

# Advanced forming techniques for Magnesium alloys

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**A** new approach (Cold Hydrostatic Forging) towards an improvement of the forming behaviour of magnesium alloys has been investigated with the alloys AZ91 (Mg-Al-Zn) and ZK30 (Mg-Zn-Zr).

The idea of the project was to use a surrounding ductile shell in order to provide a hydrostatic compressive stress state within the magnesium alloy samples during Cold Forging.

The steel Ck15 has been used as surrounding material during upsetting tests and the aluminum alloy

AA6082 for the forward extrusion experiments. High logarithmic strains up to  $\phi = 1.2$  (forward extrusion) could be obtained without the appearance of any cracks for the ZK30 alloy and just of some small ones for the AZ91 alloy and of course none in the surrounding shell. Mechanical tests showed a significant increase of the yield strength, ultimate tensile strength and hardness. At the same time, a notable reduction of elongation to failure occurred.

Parole chiave: metalli non ferrosi, estrusione, forgiatura

## INTRODUCTION

Magnesium is the lightest of all structural metals ( $\rho \approx 1.74 \text{ g/cm}^3$ ) and has a large availability all over the world. The alloys based on this metal offer a combination of lightweight, good mechanical properties, high fatigue strength and high damping. The association of these properties make magnesium alloys attractive for a large number of present and future high tech as well as ordinary applications [1, 2].

Industrial production of components made of these alloys is usually performed by casting or forming at temperatures above 250°C. The use of standard cold forming processes in order to produce required shapes made of magnesium alloys would be an enormous asset (near-net shape, increase of the mechanical properties). However, these alloys show a brittle forming behaviour during cold compressive deformation, because of their hexagonal close packed crystal structure. Cold forging of Mg-alloys was investigated in the past years [3, 4, 5]. Figure 1 shows the flow curves of a AZ31 magnesium alloy at different testing temperatures, during conventional upsetting tests [4]. It can be noticed that at room temperature the logarithmic strain at failure has a value lower than  $\phi = 0.2$ . The most promising results were obtained by using a counter punch for applying the hydrostatic compressive state within the magnesium alloy during the forming process [3].

In the study presented in this paper, a new Cold Hydrostatic Forging process was investigated. The use of a surrounding shell material in order to bring the hydrostatic compressive stress state within the magnesium specimens during deformation has been studied for the upsetting experiments (surrounding shell made of Ck15 steel) as well as for the forward extrusion ones (surrounding shell made of wrought aluminum alloy AA6082), Figure 2. These kind of mountings should lead to a high deformation of the magnesium alloy without cracking.

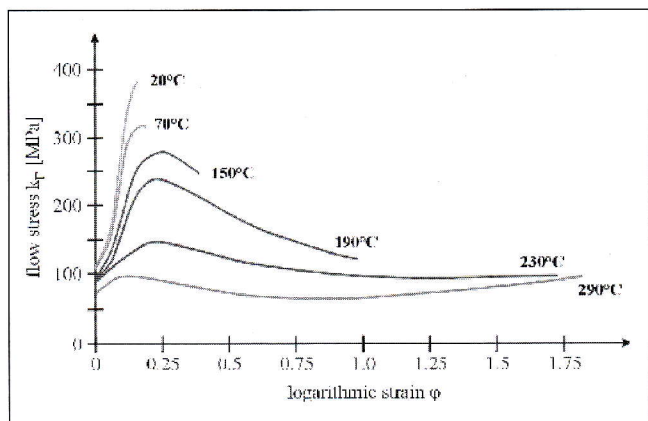


Fig. 1. Flow curves of the Mg-alloy AZ-31, recorded by upsetting test at different temperatures, deformation rate  $0.8 \text{ s}^{-1}$  [4].

Fig. 1. Curve di flusso della lega di Mg AZ-31, registrate dalle prove di ricalcatura a temperature diverse, velocità di deformazione  $0.8 \text{ s}^{-1}$  [4].

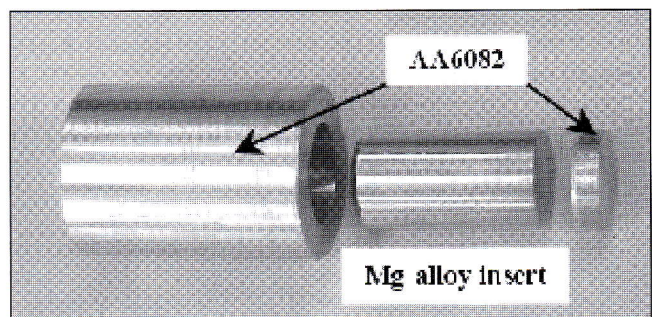


Fig. 2. Specimen for forward extrusion experiments with Mg-alloy insert before mounting.

Fig. 2. Campioni per le prove di estrusione diretta con inserti in lega di magnesio prima del montaggio.

## EXPERIMENTAL PROCEDURE

### Materials

Two kinds of magnesium alloys have been tested: the first one was ZK30 and the second one AZ91. As ductile surrounding shell, Ck15 steel was used for the upsetting tests

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	Mg	Al	Zn	element [wt. %]		Si	Fe	C	mechanical properties [MPa]	
				Zr	Mn				Rp <sub>0.2</sub>	R <sub>m</sub>
ZK30	bal.	0.01	3.0	0.65	< 0.01	< 0.01	< 0.01	-	255	305
AZ91	bal.	8.5	0.6	-	0.3	0.01	< 0.01	-	100	115
AA6082	0.95	bal.	0.10	-	0.75	1.0	0.22	-	380	400
Ck 15	-	-	-	-	0.42	0.17	bal.	0.15	335	425

Tab. 1. Chemical composition and mechanical properties of Mg-alloy inserts and aluminum shell.

Tab. 1. Composizione chimica e proprietà meccaniche degli inserti di lega di Mg e degli involucri di alluminio

and AA6082 aluminum alloy for the forward extrusion experiments. The chemical analysis, as well as the mechanical properties of these materials, are shown in table 1.

The AZ91 material showed in the as-received state a small, diffused porosity and poor mechanical properties; tensile tests showed also a very small (<1.0 %) elongation to failure. However, the high brittleness of this material was ideal to test the Cold Hydrostatic Forming method.

### Cold upsetting experiments

Cold upsetting experiments were performed at room temperature on an hydraulic press, using cylindrical specimens (Ø13.0 x 12.0 mm). In the first part of the experiments, conventional upsetting was performed. In order to induce a high hydrostatic compressive state within the brittle magnesium specimens and therefore to improve its formability, a double pre-stressed conical ring assembly has been used, Figure 3.

During conventional upsetting experiments, crack occurred for both magnesium alloys after a compressive deformation of less than 1.5%, as shown in Figure 4. It shows that nearly no plastic deformation can be realized by this conventional method and thus no conventional forming of magnesium alloys possible.

By using the new pre-stressed assembly composed by the two conical rings surrounding the magnesium cylinder, the formability of the magnesium alloys drastically increased, Figure 5. The mean logarithmic strain value reached values of  $\phi = 0.7$  for both Mg-alloys and just some small cracks were detected. The obtained hydrostatic pressure was calculated by finite element method and reached values up to 300 MPa and showed a regular distribution within the magnesium alloy specimen during the forming process, Figure 6 (a). Figure 6 (b) presents the calculated final form of the magnesium alloy cylinder and the steel rings at the end of the upsetting experiment.

### Forward extrusion

Forward co-extrusion experiments were carried out on a 250 ton hydraulic press with a punch velocity of 55 mm/s. This process concept is schematically represented in Figure 7. The magnesium alloy cylinder (Ø 18.0, 34.0) was positioned in the center of the wrought aluminum shell (external dimension Ø 32.0, 45.0). A standard lubrication system for Al-alloys was applied on the external surface of the AA6082 ductile shell, to reduce friction forces during the forming process. For the ma-

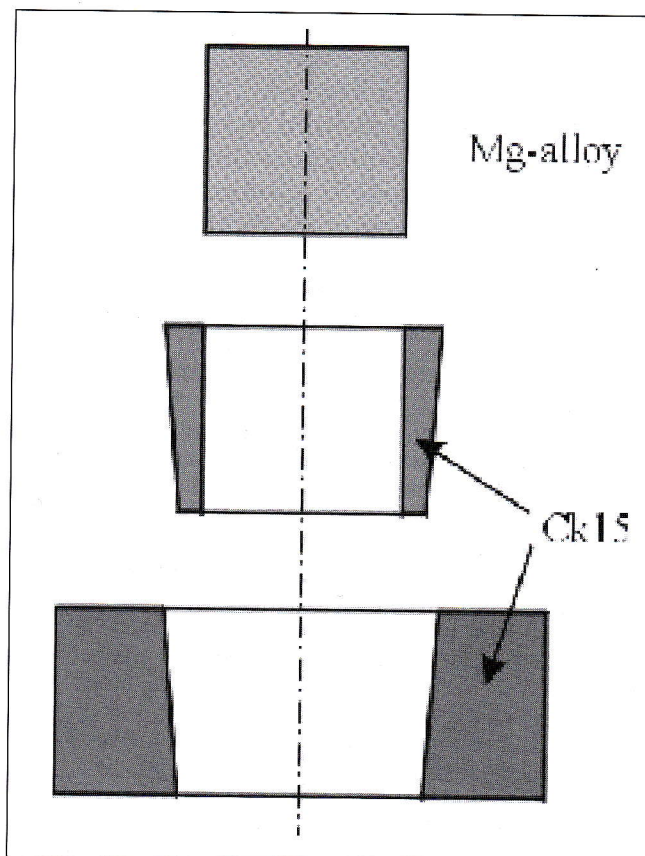


Fig. 3. Experimental set-up for upsetting with double steel ring, with pre-stressing.

Fig. 3. Attrezzatura sperimentale per ricalcatura con doppio anello di acciaio, pretensionato.

gnesium alloy insert, no surface treatment was applied. With the described workpiece and die geometry, the mean logarithmic strain after deformation had a value  $\phi = 1.2$ . Figure 8 shows the force-punch displacement diagrams for the forward co-extrusion at room temperature of ZK30 and AZ91 with the surrounding aluminum shell, in comparison with the aluminum material alone. The specimens containing the magnesium alloys show quite identical extrusion force curves, which are about 10% lower than the one of the

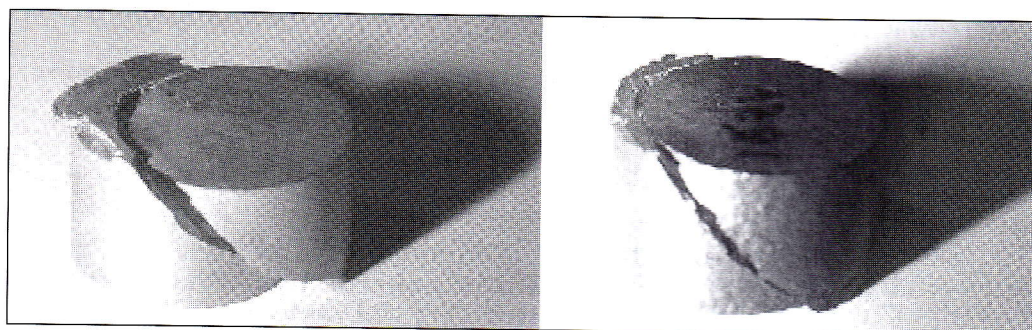


Fig. 4. ZK30 (left) and AZ91 specimens after conventional cold upsetting

Fig. 4. Campioni di leghe ZK30 (sinistra) e AZ91 dopo ricalcatura a freddo di tipo convenzionale.

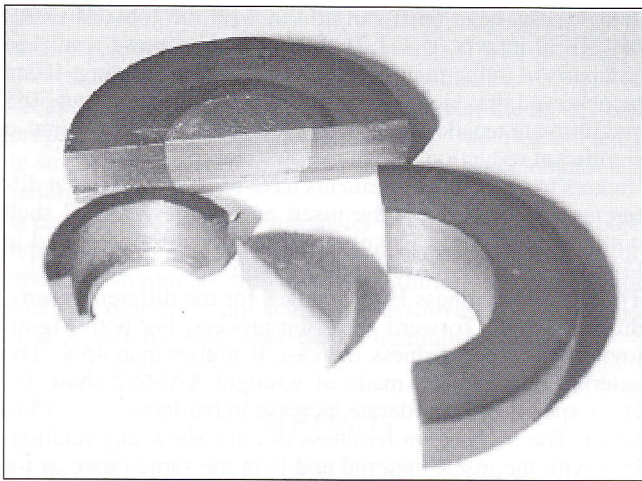


Fig. 5. Magnesium alloy AZ91 after upsetting test with the double conical ring assembly

Fig. 5. Leghe di magnesio AZ91 dopo prove di ricalcatura con il gruppo ad anello conico doppio

aluminum alloy. In the case of the magnesium alloys - aluminum shell assemblies, the maximum value of the applied force on the top of the composite specimen is about 530 kN and the flow force is about 450 kN, which correspond to an extrusion pressure of 560 MPa.

The forward extruded specimens containing the magnesium alloy inserts were cut in the longitudinal direction in order to observe the material deformation and if any cracks were present, Figure 9. No cracks were detected within the ZK30 alloy and some small ones in the central forward region, for the AZ91 alloy.

Between the magnesium alloy inserts and the aluminum alloy surrounding shell, no cold welding has occurred. As shown in Figure 10, it was possible to separate the inserts from the surrounding shell without any effort. This is due to the fact, that no or only low relative motion between insert

and shell took place during the forming process. The surfaces of the Mg-materials and of the Al-shell that were in contact show a good surface quality, with small roughness. The easy separation enhances the advantages of the Cold Hydrostatic Forging process and shows that no separating coating need to be used.

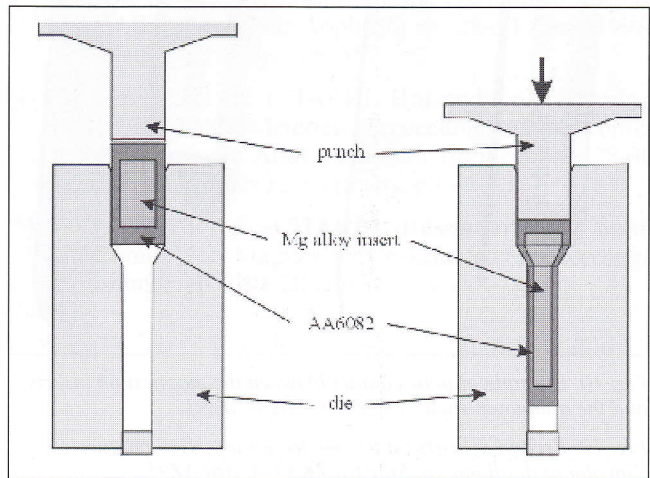


Fig. 7. Process concept for forward extrusion of magnesium alloys, prior (left) and during (right).

Fig. 7. Schematizzazione del processo di estrusione diretta di leghe di magnesio, prima (sinistra) e durante (destra).

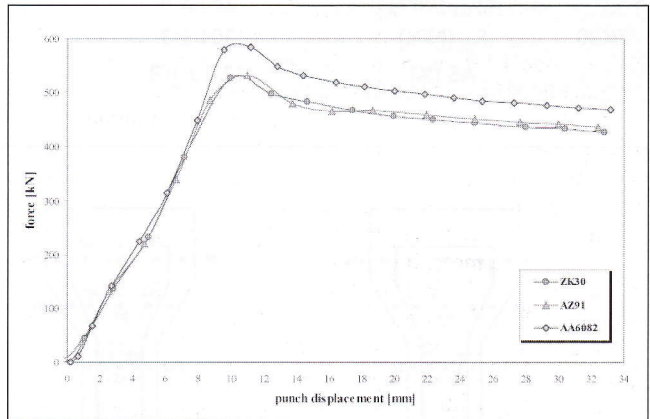


Fig. 8. Force-punch displacement diagram of the forward co-extrusion at room temperature.

Fig. 8. Diagramma forza-corsa del pistone per l'estrusione diretta a temperatura ambiente.

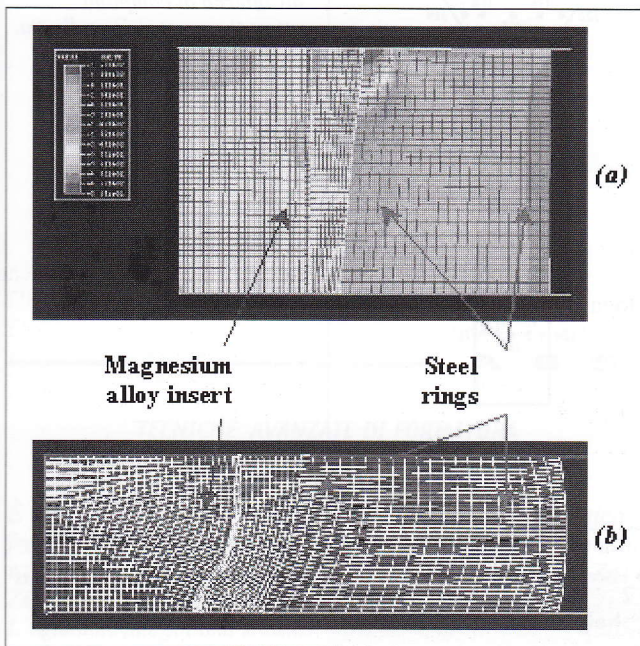


Fig. 6. FEM result representing the inner hydrostatic pressure in the Mg-alloy cylinder during forming (a) and the end-geometry of the insert and the rings after deformation (b).

Fig. 6. Risultati FEM che rappresentano la pressione idrostatica interna nel cilindro di lega Mg durante la formatura (a) e geometria finale dell'inserto e degli anelli dopo deformazione (b).

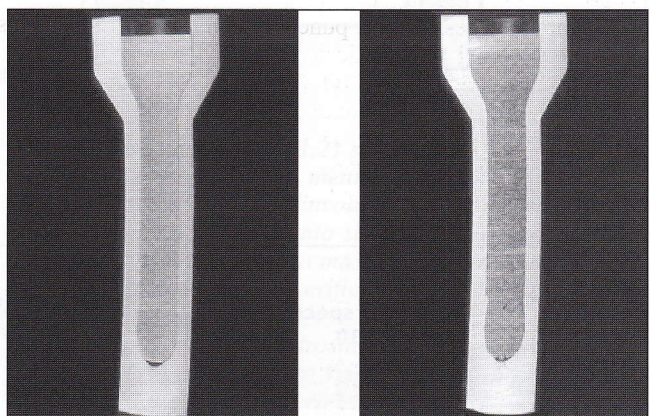


Fig. 9. ZK30 (left) and AZ91 deformed specimens cut in the longitudinal direction

Fig. 9. Campioni deformati di ZK30 (sinistra) e AZ91 (destra) sezionati in direzione longitudinale.

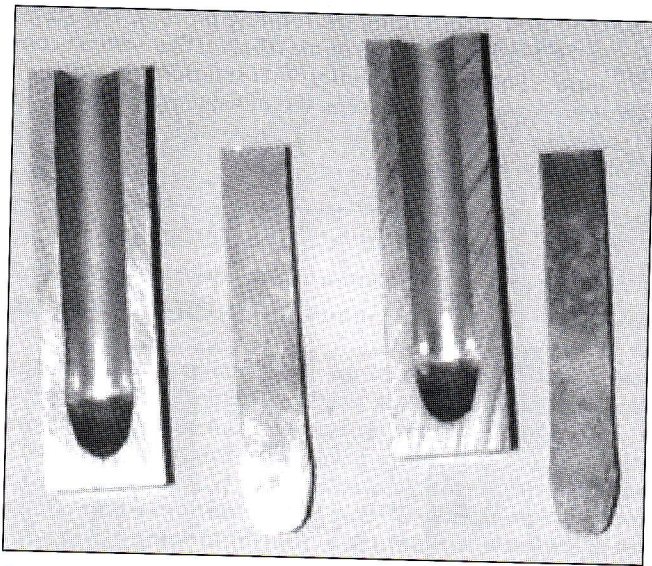


Fig. 10. Example of poor contact between the magnesium inserts and the aluminum shell. left: ZK30, right: AZ91

Fig. 10. Esempi di scarsa adesione fra gli inserti di magnesio e l'involucro di alluminio. Sinistra ZK30, destra AZ91

Tensile tests have been carried out with the forward extruded ZK30 inserts ( $\phi = 1.2$ ). Table 2 shows these results in comparison to the material properties before forming. It can be observed that yield strength was increased for about 50% and ultimate tensile strength about 35%. At the same time, a significant reduction of elongation to failure occurred.

Vickers hardness measurements have been carried out at different positions within the insert and in the AA6082 shell with a load of 5 kg. The obtained results are represented in Figure 11 and the mean values in Table 3.

The Vickers hardness HV5 changes for the different inserts, during the cold forward extrusion process. For both Mg-alloys inserts, the hardness increase is higher than 45%. The external ductile shell made of wrought AA6082 show, for every specimen, a moderate increase in hardness (5 to 10%). The increase in hardness doesn't show any relationship with the insert material and is in the same range as for the unreinforced AA6082 (+ 8%).

CONCLUSION

The Cold Hydrostatic Forging process presented in this paper has shown very promising results. It was possible to im-

insert	parameter	before Cold Forging	after Cold Forging	variation [%]
ZK30	Rp <sub>0.2</sub> [MPa]	255 ± 4	385 ± 3	+ 51
	R <sub>m</sub> [MPa]	304 ± 3	414 ± 1	+ 36
	A5 [%]	17.0 ± 0.8	8.2 ± 1.0	- 52

Tab. 2. Comparison of the mechanical properties of the ZK30-insert prior and after cold forward extrusion.

Tab. 2. Confronto fra le proprietà meccaniche degli inserti ZK30 prima e dopo estrusione diretta a freddo.

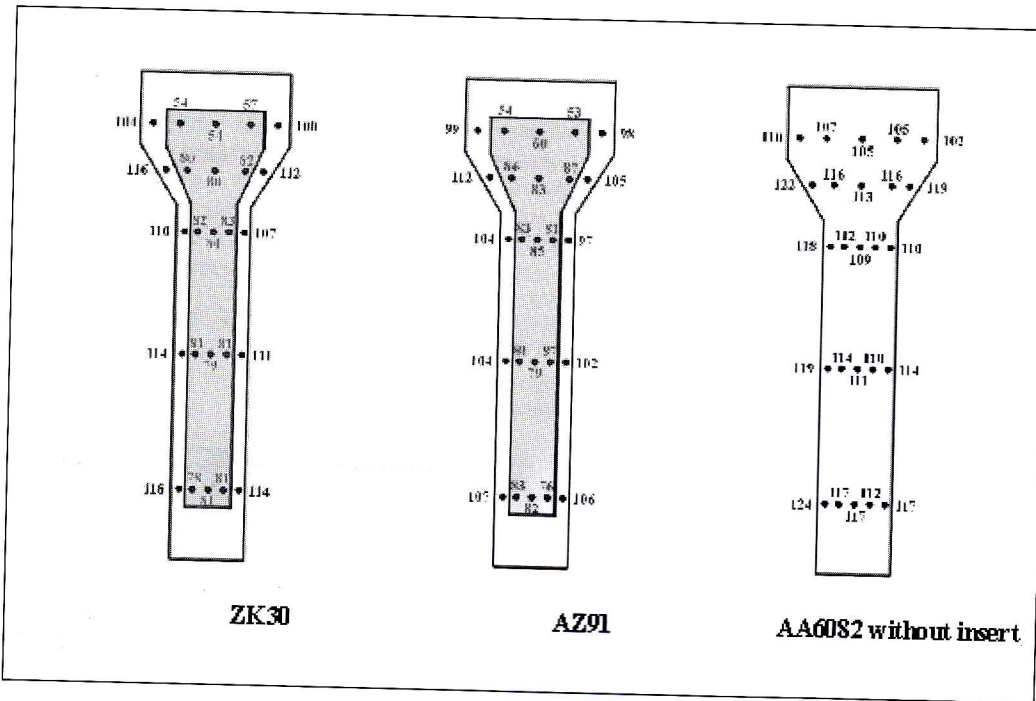


Fig. 11. Vickers hardness HV5 distribution within the forward extruded specimens.

Fig. 11. Distribuzione della durezza Vickers HV5 all'interno di campioni ottenuti per estrusione diretta.

	specimen 1		specimen 2		specimen 3
	ZK30	shell	AZ91	shell	AA6082
undeformed	55 ± 2	102 ± 3	56 ± 4	99 ± 1	106 ± 3
deformed	81 ± 2	112 ± 4	82 ± 3	103 ± 4	114 ± 4
variation due to Cold Forging	+ 47%	+ 10%	+ 47%	+ 5%	+ 8%
cracks	no	no	yes	no	no

Tab. 3. Mean Vickers hardness values HV5 for the different inserts and the surrounding AA6082 shell, prior and after Cold Forging

Tab. 3. Valori medi Vickers HV5 per i diversi inserti e per gli involucri AA6082, prima e dopo forgiatura a freddo.

prove drasticamente la formabilità delle leghe di magnesio e a raggiungere alte deformazioni ( $\phi = 1.2$ ) senza (ZK30) o con ridotta (AZ91) formazione di cricche.

Un altro aspetto importante, un cambiamento delle proprietà meccaniche è stato ottenuto: lo stress di snervamento e lo stress di rottura sono stati significativamente migliorati e l'allungamento a rottura è diminuito.

Si può prevedere che un trasferimento di questo approccio ad altri tipi di materiali fragili porterà ad un analogo miglioramento del comportamento in formatura; prove su compositi a matrice metallica a base di alluminio sono attualmente in fase di sperimentazione. Altri studi saranno effettuati anche sulle leghe di titanio.

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A B S T R A C T

TECNICHE AVANZATE DI FORMATURA PER LEGHE DI MAGNESIO

È stato studiato un nuovo metodo (forgiatura idrostatica a freddo) per il miglioramento del comportamento in formatura delle leghe di magnesio con le leghe AZ91 (Mg-Al-Zn) e ZK30 (Mg-Zn-Zr).

L'idea del progetto è stata di utilizzare un involucro duttile per portare una condizione idrostatica di sollecitazione di compressione all'interno dei campioni di lega di magnesio durante la forgiatura a freddo. Come materiale per l'involucro sono stati impiegati acciaio Ck15 durante le prove di ricalcatura e la lega di alluminio AA6082 per gli esperimenti di estrusione diretta. È stato possibile migliorare drasticamente la formabilità delle leghe di magnesio e realizzare

deformazioni elevate ( $\phi = 1,2$ ) senza (ZK30) o con ridotto sviluppo (AZ91) di cricche, mentre naturalmente non ne sono state riscontrate negli involucri. Le prove meccaniche hanno dimostrato un aumento significativo della resistenza allo snervamento, resistenza massima alla trazione e durezza. Allo stesso tempo si è verificata una notevole riduzione dell'allungamento a rottura.

Il processo di forgiatura idrostatica a freddo presentato in questa memoria ha indicato risultati molto promettenti. Si può prevedere che un trasferimento di questo metodo ad altri tipi di materiali fragili potrà portare ad un analogo miglioramento del comportamento in formatura; prove su compositi a matrice metallica a base di alluminio sono attualmente in fase di sperimentazione. Altri studi saranno effettuati anche sulle leghe di titanio.