# Efficiency Improvement and Analysis of Changes in Microstructure Associated to a Uniform Pressure Actuator

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## Abstract

*During the 1st international Conference on HIGH SPEED FORMING held in Dortmund in 2004 a new forming coil giving significant advantages was presented in the framework of ongoing R&D programs at OSU (The Ohio State University). It established the improvement provided by the return path for currents induced in the workpiece.*

*To quantify the mentioned improvement, Labein has performed classical cone forming experiments with both configurations and analyzed energetic efficiency using well known alloys, more precisely AA 6016 and 1050. Both deformation mechanisms and contour analysis of the specimens were studied. General purpose multi-turn coils provide pressure distributions not extended to the whole forming area, resulting in zones undergoing significant delay as die the deformation sequence is referred.*

*As a result, varied deformation patterns can be found along the contour of a cone specimen formed in such way. Firstly, a macroscopic survey of the specimens shows that uniform pressure distributes deformation over the entire formed area during the deformation process. Secondly, the effect on efficiency provided by this new coil concept is focuses not only on the ability for distributing deformation, but on the energy required to create such deformation.*

*Finally, to validate the whole simulation, the predicted strain level, shape, and internal energy of the workpiece are compared with the experimental specimens. A key point in the validation process is checking the internal energy. It is known that the ratio of stored energy to deformation energy ranges in the order of 30 %. The procedure for the experiments follows this methodology.*

## Keywords:

Uniform pressure coil, High velocity forming, Pressure distribution.

# 1 Introduction

The results of a global analysis of the behavior of several magnetic actuator coils are presented here. For this purpose, two coil configurations were proposed as working inductors within the scope of a comprehensive sheet metal forming operation, as it is the cone forming experiment. Basically, when dealing with sheet metal workpieces, solenoid based solutions are the basic options [2], [3], [4], known as flat multi-turn coils like those presented in Figure 1. The main advantages of such coils can be summarized by its ease of fabrication while maintaining a good distribution of magnetic properties along its surface. On the other hand, the so called uniform pressure actuator is presented as an alternative working concept in the field. The strength of this kind of configuration lies in the uniform magnetic pressure field provided within close proximity of the conductor filled surface.

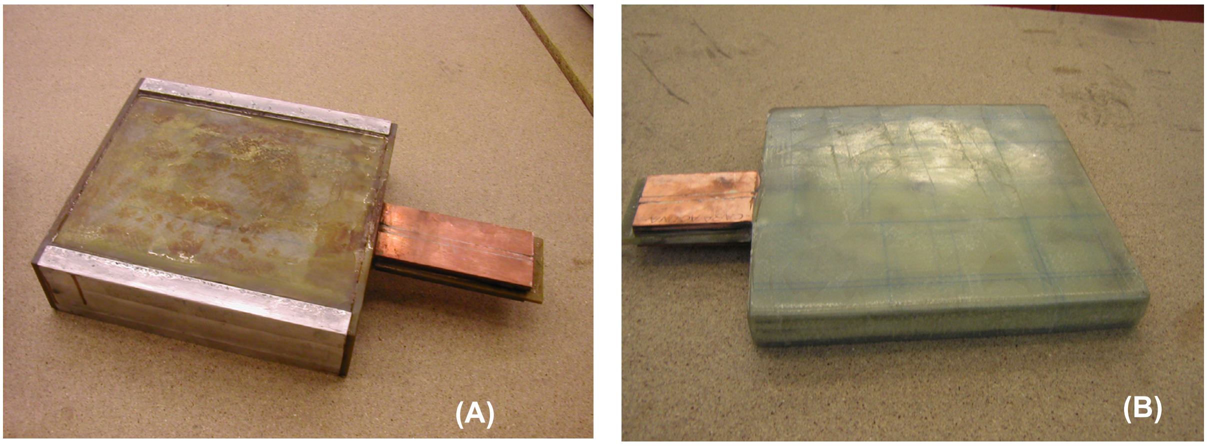

***Figure 1:*** *Uniform pressure coil (A) and multiturn coil (B)*

## 1.1 Uniform pressure coil. Basic principles.

The working principle of the uniform pressure coil is presented in Figure 2. An outer conducting channel, electrically insulated with respect to the central core where the primary winding is placed, is incorporated, allowing for an extended circulating track for induced currents.

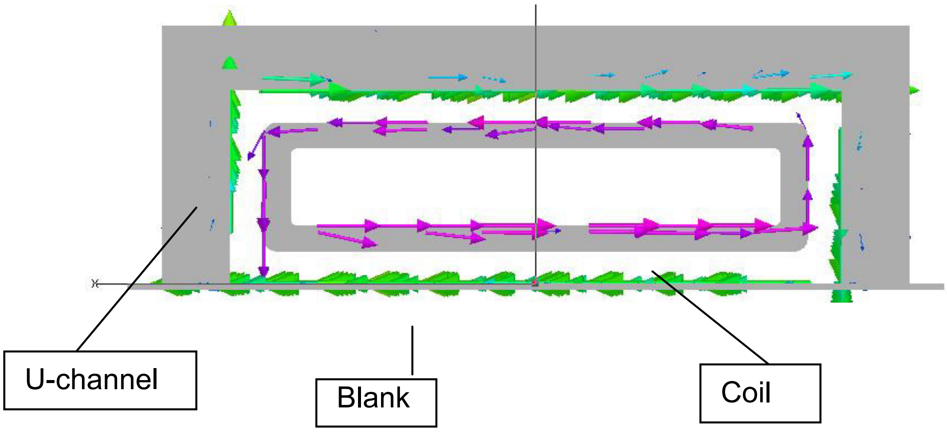

***Figure 2:*** *Primary and induced currents in the uniform coil, from Maxwell 3D*

In Figure 3 the effect of the addition of an outer channel in terms of the induced magnetic field in the surrounding space can be seen. The uniform pressure coil gives rise to a higher field while redirecting current circulation, provided that rust free and clear contacts are achieved as contact surface. The contact surface is paramount to account for undesired arcing effects.

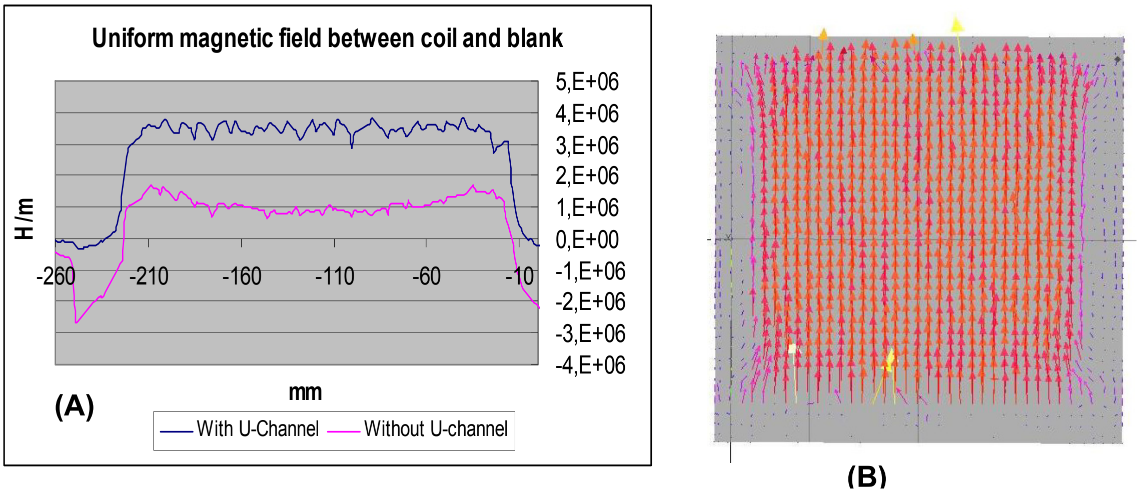

***Figure 3:*** *Magnetic field(A) and induced currents on the blank(B) for the uniform coil*

The magnetic field provided by a conventional multi-turn coil is non homogeneous in the radial direction, and it takes several winding thicknesses until it builds up with full strength. An example of this is shown by the results of magnetic field distribution analysis performed with a 22 turn spiral coil. (Figure 4)

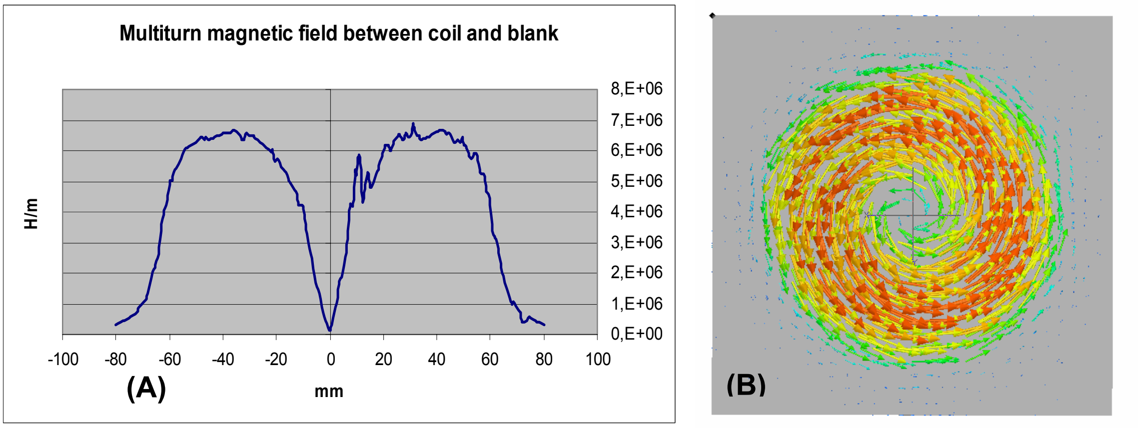

***Figure 4:*** *Magnetic field (A) and induced currents on the blank (B) for the multi-turn coil for a running current of 60 000 A in steady state regime*

Regarding the forming stage, this results in zones undergoing significant delay as to the deformation sequence.

As a result, varied deformation patterns can be found along the contour of a cone specimen formed in such way, provided in part by the encounter between die wall and workpiece and the mentioned velocity gradient in the initial instants.

## 2 Experimental procedure

The aim of this paper is to determine the improvement achieved by using the uniform pressure coil with respect to the multi turn coil; hence, the experimental possible real improvements were established as follows; more uniform strain distribution on the workpiece, less microestructural changes. Afterwards, FEM process simulation would be used as tool to explain the differences achieved between different coil samples.

In this study, a 60 Kj Energy Storage and Control Unit Magneform machine was used for the experiments. The main characteristics of this machine are listed in Table 1:

| | |
|---|---|
| Maximum energy (Kj) | 60 |
| Capacity (μF) | 1800 |
| Electric resistance (μΩ) | 956 |
| Inductance (nH) | 10,3 |

***Table 1:*** *Capacitor bank parameters*

Two different aluminum alloys with dissimilar mechanical characteristics were chosen: Firstly, AA 1050, a low alloyed material in O temper state, AA1050, and 6016 T-4 aluminum, widely spread in the automotive industry for deep drawing of body panels. Their mechanical characteristics are listed in Table 2.

| | AA 1050 | AA 6016 |
|---|---|---|
| Tensile strength, ultimate, MPa | 76 | 230 |
| Tensile strength, yield, MPa | 28 | 120 |
| Elongation at break, % | 39 | 27 |
| Poissons ratio | 0.33 | 0.25 |
| Thickness, mm | 1 | 1 |

***Table 2:*** *Mechanical properties of AA 1050-0 and AA 6016-T4*

## 2.1 Experimental set-up

The experimental set up is shown in Figure 5 and Figure 6.

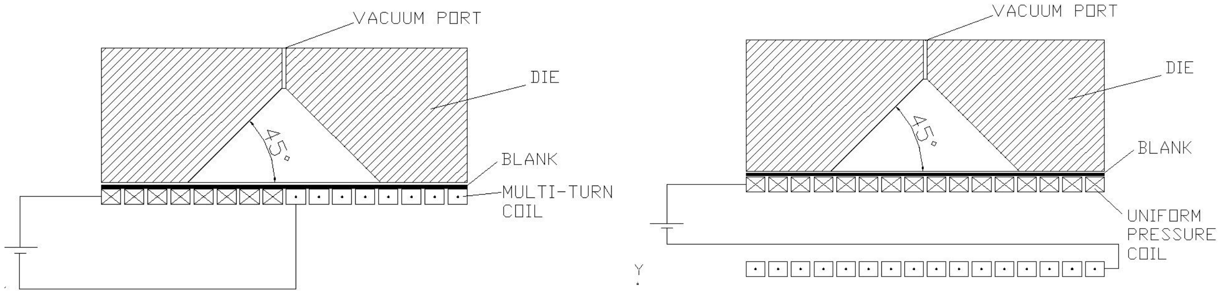

***Figure 5:*** *Experimental setup for multi-turn and uniform coil*

A cone-shaped die with a 90 ° apex angle was chosen where the radius in die entrance was machined down to 3 mm. Material samples were squared to 240 mm side dimension and to fully account for reaction of the coil as a result of the exerted magnetic pressure, the entire assembly (coil, sheet metal and die) was clamped using a 100 ton hydraulic MTS machine. Reaction force value present during each discharge was recorded. Clamping force was gradually increased to avoid non-desired arcing in contact surfaces when using the uniform pressure coil. During the experiments charging energy was gradually increased until failure or localized necking occurred in the sample. Current pulse values were stored using a 192 –B Fluke Series Oscilloscope to serve as input for the simulation iteration.

## 2.2 FEM simulation

Based on practical considerations, an uncouple scheme was selected to estimate the forming mechanism of samples, the FEM procedure was stated as follows:
Maxwell 3D was initially used to simulate the electromagnetic aspect of the problem without consideration of the mechanical aspect. This part of the simulation starts with the electric pulse introduced as input for the coil for every experiment performed. As said, the pulse was firstly obtained with a 192 B Fluke series Oscilloscope by means of the Rogowski coil present in the ESCU 60 Kj Series Magneform machine used for the experiments. Afterwards, Maxwell 3D will perform the calculation of the electric current distribution running in the coil as well as the induced currents obtained in the workpieces

located nearby assuming a steady state regime. Associated with induced currents, the software obtains the magnetic field between the coil and the blank as well as the average force value exerted in the workpiece.

With this iterative process the estimation of the total average force applied on the sheet metal part is calculated and subsequently brought as an input load for the simulation of the deformation process, which is done by means of PAM-STAMP2G, a specific code devoted to sheet metal forming simulation.

A quantitative match of the mentioned force parameter is pursued by adjusting the peak value of the pressure or force pulse that serves as an input in Pam –Stamp. In this context, the need for such adjustment is justified if we consider the nature of the magnetic simulation:

1) A steady state regime of current circulation is assumed in the electromagnetic computation.
2) The computation time is restricted to a full cycle of a running current having a ringing frequency and amplitude equal to the ones present in the experimentally obtained current trace.
3) Relative movement between sample and coil is not taken into account.
4) The computed values correspond to mean values associated to a full current cycle.

The critical point is focuses on how to transfer this force value into the deformation code as an input load, i.e. the force vs. time curve. As such, the set of experiments proposed is not envisioned as a benchmark problem to asses the feasibility of the iteration scheme, but to obtain coarse trends as to the studied variables is referred:

a) Global shape of formed samples.
b) Evolution of deformation pattern.
c) Strain levels present in the samples.
d) Contour microstructure analysis.

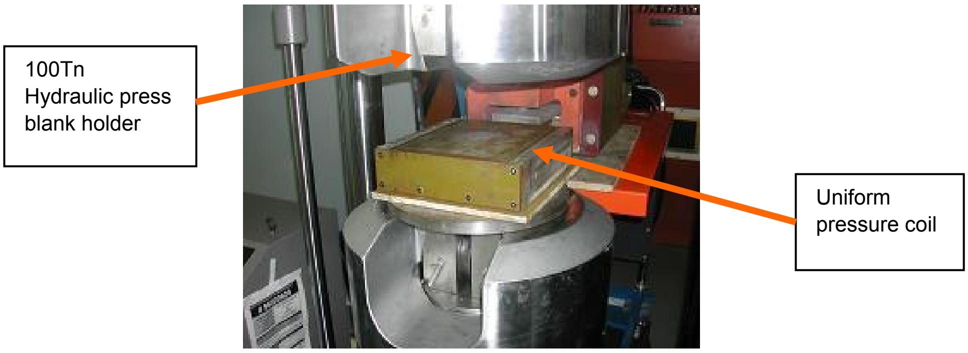

***Figure 6:*** *Experimental setup*

# 3 Results and discussion

## 3.1 Energy considerations, maximum vertex height

For each of the materials tested the following procedure was followed:

Initially, a maximum energy was determined for each alloy. In a sequence of experiments, energy was increased until fracture occurred either on the vicinity of the cone tip or near the die entrance. For each coil configuration a maximum energy was determined, resulting in 4 energy limits.

In case no rupture took place, as observed with the 1050-O alloy, the maximum energy was determined by geometrical considerations where the proximity to the desired final shape was the decisive factor. On the contrary, for the 6016 alloy fracture took place with both coil configurations.

Subsequently, four intermediate energies were chosen in a way that a significant difference in final shape would take place with each one. Three repetitions were made for every case.

Afterwards, the profile of the formed samples was captured for the sake of comparison with the desired final shape. In following figures (Figure7, Figure 8), a comparison of the profiles can be observed.

The profiles obtained with the uniform pressure actuator show a smoother contour as a result of the initial energy distribution. The profiles with the spiral coil are the classical ones, exhibiting zones with different curvatures denoting distinct strain distribution.

The energy necessary for the uniform pressure coil is higher than the one needed for the spiral coil. A higher cone height is achieved with the uniform pressure coil as a result of the optimization in strain distribution. The maximum heights achieved are listed in the Table 3.

| | **AA 1050** | **AA 6016** |
|---|---|---|
| **Multi-turn coil** | 41 mm | 30,6 mm |
| **Uniform coil** | 43,3 mm | 31,4 mm |

***Table 3:*** *Maximum height obtained for the different configurations*

The height obtained with the AA 1050 aluminum is close to the final. The uniform coil gives us a higher height due to the more uniform distribution of the deformation .This uniform distribution of the deformation allows the blank to have a final bigger elongation in terms of total distance (Figure 7).

## 3.2 Profile measurement

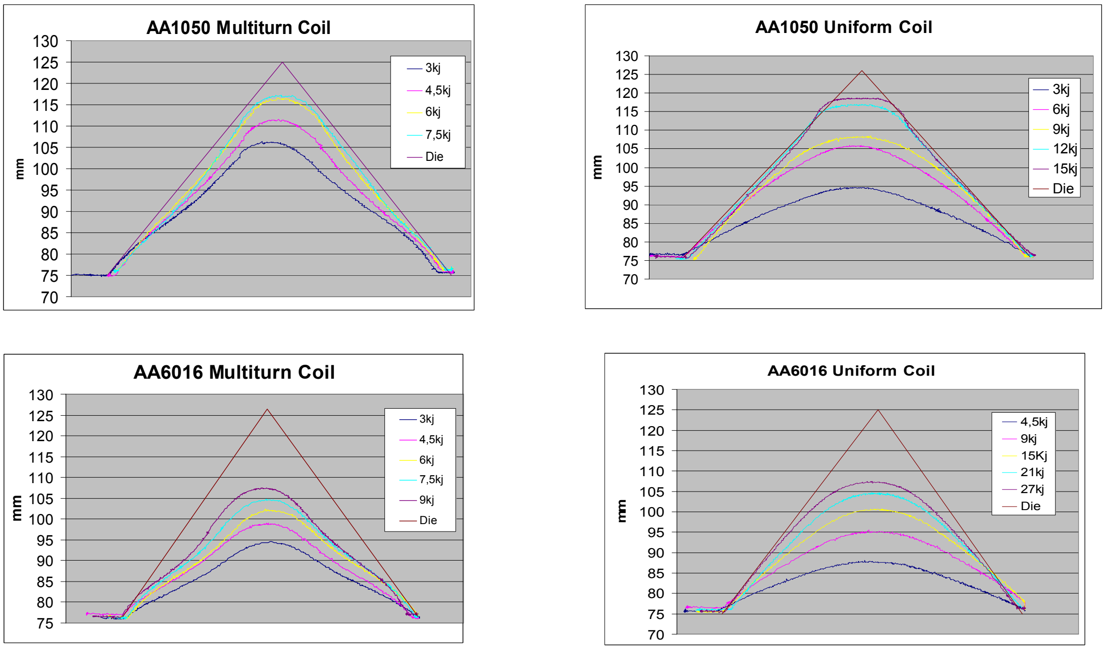

***Figure 7**: Cone profile progression for AA1050 and AA6016 formed with the uniform pressure coil (right) and multi-turn coil (left)*

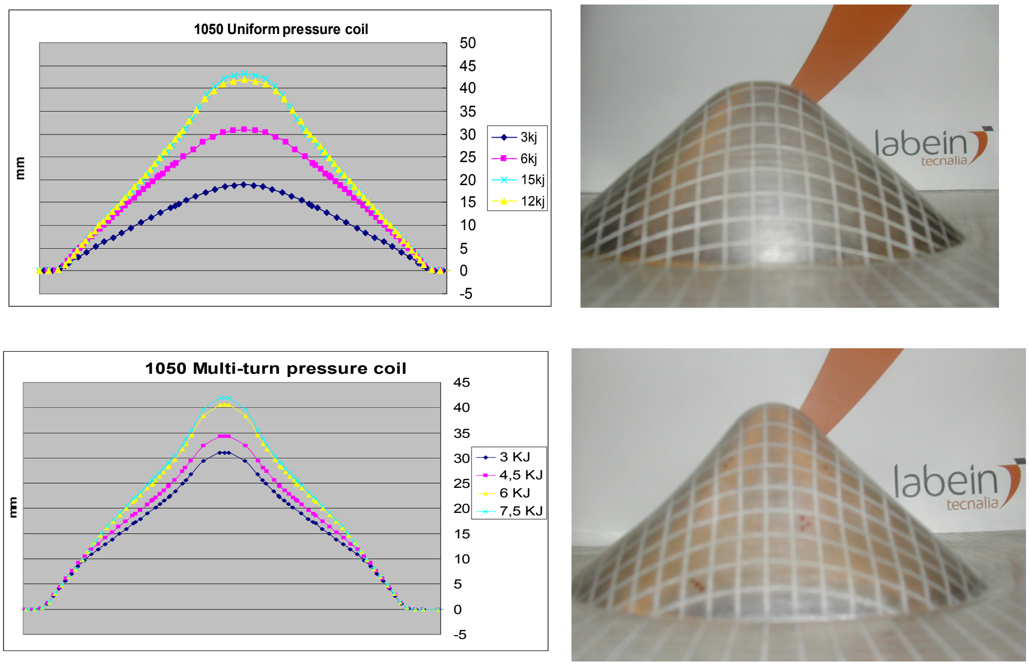

***Figure 8:** Results of simulations with final shapes of AA1050 samples formed at different energies (left) and AA1050 sample formed at 12 kj (right) using a uniform pressure coil (bottom) and a multi-turn coil (top)*

## 3.3 Strain and thickness distribution along the contour of the specimen

The well-known measurement environment system ASAME of CamSys was used to monitorize the evolution profile of the major, the minor, and the thickness strain distribution over the specimen. Bellow, some plots are depicted.

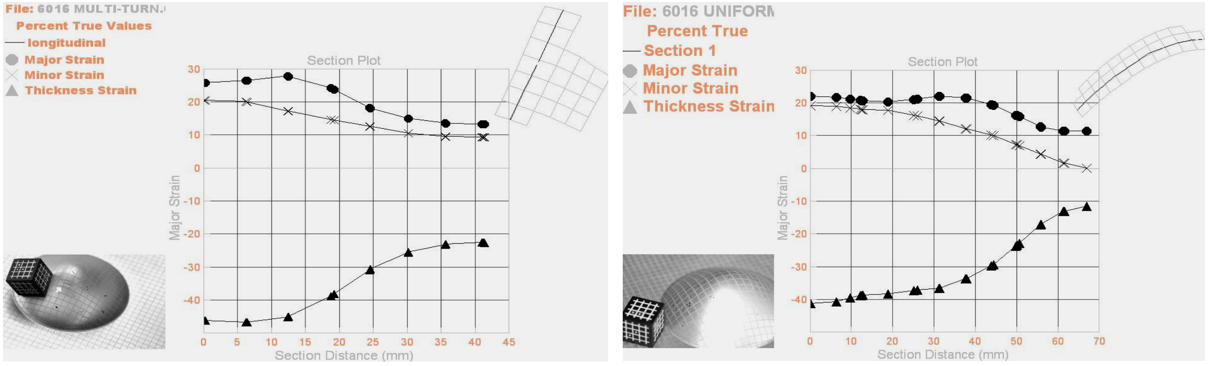

***Figure 9:*** *Major, minor and thickness strain distribution for the AA 6016 aluminum with the multi-turn coil (left) and the uniform pressure coil (right)*

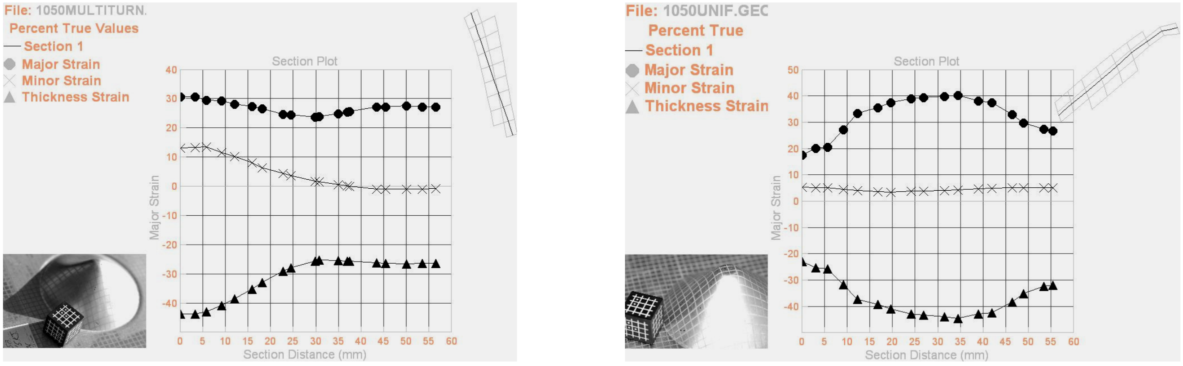

***Figure 10:*** *Major, minor and thickness strain distribution for the AA 1050 aluminum with the multi-turn coil (left) and the uniform pressure coil (right)*

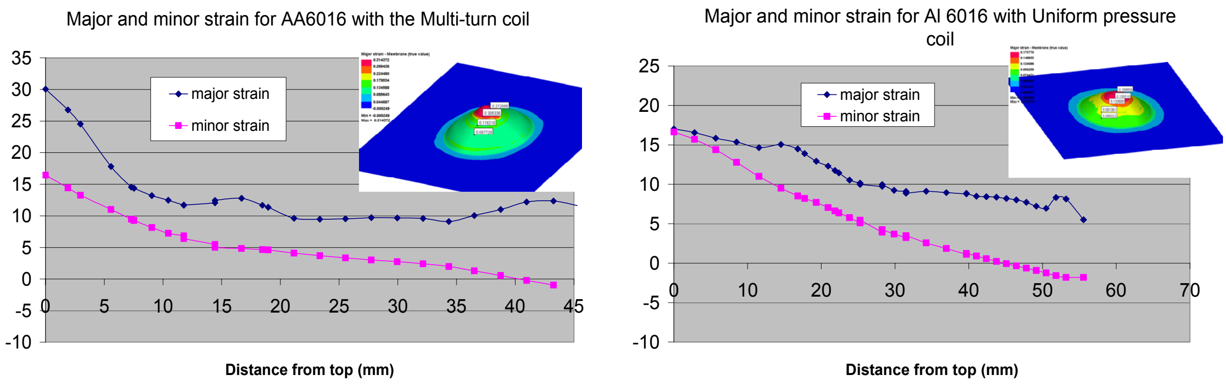

***Figure 11:*** *Major and minor strain distribution for the AA6016 alloy simulation with the multi-turn coil (left) and the uniform pressure coil (right)*

As it can be seen from the plots, AA6016 comparison in Figure 9 and AA1050 in Figure 10, and supported by FEM predictions of strain distributions Figure 11, the following conclusions can be stated:

- The thickness distribution obtained with the uniform pressure coil is more uniform along the part, less ratio % strain variation / section distance. This means that, the thickness reduction is more uniformly distributed over the whole sample, hence larger forces than in the multi-turn coil would be withstood by the sample with failure
- Accordingly, with the previous statement the major and minor strain distributions are also more uniform along the part for the uniform pressure coil case. Furthermore, the strain field on the uniform pressure samples tends to be an equiaxial strain distribution. According to quasi-static FLC's, it is well-known tha these strain states delay the failure predicted by the uniaxial equivalent strain criteria.
- Due to the uniform pressure distribution of the first coil the forming process looks like, in some aspects, a bulge free hydroforming process. So, a uniform distribution of strain is achieved. On the other hand, the multi-turn coil concentrates the pressure over some specific areas of the workpiece at the initial stage and, hence deformations achieved are also non-uniform.
- The major strain obtained in the electromagnetically formed parts is slightly higher than the one obtained by conventional mechanical characterization methods. Furthermore, the AA 1050 gives a higher elongation without failure.

## 3.4 Contour microstructure analysis

A microstructural analysis of the parts was carried out. Samples of both alloys from each of the coils were analyzed. A cone section containing the vertex was cut off for the analysis using a SEM. Special emphasis was put on the fracture zone. Figure 11 shows the fracture zone for an AA6016 alloy formed with the uniform pressure coil (left) and the multi-turn coil (right).

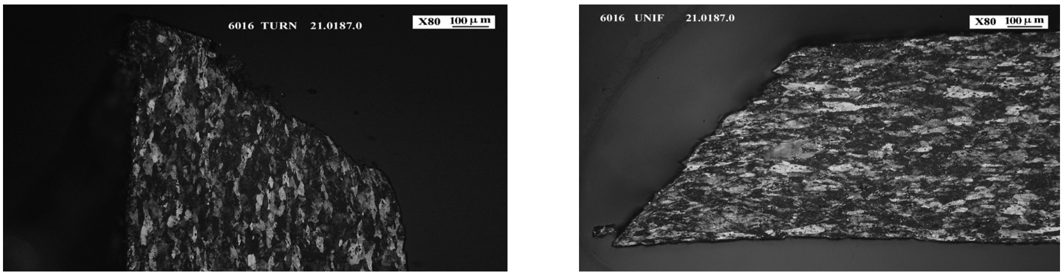

***Figure 12:*** *Microstructures observed for the AA6016 alloy with the multi-turn coil (left) and the uniform pressure coil (right)*

The analysis of the microstructural study reveals that the main difference between both configurations lies in the elongation distribution. According to grain size, uniform coil samples exhibited a homogeneous elongation distribution along the cone generatrix whilst multi-turn samples have a non-homogeneous one, having isolated areas with highest elongation values.

A thickness distribution measurementwas also made along the section with the microscope. The results are shown in Figure 12.

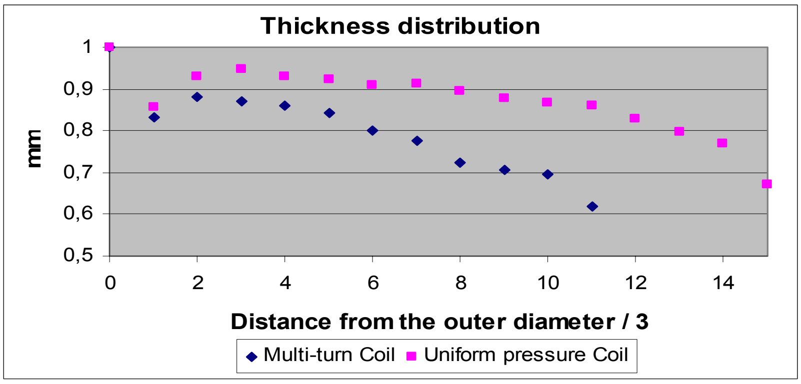

***Figure 13:*** *Thickness distribution for the AA 6016 with both coils*

## 4 Summary

The improvements achieved by using the uniform pressure coil with respect to the multiturn coil have been proved. Samples of AA 6016 and 1050 have been tested in comparison with a conical shaped die. The following concluding remarks can be stated:

- More uniform strain distribution on the workpiece has been achieved
- A better fit to die walls was obtained
- Less microstructure changes along the generatrix of specimens were observed
- FEM process simulation has been used to asses the empirical evidences
- A reasonably good agreement between experimental samples and prediction with the uncoupled scheme of simulation was achieved

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