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Numerical and experimental analysis of the Warm Deep Drawing process for Mg alloys

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Analysis and modelling

ABSTRACT

Purpose: The present work is aimed to investigate the Deep Drawing process of Mg alloy sheet in Warm conditions, since through the temperature temperature the number of independent slip systems of the Mg alloys can be enlarged.
Design/methodology/approach: A FE model and an equipment for warm deep drawing tests were created, since an experimental-numerical method was adopted; the most efficient heating positioning and the most suitable way of performing the WDD process was evaluated using data coming from the numerical model and temperature and punch load acquisition coming from experimental activity.
Findings: Limit Drawing Ratio (LDR) equal to 2.6 for AZ31 Mg alloy (cross rolled, thickness 0.6mm) was obtained at the temperature 170oC using heater embedded in the female die; Drawing Ratio equal to 3.1 for the same Mg alloy (thickness 0.6mm) was obtained setting the temperature of the blank holder at 250oC (throughout heaters embedded in it) and cooling the central part using a water cooled punch.
Research limitations/implications: Next step of the research will be to evaluate the optimal value of process parameters (speed, temperature and blank holder pressure) in order to draw the process window.
Practical implications: The process with controlled heating and cooling technology can be applied in industrial production of a wide range of Mg alloy parts (structural components, covers for computer, communication and customer electronic, sportive equipments).
Originality/value: Specific heating and cooling system were designed to analyse the influence of the different heating strategies combined with or without punch cooling on the WDD of AZ31 Mg alloy sheets.
Keywords: Plastic forming; Magnesium alloy; Warm Deep Drawing; Finite Element method; Formability.

1. Introduction

Due to its lightweight and high specific strength, Magnesium (Mg) alloys are widely used by aerospace and automobile industries (production of structural components) and by computer, communication and customer electronic industries (production of covers and thin-walled parts for any kind of devices, like laptop, cell phone, cameras, CD and DVD players). In recent years the most largely adopted production technique has been the die casting process. However, in the fabrication of high-precision and thin-walled components with large surface areas this process is not ideal because of excessive amount of waste material, low production efficiency, bad process stability and poor mechanical properties of the component. A potential solution would be to resort to a new technique, first used by the “American Aerospace Industry”, which consists in the sheet forming process at elevated temperature. In fact, because of its Hexagonal Closed-Packed (HCP) crystal structure, in which only the basal plane can move at room temperature, Mg alloys show limited straining capability; for this reason, thermal activation of further deformation mechanisms [1, 2] becomes necessary to improve ductility and formability. Nowadays, many research activities are focused on exploring and tuning innovative sheet forming processes for Mg alloys adopting warm or hot conditions for industrial applications [3, 4]. However high cost of Mg alloy sheets and lack of a sufficient knowledge about its formability are often main causes of the actual small number of industrial applications; nevertheless the sheet forming process is very attractive and competitive for both the productivity and the components' performance. As concerns the economic problem, the solution could be represented by new emerging countries characterized by large enough material resource and very competitive production costs. For example China, as leader producer of Mg, has by now the attention of most leader western automotive companies focused on it just for the two reasons previously highlighted. Of course the target is to produce the component directly in China to reduce the production cost. As concerns the technical problem, in the last decades an intense research activity in the field of the sheet forming of lightweight alloys has been developing both in the academic and industrial world [5, 6, 7, 8]: recent studies highlighted that a uniform heating of lightweight sheet metal blanks in a conventional deep drawing process does not lead to a formability improvement, since a temperature gradient able to counterbalance the stress gradient which is originated throughout the blank during the drawing process is necessary in order to form the part as uniformly as possible.

The present work is aimed to investigate the Warm Deep Drawing (WDD) process; experimental activities were combined with numerical simulations using the Finite Element (FE) technique which is nowadays largely diffused as optimization tool [9, 10, 11]. The research activity is based on the cooperation between the Department of Mechanical & Management Engineering (DIMeG) of the Politecnico of Bari and the Institute of Metal Research (IMR) of the Chinese Academy of Sciences in Shenyang [12]. WDD tests on circular blanks in AZ31 were performed both at IMR and DIMeG adopting different heating strategies. In addition a thermo-mechanical Finite Element (FE) model was used for investigating the more efficient positioning of the electric heaters (into the Blank Holder or into the Draw Die); the prediction of critical conditions occurrence was based on the qualitative comparison with the AZ31 Forming Limit Diagram from literature [11].

2. Warm Deep Drawing tests by heating the Draw Die

A preliminary experimental activity on the WDD process of AZ31 Mg alloy sheet was performed at IMR using a set of circular section tools (draw dies and punch). The Mg alloy AZ31 cross- rolled sheet with thickness 0.6mm was used.

WDD tests were performed by heating the die and without any punch cooling. The schematic diagram of the equipment designed and adopted at IMR is shown in Figure 1.

The electric heating elements were distributed axial symmetrically inside the female die to heat the blank. The experimental procedure in the WDD tests is followed: 1) to heat the female die and the blank holder up to the test temperature, being the punch and the blank at room temperature; 2) to assemble the blank; 3) waiting few minutes for heating the blank up to the temperature of the female die; 4) to move down the punch to deform the blank. In such a condition the temperature of the punch before the deformation of the blank, depending on the aimed test temperature and the time interval between the runs, was changed from room temperature to 80°C. WDD tests aimed to form cylindrical cups were performed using a constant punch speed 10mm/min and different temperature levels(120°C, 140°C, 150°C, 160°C, 170°C).

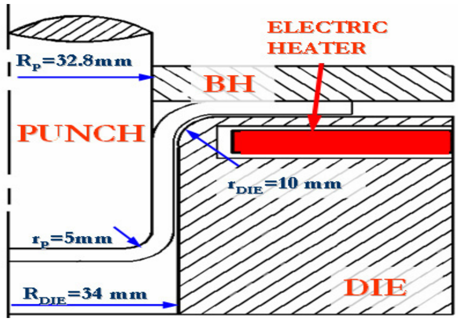


Fig. 1. Equipment for cylindrical cups

T=120°C DR = 1.83	T=140°C DR = 2.13	T=150°C DR = 2.30	T=160°C DR = 2.44	T=170°C DR = 2.60

Fig. 2. Examples of Mg parts obtained by the WDD process

On the contrary the temperature of the punch was not controlled during tests. A fixed gap of 0.95mm between the blank holder and the die was applied during the WDD tests. A PTFE solution (1%) was used as lubricant. Cylindrical cups shown in figure 2 were obtained at different temperature levels; the highest drawing ratio (DR) reach up to 2.6 at the die temperature 170°C.

3. Numerical analysis for determining the best heating strategy

Large improvements in the sheet formability can be obtained superimposing a thermal gradient in the sheet, by local heating and cooling technique [5]. This permits to keep higher material strength in the sheet close to the punch region and in the cup wall also, and to lower the flow stress in sheet material between blank holder and die. For this reason a specific WDD equipment was designed and created at the DIMeG with the aim of performing WDD tests superimposing a thermal gradient in the blank also using a punch water cooling. The proper heating strategy (heating the Blank Holder or the Die) was performed adopting a Finite Element approach.

3.1. Adopted experimental equipment

As shown in the schematic diagram in Figure 3, the experimental equipment is composed by a Blank Holder and a female Die with an electric heating system embedded in each tool; in addition internal channels for the water cooling inside the 32mm punch were created [8]. Moreover die, punch and blank holder have holes for the thermocouples positioning.

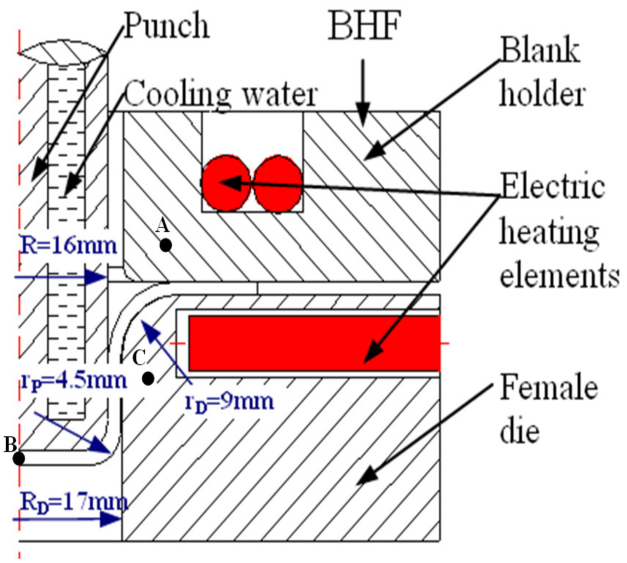


Fig. 3. Schematic diagram of equipment with local heating and cooling system

The electric heating elements inside the blank holder and the female die, allow to perform tests with different approaches (the heating of the blank holder or of the female die only, the heating of both blank holder and female die). The punch cooling system was designed to control the temperature of the punch. Finally a data acquisition system was developed to acquire, during each test, (*i*) the punch load as a function of the punch displacement and (*ii*) the temperature evolution at the centre of the blank (B), in the Blank Holder (point A) and in the Die (point C). In Figure 4 examples of the temperature evolutions in the blank centre and in the Blank Holder during the heating phase are shown. Data concern the test performed on a 80mm diameter blank in one-way rolled [4] AZ31 Magnesium alloy (thickness: 0.7mm) at a punch speed of 15mm/min and adopting a Teflon based lubricant.

Such test was carried on tuning the power of the Blank Holder electrical heating system and the temperature in the centre of the blank respectively to 1000W and 210°C;

In addition the cooled punch was kept far from the blank during the whole heating phase. The initial temperature of both the Draw Die and the Blank Holder was 30°C. In Figure 5 also experimental data acquired during the Deep Drawing phase are shown for the such a test.

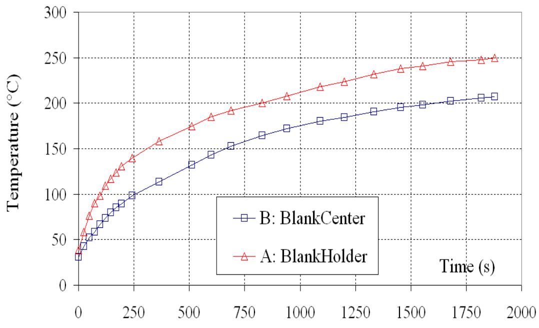


Fig. 4. Temperature evolution in the heating phase

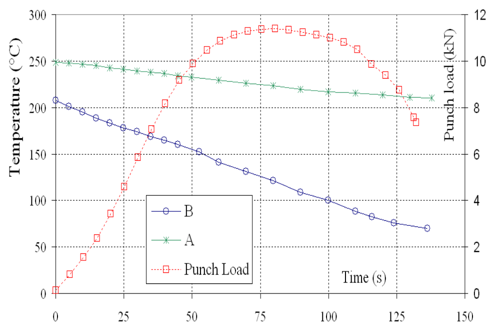


Fig. 5. Temperature evolution and punch loads in the DD phase

3.2. Setting and calibration of the FE of the WDD process

The DD process of cylindrical cups was simulated using ABAQUS\Standard FE code. The reason why the attention was focused on the DD of circular blanks is its high symmetry (the model is low time consuming).

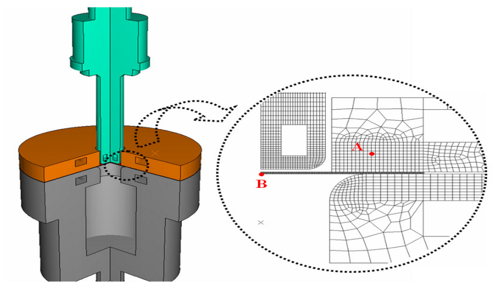


Fig. 6. FE 2D fully coupled thermo-mechanical model

Nevertheless the main feature of the WDD process (i.e. the strict relationship between local temperature value and material properties) could be taken into account. The 2D (axially symmetric) fully coupled thermo-mechanical FE model was created using data from both the experimental activity [4, 12] and from literature [7, 8, 11]. Tools were modelled as bodies with thermal and elastic mechanical properties; in addition rigid body constraints were adopted (the displacement of all nodes of tools was defined by the displacement of a correspondent Reference Node). The axially symmetric quadrilateral element typology chosen for the mesh of the whole model (the blank and the tools) was characterised by both temperature and displacement degrees of freedom. The blank (0.7mm thick) was meshed using 4 elements along the thickness. In figure 6 the whole 2D FE thermo-mechanical model together with the detail of the adopted mesh are shown. Symbols A and B highlight where the temperatures were monitored during the simulation for the comparison with the experimental ones.

An isotropic yielding condition (von Mises) was used in the model. In addition mechanical properties according to the temperature and strain rate level were considered for modelling the Mg alloy plastic behaviour; in particular data coming from the experimental activity (tensile tests) were adopted in the model instead of specific the flow stress formula keeping into account the strain and strain rate effect on the flow stress [13].

The simulation was performed setting the proper heat flux value in the Blank Holder cavity; when the punch cooling was assumed, the convection by the water cooling was simulated setting the proper coefficient in the punch cavity (where cooling water flows with a temperature equal to 20°C); a convective heat flux with the ambient was modelled for tools and sheet surfaces. The Blank Holder Force was modelled using a spring element connected to the reference node of the tool; the compression of this element allows to simulate the experimental value of the Blank Holder Force (2.5kN in the deep drawing of the 80mm diameter blank).

The Coulomb friction model was used to define the tangential behaviour at contact surfaces. Both the friction coefficient and the thermal convection parameters between tools and the specimen were modelled using an inverse analysis.

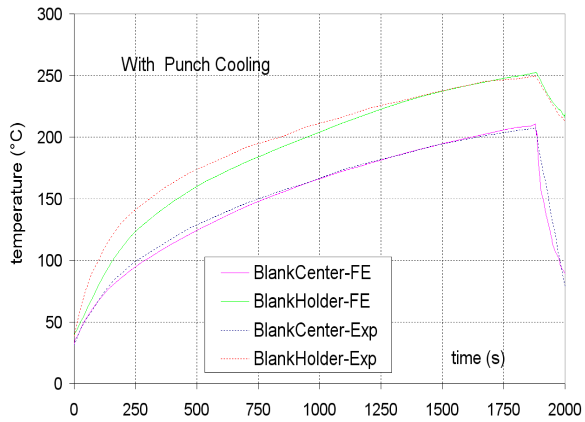


Fig. 7. Thermal cycles in the points A and B; set up with the punch cooling

In particular the FE model was calibrated using experimental data coming from preliminary WDD tests performed using the equipment previously described. Both temperature evolutions (in the blank centre and in the Blank Holder) and punch load values concerning a test carried on with the water cooling effect in the punch and keeping the punch far from the blank during the heating phase (figures 4 and 5) were used as reference; experimental temperature data were acquired both in the heating phase and in deep drawing one. Such test and thus all numerical simulations were realised on a 80mm blank (DR=2.5);

In figure 7 the comparison between experimental and numerical result furnished by the tuned FE model are presented in terms of temperature values during the WDD test. A generally good agreement can be recognised, especially as final temperature values of the heating and drawing phases. Light differences in the transient period at the very beginning of the heating phase can be noted in the temperature evolution. The above mentioned differences did not influence the numerical analysis aimed to evaluate the best heating strategy.

3.3. Numerical evaluation of the best heating strategy

Numerical simulations allowed analyzing the temperature evolution in the sheet when adopting different heating strategies; in particular FE analysis was focused on the heating of the specimen through the heater into the Blank Holder or the one into the Die.

The first group of simulations was aimed to investigate the effect of both cooling the Punch and heating the Blank Holder in order to obtain a temperature at the blank centre roughly equal to 200°C. In figure 8 results concerning such heating strategy are reported in terms of temperatures along the blank section (as a function of the undeformed radial position of blank nodes) at increasing values of the punch stroke. It can be easily noted that the temperature difference in the blank section gradually increase during the process; in fact, while the cooled punch is coming down, it draws the blank and, as a consequence, the portion of the specimen surface in contact with the punch increases, while the portion of the surface in contact with the heated Blank Holder decreases.

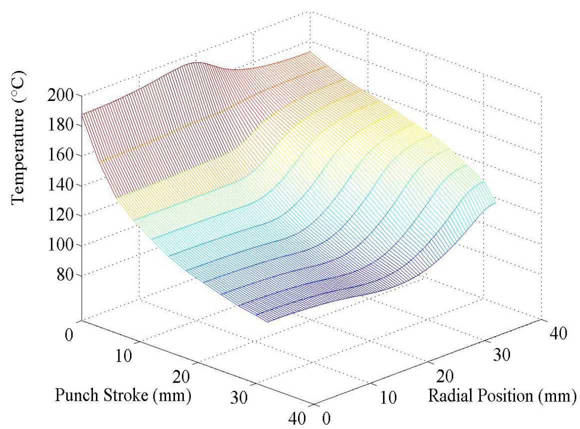


Fig. 8. Temperatures in the blank section during the DD phase

It could be also noted that the minimum value of the temperature is not reached at the blank centre, but beside it (the lowest temperatures in the graph are concerning the punch radius region). Such a numerical result can be explained with the inflection of the material in the central part during the DD phase, which determines lower contact pressure and consequently lower thermal flux.

Major and Minor strain pairs have been plotted in Figure 9 together with different FLDs from [11] (since different temperature levels are in the blank section). Even if the strain limit is affected by the yield locus [14] and it could be probably also changed according to the activation of new independent slip systems caused by temperature increase [1, 15], a qualitative safe condition can be obtained from the comparison of Major and Minor strain pairs with FLDs.

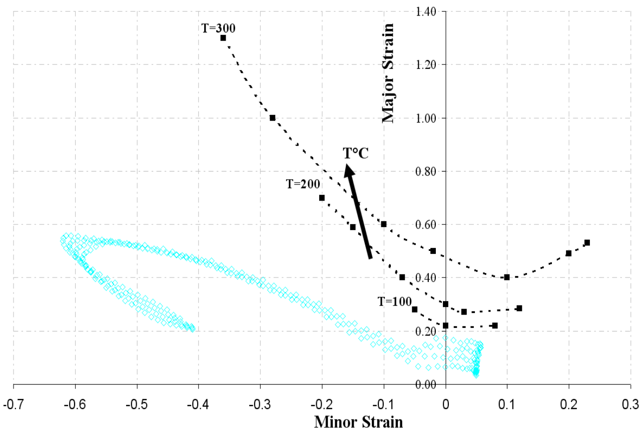


Fig. 9. Major and Minor strain pairs when cooling the Punch and heating the Blank Holder in order to have 200°C at the blank centre (FLDs from [2])

Additional simulations were performed varying the punch cooling efficiency (i.e. simulating the absence of the cooling water or the presence of a forced convection condition for improving the heat fluxes in the channels inside the Punch).

In Figure 10 the Major and Minor strain pairs concerning the simulation adopting no water cooling are plotted at increasing values of the punch stroke, highlighting the occurrence of a critical condition (also the highest FLD overcome) just in the region of the punch corner radius. It should be noted that in such simulation the initial temperature of the punch was set at 160°C, being the aim to simulate the effect of the absence of the water cooling coupled with the realization of consecutive tests (industrial application of the process).

On the contrary results from simulation performed setting an improved convection efficiency in the punch water channels are shown in Figure 11 in terms of temperature values along the blank profile at the end of the WDD process. If compared to the case when no cooling is provided and the steady state temperature is 160°C, advantages obtained in terms of temperature reduction in the central part (and thus in terms of thermal gradient in the material) are obvious.

However, from the comparison with the real cooling efficiency, it is possible to note that the contribute of the punch cooling in terms of temperature reduction cannot be considerably improved because of the small contact surface.

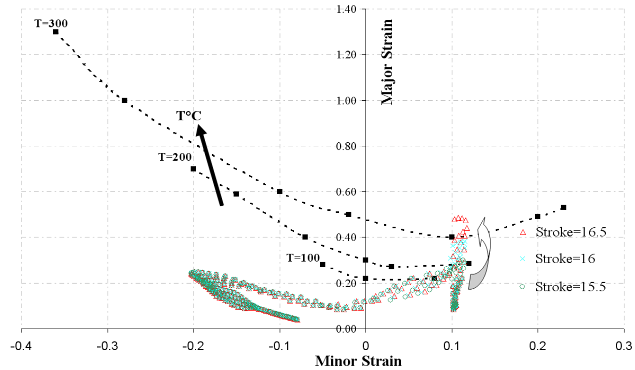


Fig. 10. Major and Minor strain pairs when considering increasing values of the punch stroke

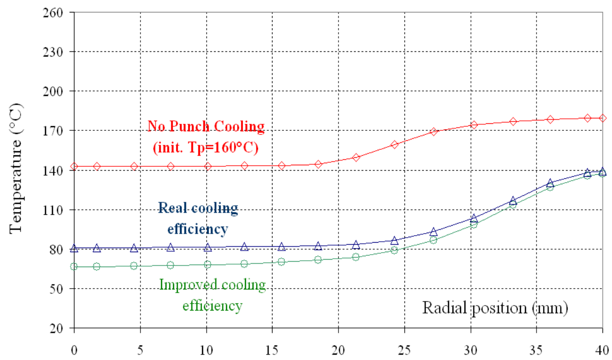


Fig. 11. Temperatures in the blank at the end of the WDD when simulating different punch cooling capabilities

The second group of simulations was aimed to investigate the effect of heating the Die up to different target temperature, always using a cooled punch. The simulation was performed choosing a heating time that allowed in the blank a temperature close to 160°C; numerical results show the failure at the beginning of the deep drawing similarly to the case evidenced in figure 11. This can be justified analyzing the temperature gradient in the blank as a function of the punch stroke, from the beginning of the deep drawing until the cup failure (Figure 12).

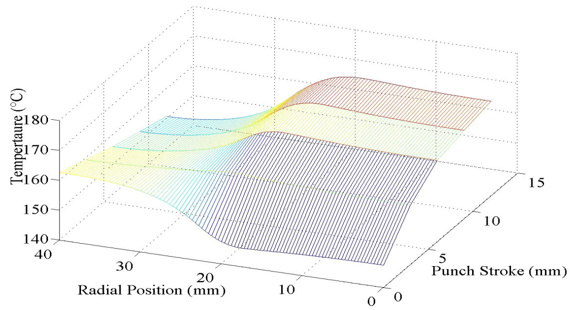


Fig. 12. Temperatures in the blank section during the DD phase when the heating system is the Die one

At the very beginning of the DD phase, a temperature reduction in the blank centre can be recognised, due to the contact with the bottom punch surface. However, as the punch continues its stroke downward, an increase of the temperature in the blank is highlighted, since the contact area between the heated die and the blank progressively increases. The graph in Figure 12 has been drawn up to blank rupture occurrence.

As a consequence, it can be stated that when the WDD process is performed adopting the heating system placed in the die and without the punch cooling, the initial temperature of the blank need to be reduced with respect to the process performed with the heating system in the blank holder.

4. Warm Deep Drawing tests adopting different heating techniques

As a consequence of the numerical results, WDD tests were performed at DIMeG adopting the electric heater embedded into the Blank Holder. The commercial and one-way rolled AZ31 Mg alloy sheet (thickness: 0.7mm) was used to draw cylindrical cups with a diameter equal to 80mm. WDD tests were carried out at a temperature level of about 250°C in the flange region of the specimen and using a constant punch speed (15mm/min); in addition an initial Blank Holder Pressure equal to 0.75MPa and Teflon based lubricant were used.

The aim of the experimental activity carried on in Bari was to investigate the effect of: (*i*) different ways of performing the heating phase; (*ii*) different temperature levels on both the flange and the centre of the specimen.

Three heating techniques in the WDD tests were tried:

- using the punch cooling system and keeping the punch far from the blank during the heating phase (labelled in the following with *CP*);
- not using the punch cooling system and keeping the punch far from the blank during the heating phase(labelled in the following with *P*);
- using the punch cooling system and keeping the punch in contact with the blank during the whole heating phase (labelled in the following with *CPC*).

In figure 13 the comparison between the temperature values acquired both in the blank centre and in the Blank Holder and concerning the different explored heating techniques is presented.

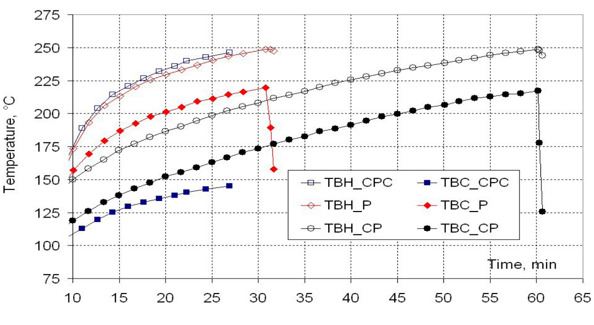
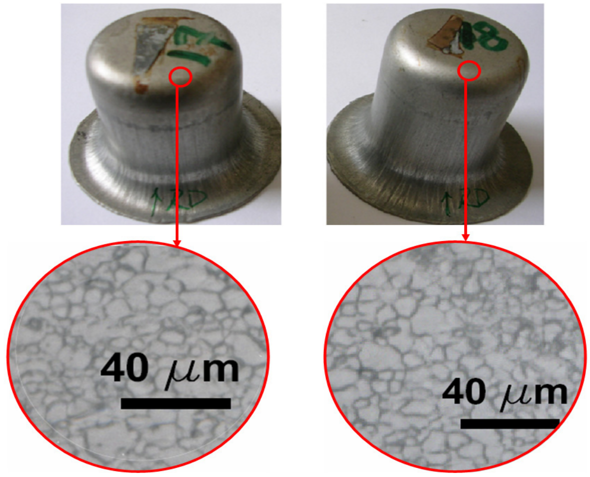


Fig. 13. Temperature evolutions when adopting different heating techniques

It can be noted that the temperature gradient in the blank just at the beginning of the Deep Drawing phase is almost the same if keeping the punch always in contact with the blank or moving it in contact some seconds before the Deep Drawing phase starts (compare curves labelled with *CPC* and *CP*).

During the whole heating phase the blank centre experiences a temperature level higher in the case the punch is not kept in contact. However the analysis of the microstructure in different locations of the specimens obtained with both the heating techniques, did not evidenced any difference, as shown in Figure 14, since usually the size of grains is strain dependent [16]



CP (Cooled Punch) CPC (Cooled Punch in Contact)

Fig. 14. Comparison of the microstructures of samples from specimens obtained with the *CP* and the *CPC* technique

During the Deep Drawing phase no difference is any longer present in the temperature at blank centre when comparing the *CPC* and *CP* heating technique, as shown by Figure 15; of course when the punch was not cooled by water (label *P*), the temperature at the blank centre was constantly higher than the other heating techniques. The heating during the Deep Drawing phase was aimed to establish different temperature values in the Blank Holder; in particular the power supply was allowed when performing the WDD process adopting the *CPC* heating technique (the temperature is almost constant during the whole Deep Drawing phase), while the heater was switched off when adopting both the *CP* and the *P* heating technique.

If considering simultaneously the temperature evolutions in Figure 15 together with the Punch Load curves in figure 16, additional considerations and useful comparisons can be made.

If the temperature at the blank centre and in the Blank Holder concerning WDD tests performed adopting the *P* and the *CP* techniques are compared, it maybe noted that in both the regions the temperature is higher for the case *P* (because of the absence of the water cooling). It is thus not so much easy to clearly understand if the corresponding lower Punch Load for the case *P* is due to the effect of the higher temperature in the Blank Holder or at the Blank Centre.

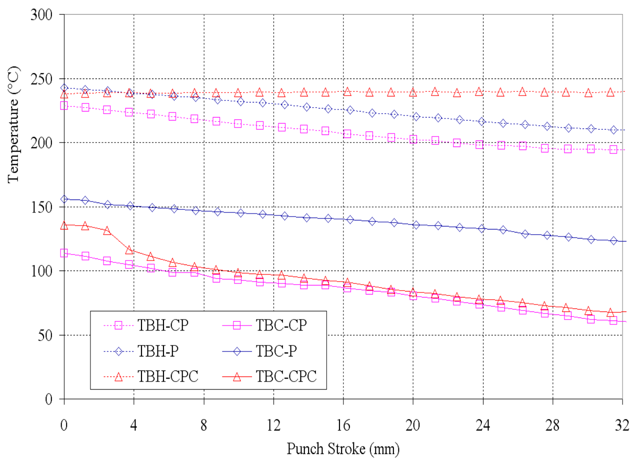


Fig. 15. Temperature evolutions during the Deep Drawing phase when adopting the three heating techniques

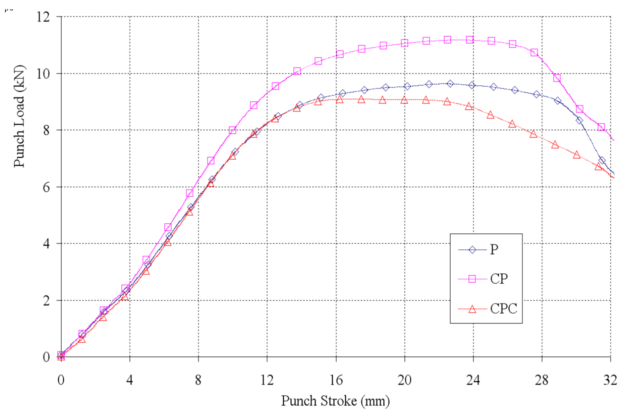


Fig. 16. Punch Load versus Punch Stroke when adopting the three heating techniques

However if the attention is moved to WDD tests performed adopting the *CPC* and the *CP* techniques, it maybe noted that now the temperature at the Blank Centre is almost the same in the two cases, while differences are limited to the Blank Holder region. Thus the corresponding higher Punch Load for the case *CP* can be justified with the lower temperature in the flange region of the blank.

Finally the comparison between the *P* and the *CPC* technique evidences small differences in terms of both final temperatures at the very beginning of the Deep Drawing phase and in terms of Punch Load values. However, as previously highlighted, industrial applications of such a technique and high number of stampings can increase the temperature very fast in the equipment without the punch cooling by water flow.

Further experimental tests were thus performed with the adoption of a continuous heating of the Blank Holder and cooling of the Punch also during the Deep Drawing phase (*CPC* heating technique), confirming the possibility of much improving the process feasibility. In fact sound cups from an initial diameter equal to 100mm (DR=3.1) were obtained as shown in Figure 17.

Fig. 17. Cups from a 100mm blank (DR=3.1) when using the *CPC* heating technique (left) and the *P* one (right)

On the contrary when no punch cooling was used while heating the blank holder all the process long, ruptures occurred in the cup wall, due to the absence of the proper thermal gradient in the specimen and in particular due to the lack of material strength in the wall region since too high temperatures were reached.

5. Conclusions

The Mg alloy formability improvement is actually under investigation both at the Institute of Metal Research (China) and the Politecnico of Bari (Italy). The final aim of the joint research activity is to define the optimal WDD process conditions which allow the production of parts for the electronic industry.

An initial experimental campaign was undertaken at the IMR, adopting a in-home designed and realised equipment which simply allowed the heating of the Draw Die. WDD tests performed using a common circular section Die highlighted that an improvement of the Limit Drawing Ratio from 1.8 up to 2.6 is feasible when adopting a Draw Die temperature equal to 170°C.

The experimental analysis was also carried on at the DIMeG (Politecnico of Bari); in particular a specific equipment was designed to perform WDD tests superimposing different thermal gradient by (*i*) heating the blank holder and/or the female die; (*ii*) cooling the punch using a water flow. The FE approach allowed reducing the experimental tests to be performed. In particular 2D fully coupled thermo-mechanical model of the WDD process was created and tuned using preliminary experimental data as a reference; it was used to investigate the best heating strategy, i.e. for choosing if using the electric heating system placed into the Die or the one into the Blank Holder. Numerical simulations revealed the strategy characterised by the Blank Holder heating to be more critical for the drawing of the 80mm diameter blank (DR=2.5), obtained from sheets one-way rolled. However the validation of such numerical results will be necessary in the following experimental campaign.

As a consequence of the numerical results, the experimental activity carried on in Bari was performed using the electric heater system placed into the Blank Holder to investigate the effect of: (*i*) different ways of performing the heating phase; (*ii*) different temperature levels on both the flange and the centre of the specimen.

The three heating techniques which were investigated (punch cooled and kept far from the blank during the heating phase, *CP*; punch not cooled and kept far from the blank during the heating phase, *P*; punch cooled and kept in contact with the blank during the whole heating phase, *CPC*) revealed that no variation in the microstructure occurred in the specimen if the temperature is kept lower during all the process (the *CPC* heating technique instead of the *CP* one).

In addition a stronger influence of the temperature of the material in the flange region was highlighted on the Punch Load; in particular when comparing the maximum DD force concerning the *CP* and the *CPC* heating conditions, considering the very similar temperature levels in the blank centre region, a large difference was recognised, which could be due to temperature difference realised in the Blank Holder.

Experimental tests were performed with the adoption of a continuous heating of the Blank Holder and cooling of the Punch also during the Deep Drawing phase (*CPC* heating technique), allowed to obtain sound cups from an initial diameter equal to 100mm (DR=3.1). Next investigations will be aimed to explore the operating window for the WDD and the maximum improvement which can be obtained adopting the WDD process.

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