and the historical Alenia data have been used. Knowing the process temperature, the kind of material and the target strain rate, the right coefficient have been found:

n=.61 B=509.69 N*sec$^{.61}$/mm$^2$

To simulate correctly the constraining of the process, the edges of the initial plate have been clamped.

To simulate the presses loading, the real loading - used during the process - has been applied; the differential pressure applied to the plate is shown if fig. 3

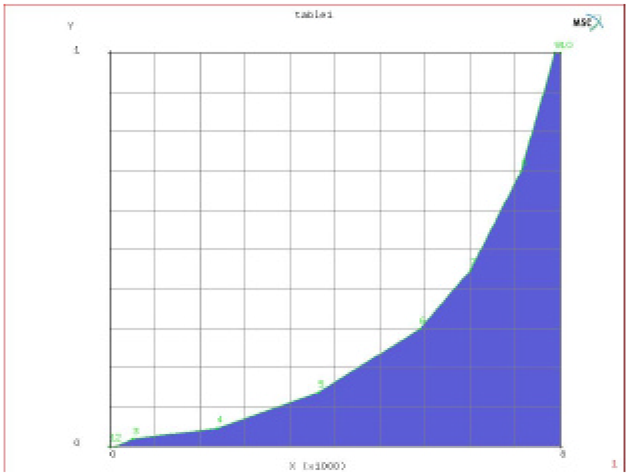


*Fig. 3: Pressure curve for the real EF2000 S.P.F. process*

## RESULTS OF THE MARC ANALYSIS FOR THE EF2000 U/C DOOR S.P.F. SIMULATION

In the light of all the considerations till now drawn, a Marc analysis of the process has been performed. In the figures shown in the next pages, the history of the numerically simulated forming process of the plate has been shown, from the initial increment of the loading till to the final one. In those figures, the level of the thickness of the plate has been shown under the deforming piece.

In the final configuration, a numerical-experimental correlation has been performed between the thickness read on the real door and the corresponding ones, available thanks to the numerical analysis. The locations in which the experimental and numerical readings have been performed are shown in the figures 5. The results are resumed in tables 2 and 3 of the attachment 1.The numerical-experimental correlation makes very good results: the percentage difference between numerical and experimental readings is on average less than 4%; the punctual difference is quite high only for the points on the upper part of the door, where the proximity of the edge gives very difficult every numerical simulation. Therefore, the proof has been positive, and the Marc code has confirmed its goodness in simulating a complex process like S.P.F..

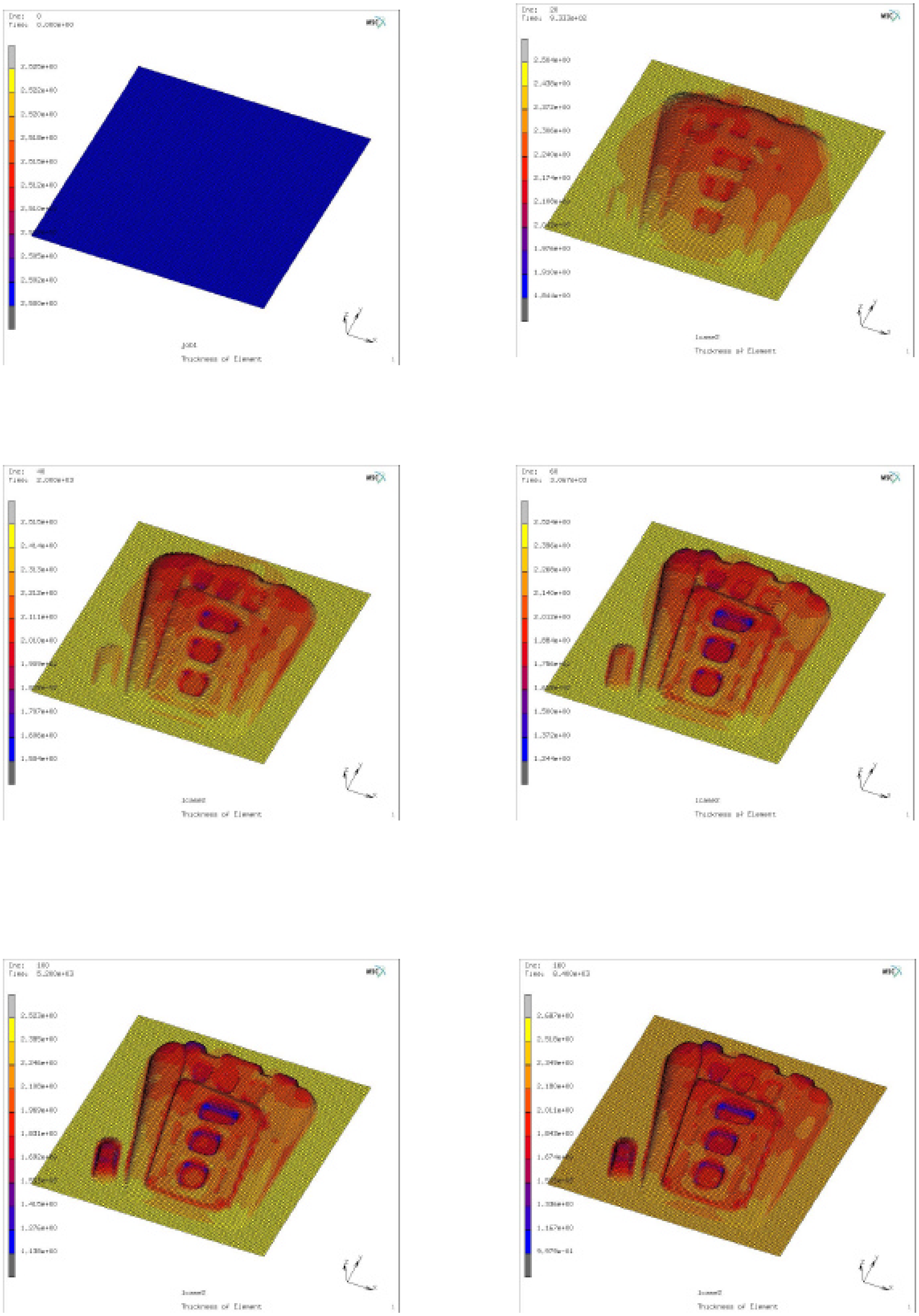
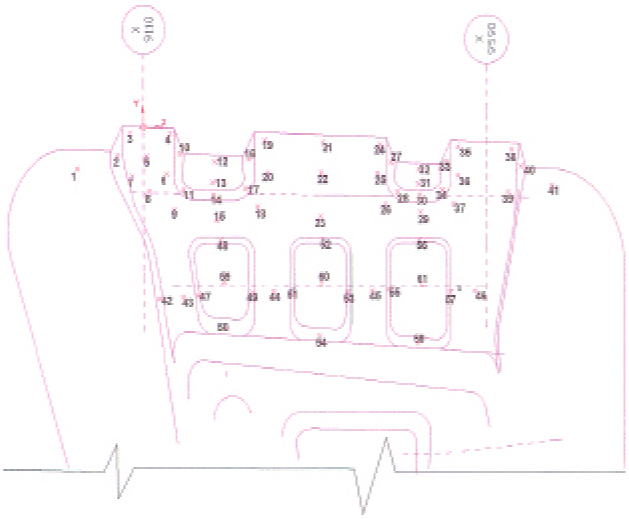


Fig. 4: Time history of U/C Door forming – Thickness distribution

UC Door Serial num. NC 004 (FAQ) J52850560-001
Thicknesses map as per CdQ data 28/03/2000
PART A



UC Door Serial num. NC 004 (FAQ) J52850560-001
Thicknesses map as per CdQ data 28/03/2000
PART B

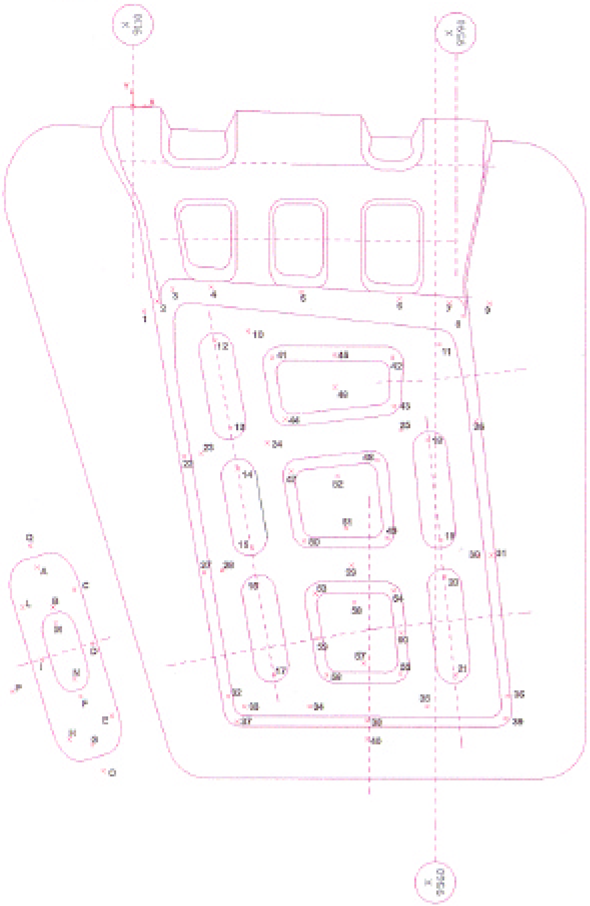


*Fig. 5: Location of experimental and numerical readings of the thickness*

## STUDY OF DIE- PLATE FRICTION

To better understand why a little number of numerical readings ( only 9, see table 1 ) doesn't coincide perfectly with the experimental ones, and also to study the new Marc capabilities, after the acquisition of the methodology performed in the previous paragraph, at the beginning the attention has been turned to the "test" of the door, shown in fig. 1, so that we could have an easy and quick tool for every attempt. A specific detailed F.E.M. model of the "test" has been produced (see fig. 6), and a new numerical-experimental correlation has been performed, so that the causes of the non perfect correlation in some points could be understood. The most probable cause has been found in the die-plate friction . For this reason, a study about the way to numerically simulate the friction has been performed.

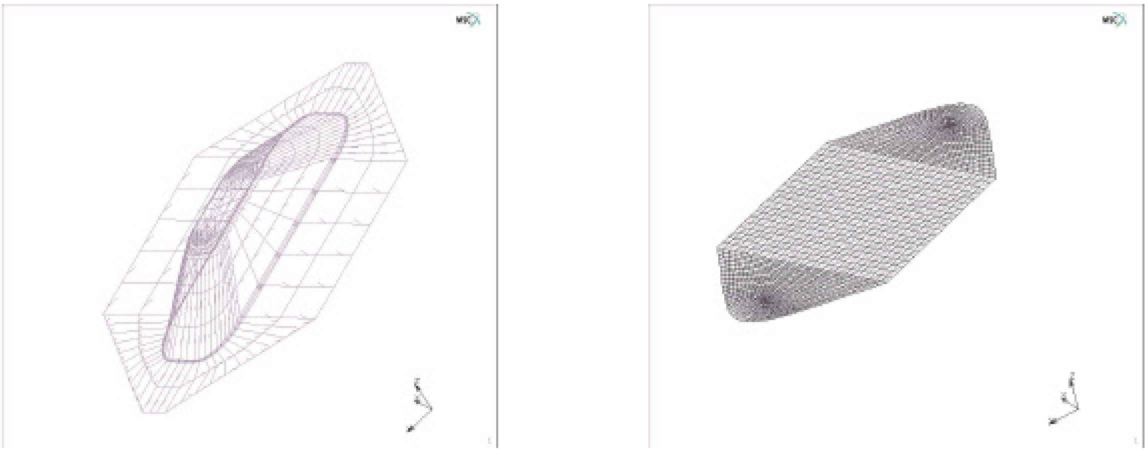


*Fig. 6: F.E.M. model for the die and for the initial plate of the EF200 U/C Door "test" article*

Because of the fact that the real friction coefficient is unknown, various attempt have been realised, by using different values of the friction coefficient, so that we could have a numerical valuation of the real friction coefficient.

The Marc code uses different model for the friction. In our process, the Coulomb friction is the more reliable one, in the classical formulation:

$$F_{fr}=\mu F_n \qquad [\alpha]$$

where $F_f$ is the tangential force between two bodies in contact, $F_n$ the relative normal reaction and $\mu$ is the Coulomb friction coefficient.

In the Marc code the complete formulation for the Coulomb friction is:

$$F_{fr}=\mu F_n 2/\pi \ast \arctan(V_r/RVCNST) \ast t \qquad [\beta]$$

With respect to the [$\alpha$] formulation, in the $\beta$] formulation there are some added factors, i.e.: $v_r$, the relative sliding velocity between the bodies in contact; RVCNS,T the value of relative velocity when sliding occurs (its value can be chosen by the Marc user); t the tangential vector in the direction of the relative velocity. Physically, those terms are able to represent the friction in some contact problems, when along a contact surface the material flows in a part of the surface in one direction and in the opposite. In those cases, the friction force can be represented like a step function of the two bodies relative velocity.

In our process, we have chosen to give to the parameter RVCNST an opportune value, to bring back the [$\beta$] formulation to the classical form, expressed into the [$\alpha$].So, the parameter that could be varied into the[$\alpha$]n is the coefficient $\mu$.

Giving to the $\mu$ coefficient the values: $\mu = 0$, $\mu = 0.1$, $\mu = 0.25$, $\mu = 0.5$, the Marc analysis has been performed ; then, a numerical-experimental correlation has been performed for the thickness, in correspondence with the points shown in fig. 1. The results have been reported in the table:

| Punto | Letture Sperimentali | Letture numeriche (m=0) | Letture numeriche (m=1) | Letture numeriche (m=25) | Letture numeriche (m=5) |
|---|---|---|---|---|---|
| A | 237 | 233 | 236 | 237 | 238 |
| B | 18 | 175 | 172 | 167 | 166 |
| C | 189 | 182 | 182 | 185 | 187 |
| D | 181 | 155 | 166 | 17 | 175 |
| E | 192 | 198 | 199 | 2 | 203 |
| F | 175 | 173 | 173 | 171 | 17 |
| G | 237 | 228 | 228 | 228 | 23 |
| H | 185 | 205 | 201 | 199 | 198 |
| I | 178 | 16 | 166 | 17 | 175 |
| L | 187 | 186 | 187 | 189 | 19 |
| M | 168 | 162 | 158 | 154 | 152 |
| N | 169 | 162 | 158 | 154 | 151 |
| O | 263 | 249 | 249 | 249 | 25 |
| P | 226 | 248 | 249 | 249 | 249 |
| Q | 25 | 249 | 249 | 249 | 25 |

*Table 1: Numerical-Experimental correlation for the "test" article – Various friction coefficient*

The table shows that the numerical thickness on more inclined sides of the "test" article, by increasing the friction coefficient, becomes higher and nearest to the experimental value. But not in every point there is an improvement, maybe because a variable coefficient would have to be introduced. Those considerations could be totally transferred to the entire door, so the not perfect agreement between numerical and experimental reading in the 9 points of table 1 could be explained.

In the future, it could be possible to split the contact surface in different zones, with different friction coefficients, so that we could found the unknown friction coefficient thanks to a numerical-experimental correlation.

## STUDY OF THE OPTIMIZED LOADING CURVE

In order to operatively apply the discussion conduced till now, for example to improve the parameters of the real process, a new Marc capability has been analysed. This capability provides an optimized loading for the process, which is able to produce the forming process at the least time period. Those results have been applied at the beginning to the "test" article and in a second moment to the entire door, so that an optimized loading curve for the process will be proposed.

The F.E.M. U/C Door model and the constraints are still the ones used for the analysis of forming under the real loading; in this case, therefore, the loading curve changes, and it will be the main result of our analysis. For this kind of simulation, it has been necessary to indicate the direction and the versus of the loading, and the maximum value of pressure to be achieved during the process. This value of the pressure has been fixed – according to the one used in the actual real process - at 1 $N/mm^2$. The code stops automatically the analysis when an "ending condition" has been achieved. We have decided to finish the analysis when all the points of the plate are in contact with the die, that is the forming process is effectively ended. After a study to find the right coefficients of convergence for the analysis, for the EF2000 U/C Door the Marc code suggests the new loading curve shown in fig. 7.

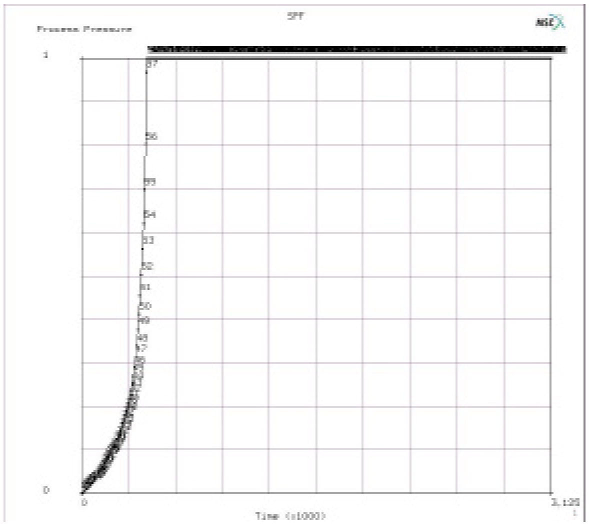


*Fig. 7: Numerical optimized loading curve for the S.P.F. process of EF2000 U/C Door*

Notice how the loading curve becomes horizontal after 430 seconds from the beginning of the process (corresponding to the 58 loading increment). So, we could affirm that the new process examined ends after only 430 second ( against the 7800 seconds of the actual process). In effect, the figure 8 shows as globally after 430 seconds the form of the die has been kept by the plate. But the strain rate distribution at the same instant ( see fig. 9) shows that in some points there is a value of strain rate still high, what means that the material would still flow, above all in correspondence of the horizontal basins.

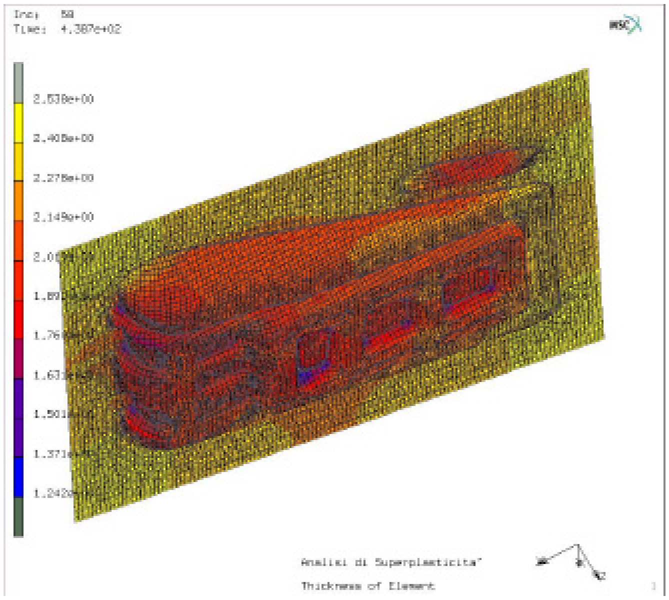


*Fig. 8:Thickness distribution on U/C Door - Increment 58 – Optimized loading curve*

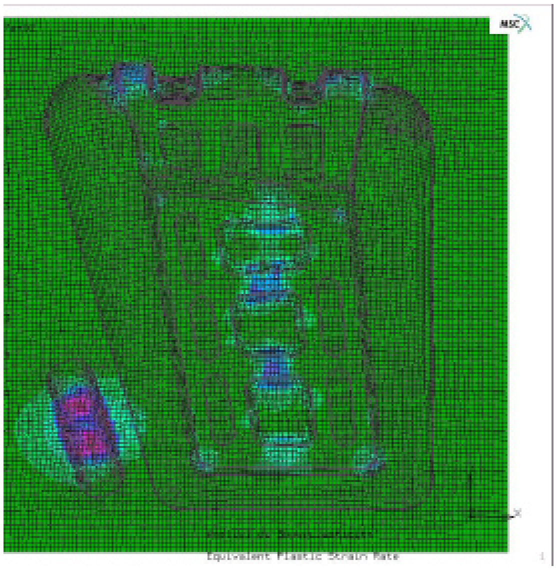


*Fig. 9: Strain rate distribution on U/C Door - Increment 58 – Optimized loading curve*

By zooming on a basin and following its history in terms of thickness distribution on the deforming piece (see the following figures) it emerged that not in every point the die form is kept by the plate: in the lower angle there is an empty space. The strain rate distribution confirms that the material would flow to fill the empty space, but the correct form is not achieved. A cause has been found into the not sufficiently finer meshing in this zone: the angle of the basin can't be achieved for numerical reasons.

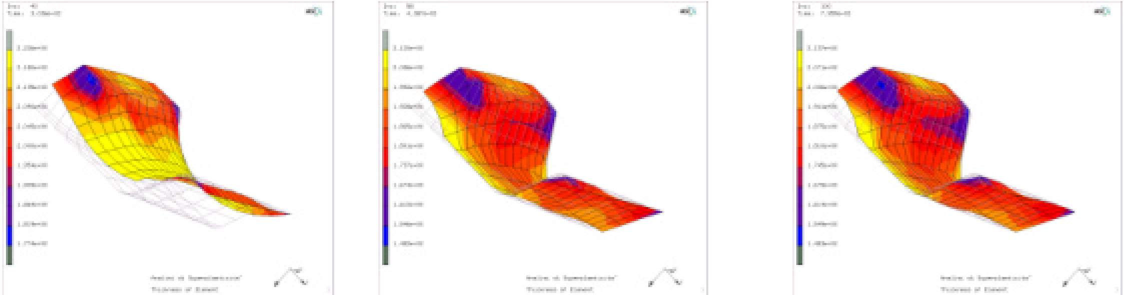


*Fig. 10: Thickness distribution on deformed shape– Increments 40,58 and 100 - Optimized loading curve – Zone between two horizontal basins*

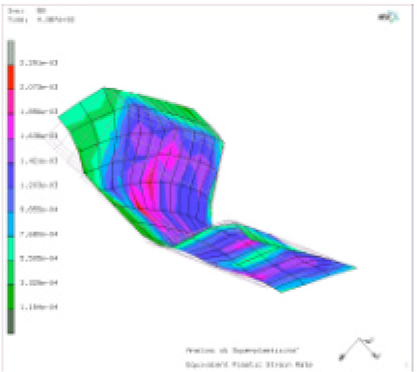


*Fig. 11: Strain rate distribution on deformed shape – Increment58 - Optimized loading curve – Zone between two horizontal basins*

To have a local and automatic finer remeshing, another capability of the Marc has been studied: the auto-adaptive remeshing.

## STUDY OF THE AUTO-ADAPTIVE REMESHING

It has been decided to evaluate this new Marc capability in the zone between the two horizontal basins, where the previous analysis had shown some matters. It has been chosen to have a remeshing such as when a node of the plate touches the die, every element arriving in that node has to be split in four elements. We have chosen that this subdivision has to stop at the first level. By performing the Marc analysis, the following results have been obtained.

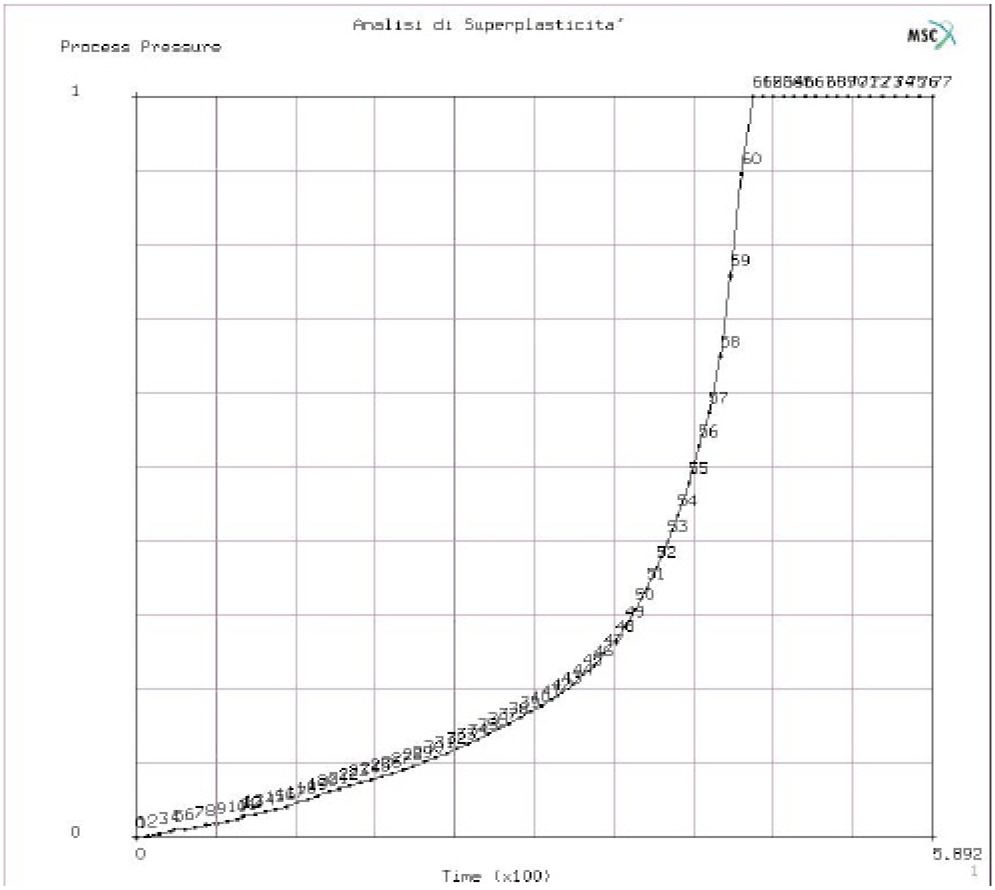


*Fig.12 : Optimized loading curve for EF2000 U/C Door S.P.F. - Application of the capability:"Auto-adaptive remeshing "*

The optimized curve is slightly different with respect to the one obtained without remeshing; the horizontal behaviour of the curve starts after 456 seconds, and not after the 430 seconds of the previous analysis. In next figure the thickness and strain rate distribution at this instant have been reported.

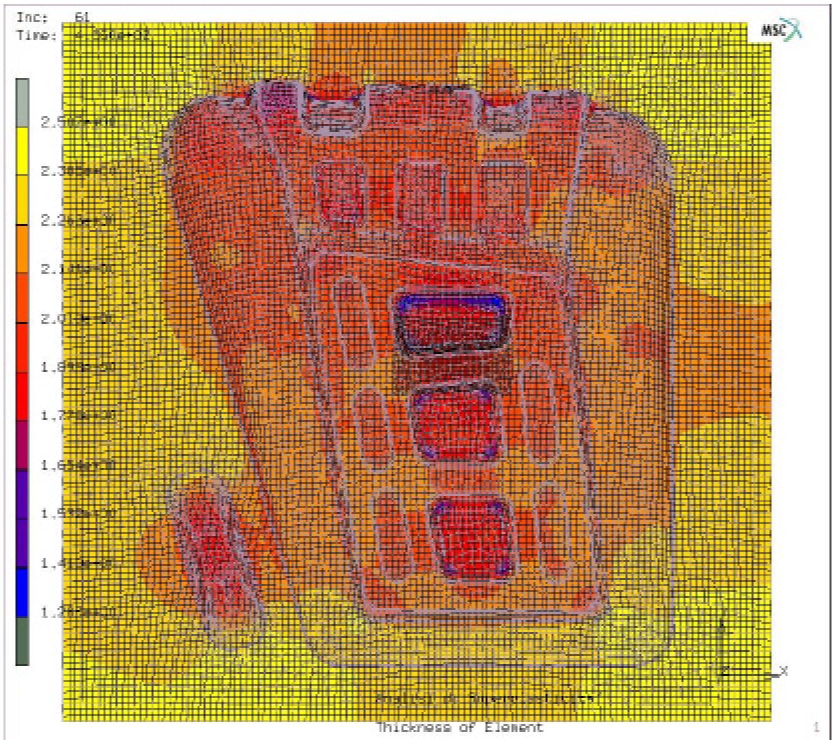


*Fig. 13: Thickness distribution for EF2000 U/C Door – increment 61 – Optimized loading curve – Application of the capability: Auto-adaptive remeshing*

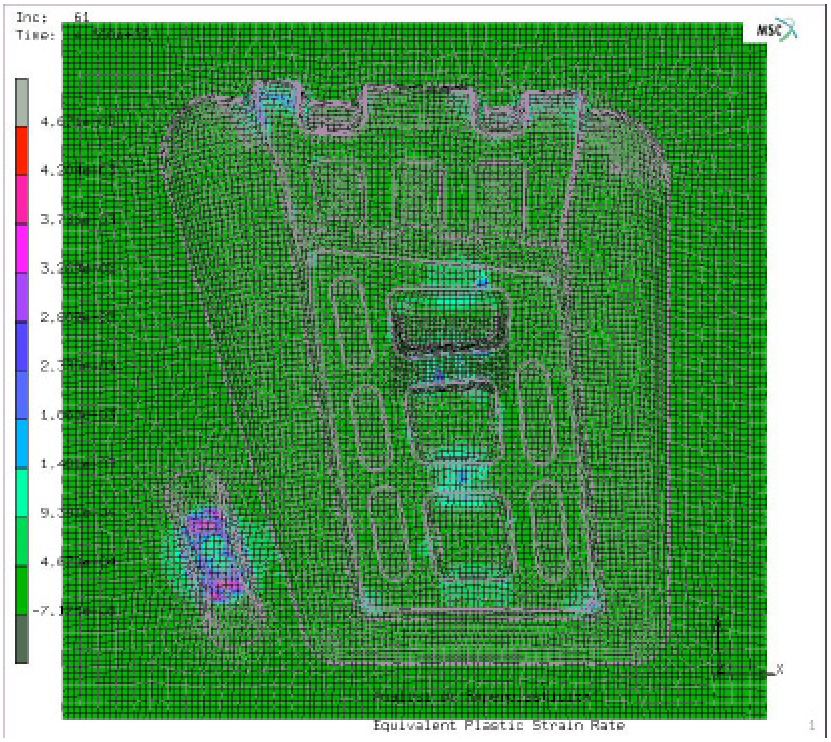


*Fig. 14: Strain rate distribution for EF2000 U/C Door – increment 61 – Optimized loading curve – Application of the capability: Auto-adaptive remeshing*

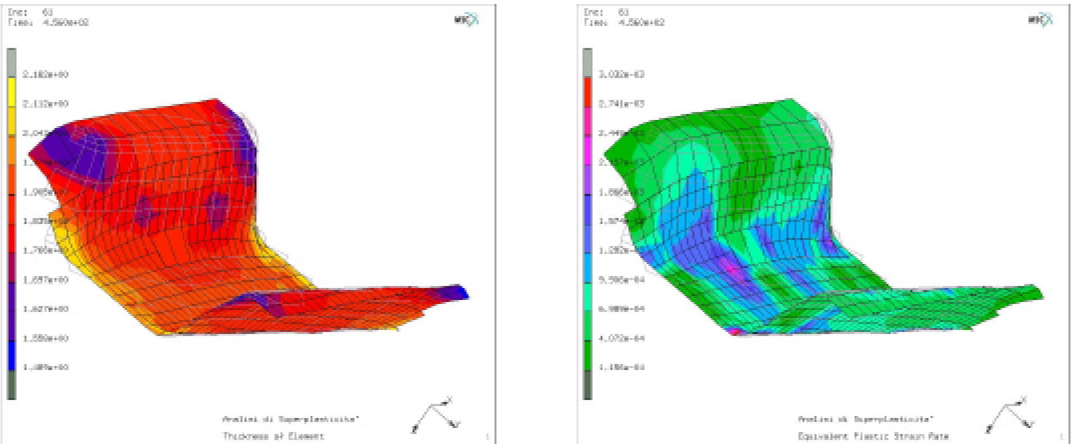


*Fig. 15 :Thickness and strain rate distribution on deformed shape – Increment 61 – Optimized loading curve with application of the capability :Auto-adaptive Remeshing – Zone between two horizontal basins*

Globally, it is evident that the form of the die has been kept by the plate. Zooming on the remeshed zone, notice how the form is followed by the plate in a quite perfect way. The analysis of the strain rate distribution shows still a flowing tendency, but in a very limited zone.

So the performed analysis shows that a new S.P.F. process could be imagined for the EF2000 U/C Door, by using the numerical loading curve shown in fig. 11, stopped in correspondence of the point in which the curve becomes horizontal.

## CONCLUSIONS

In this work, an accurate study of the MSC Marc code has been performed.

The good agreement between thickness numerical and experimental readings has shown that the Marc code is able to correctly represent the complex process of S.P.F. for the EF2000 U/C Door.

A study about the possibility of simulating the die-initial plate friction has been performed. Various important capabilities of the code have been examined and applied, like the possibility to obtain an optimized curve in terms of times and costs for the S.P.F. process, and the opportunity of realizing an auto-adaptive remeshing of the critical zones.

The immediate application of this study could be the utilization of the new loading curve found through the numerical analysis.

Then this study could open the doors to analyze numerically every kind of component to be formed by S.P.F., to know all the parameters of the process. Thanks to the numerical analysis, for example, it could be possible to choose the optimised loading curve. This would signify a more reasoned utilization of the presses, or it could be possible to buy the more opportune machinery. The influence of every parameter on the finite component could be evaluated numerically, too, with a significant reduction of the expensive tests of the part to be formed. And, finally, the optimized distribution of thickness for the plate to be formed could be numerically studied, so a piece with dimensions very close to the project ones could be realized.

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# ATTACHMENT 1

| **Location** | **Exp. Readings** | **Numerical Readings** | **Percentage Gap** |
|---|---|---|---|
| 3 | 1.82 | 1.95 | 7.14 |
| 4 | 1.84 | 1.81 | 1.63 |
| 5 | 1.61 | 1.59 | 1.24 |
| 6 | 1.45 | 1.46 | 0.69 |
| 7 | 1.53 | 1.43 | 6.53 |
| 8 | 1.6 | 1.57 | 1.87 |
| 9 | 1.86 | 1.85 | 0.54 |
| 10 | 1.66 | 1.66 | 0.00 |
| 11 | 1.6 | 1.6 | 0.00 |
| 12 | 1.95 | 1.61 | 17.43 |
| 13 | 2 | 1.97 | 1.50 |
| 14 | 1.95 | 1.99 | 2.05 |
| 15 | 2 | 2.03 | 1.50 |
| 16 | 1.83 | 1.84 | 0.55 |
| 17 | 1.8 | 1.84 | 2.22 |
| 18 | 2 | 1.98 | 1.00 |
| 19 | 1.95 | 1.92 | 1.54 |
| 20 | 1.8 | 1.7 | 5.50 |
| 21 | 2.02 | 1.94 | 3.96 |
| 22 | 1.96 | 1.9 | 3.06 |
| 23 | 2.04 | 1.97 | 3.43 |
| 24 | 1.88 | 1.85 | 1.59 |
| 25 | 1.77 | 1.97 | 11.29 |
| 26 | 2.1 | 2.09 | 0.49 |
| 27 | 1.85 | 1.76 | 4.86 |
| 28 | 1.81 | 1.87 | 3.31 |
| 29 | 2.14 | 2.17 | 1.40 |
| 30 | 2.12 | 2.13 | 0.47 |
| 31 | 2.1 | 2.09 | 0.47 |
| 32 | 1.96 | 1.78 | 9.18 |
| 34 | 1.78 | 1.73 | 2.80 |
| 35 | 1.91 | 1.87 | 2.09 |
| 36 | 1.7 | 1.63 | 4.12 |
| 37 | 2 | 2.03 | 1.50 |
| 38 | 1.67 | 1.77 | 5.98 |
| 39 | 1.8 | 1.74 | 3.33 |
| 40 | 1.81 | 1.64 | 9.39 |
| 42 | 1.9 | 1.84 | 3.16 |
| 43 | 1.93 | 1.97 | 2.07 |
| 44 | 2.05 | 1.91 | 6.83 |
| 45 | 2.11 | 1.97 | 6.63 |
| 50 | 2.02 | 1.96 | 2.97 |
| 54 | 2.07 | 2 | 3.38 |
| 55 | 2.11 | 1.89 | 10.42 |
| 56 | 1.91 | 1.94 | 1.57 |
| 57 | 2 | 2.02 | 1.00 |
| 58 | 2.02 | 2 | 1.00 |
| 59 | 2.05 | 1.77 | 13.65 |
| 60 | 2.11 | 1.9 | 9.95 |
| 61 | 2.09 | 2.06 | 1.43 |

*Table 2 – Numerical-Experimental correlation on thickness – Part A*

| Location | Exp. Readings | Numerical Readings | Percentage Gap |
|---|---|---|---|
| 1 | 2.14 | 1.99 | 7,00 |
| 2 | 1.94 | 1.98 | 2.06 |
| 3 | 1.94 | 2 | 3.09 |
| 4 | 1.97 | 1.96 | 0.51 |
| 5 | 1.97 | 2.02 | 2.53 |
| 6 | 1.98 | 2.07 | 4.54 |
| 7 | 1.8 | 2.11 | 17.20 |
| 8 | 1.9 | 2.04 | 7.30 |
| 9 | 2.06 | 2.14 | 3.88 |
| 10 | 21 | 1.99 | 5.23 |
| 11 | 1.9 | 1.89 | 0.52 |
| 12 | 2.06 | 1.91 | 7.28 |
| 14 | 2.08 | 2.01 | 3.36 |
| 16 | 2.15 | 2.08 | 3.25 |
| 18 | 2.1 | 2 | 4.76 |
| 20 | 2.14 | 2.05 | 4.20 |
| 22 | 2.08 | 2.03 | 2.40 |
| 23 | 2.02 | 2.01 | 0.49 |
| 24 | 2.23 | 2.13 | 4.48 |
| 25 | 2.13 | 2.08 | 2.34 |
| 26 | 1.97 | 1.96 | 0.51 |
| 27 | 2.1 | 2.05 | 2.38 |
| 28 | 2.13 | 2.13 | 0.00 |
| 29 | 1.95 | 2.07 | 6.15 |
| 30 | 2.2 | 2.14 | 2.72 |
| 31 | 2.02 | 2.06 | 1.98 |
| 32 | 2.04 | 2.04 | 0.00 |
| 33 | 1.93 | 1.91 | 1.03 |
| 34 | 2.13 | 2.22 | 4.22 |
| 35 | 2.16 | 2.22 | 2.77 |
| 36 | 2.03 | 1.92 | 5.42 |
| 37 | 2.07 | 2.04 | 1.45 |
| 38 | 2.05 | 2.12 | 3.41 |
| 39 | 2.01 | 2.04 | 1.49 |
| 40 | 2.29 | 2.35 | 2.62 |
| 46 | 2.05 | 1.87 | 8.78 |
| 47 | 2 | 2.05 | 2.50 |
| 48 | 1.95 | 1.96 | 0.51 |
| 49 | 2.03 | 2.05 | 0.98 |
| 50 | 2.12 | 2.12 | 0.00 |
| 51 | 2.12 | 1.85 | 12.73 |
| 52 | 2.06 | 1.81 | 12.13 |
| 57 | 2.09 | 2.02 | 3.35 |
| 58 | 2.09 | 1.99 | 4.78 |
| A | 2.37 | 2.3 | 2.95 |
| B | 1.8 | 1.77 | 1.66 |
| D | 1.81 | 1.68 | 7.18 |
| F | 1.75 | 1.75 | 0.00 |
| G | 2.37 | 2.36 | 0.42 |
| M | 1.68 | 1.65 | 1.78 |
| N | 1.69 | 1.66 | 1.77 |

*Table 3 – Numerical-Experimental correlation on thickness – Part B*