Advanced forming techniques for aluminum–based metal matrix composites

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ABSTRACT: Two new approaches (Cold Forging and Thixoforging) towards an improvement of the forming behaviour of metal matrix composites (MMC) have been investigated. Cold Forming was performed with two aluminum based MMCs (AA6082 with Al_2O_3 short fibers and AA6061 with Al_2O_3 particles). The MMC samples were inserted in a ductile shell (aluminum alloy AA6082) to provide a hydrostatic compressive stress state during forward and backward extrusion. In a second investigation, aluminum alloy AA6061 reinforced with Al_2O_3 particles was backward extruded under semi-solid conditions (Thixoforging). High deformation rates were obtained with crack free MMC samples by the cold forming process and gradient distribution of the ceramic reinforcement was observed in dependence of the parameters of the semi-solid process.

Key words: metal matrix composite, hydrostatic compressive state, Cold Forging, Thixoforging

1 INTRODUCTION

Metal matrix composites (MMC) consist of a ductile matrix usually reinforced by ceramic particles or fibers. Compared to unreinforced alloys, MMC offer a combination of different, superior properties for various applications, as they have higher stiffness, strength, elastic modulus, improved wear resistance, and better fatigue resistance [1]. Due to the reinforcement, MMCs are hard to machine. Therefore, near-net shape forming technologies are preferred for industrial applications. However, the use of standard forming processes in order to produce required shapes made of discontinuously reinforced MMCs would be an enormous asset [2]. The main problems for these processes are the brittleness of the composite and the complex tribological interactions between non-metallic reinforcement phase, conventional tool material and lubricants. In consideration of these problems, Cold Hydrostatic Forging and Thixoforging processes were investigated.

2 APPROACH

Cold Forging of MMCs has been investigated in the past years using a counter punch for applying the hydrostatic compressive state within the MMC during the forming process [3, 4]. In the study presented in this paper, the MMC material was inserted in a surrounding shell made of a aluminum-based wrought alloy, Figure 1. During Cold Forging, hydrostatic compressive stress state was generated by co-extrusion of the MMC and the ductile shell material and should lead to a high deformation of the MMC without cracking.

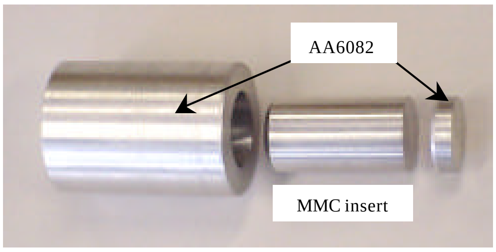

Figure 1: specimen with MMC insert before mounting.

The second investigated variant is a Thixoforging process, which is a forming technology for metal alloys in semi-solid state. Under this special conditions it is possible to combine the formability of liquid metals with the quality of solid-state formed products [5, 6]. In the case of particle reinforced MMCs, the ceramic particles should be transported in the same way as the solid metallic phase. Therefore, forming forces will be smaller compared to conventional solid state forming processes and, in addition to that, the geometrical precision of the produced specimens will be high.

3 COLD HYDROSTATIC FORMING

3.1 *Materials*

Two kinds of MMCs have been tested: the first one was an AA6082 containing 15% vol. Al_2O_3 short fibers (Saffil) and the second one a AA6061 containing 22% vol. Al_2O_3 particles. As ductile surrounding material, AA6082 aluminum alloy was used.

3.2 *Cold Forging experiments*

Forward and backward extrusion experiments were carried out on a 400 ton hydraulic press with a punch velocity of 55 mm/s. This process concept is schematically represented in Figure 2.

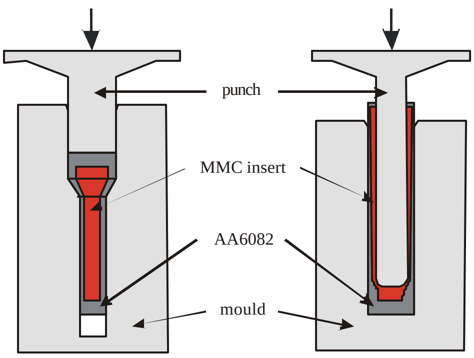

Figure 2: process concept for forward and backward extrusion.

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 MMC inserts, no surface treatment was applied.

The resulting geometry of the AA6082 specimens containing short fiber reinforced MMC inserts after forming at room temperature is shown in Figure 3 (forward extrusion) and Figure 4 (backward extrusion).

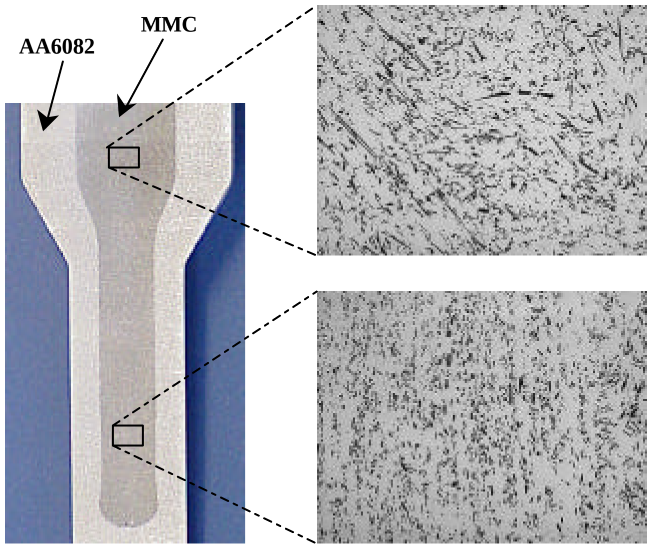

Figure 3: forward co-extrusion of short fiber reinforced MMC in the AA6082 surrounding shell.

The logarithmic strain of the cold forward extruded MMC insert was about $\varphi = 1.2$. In case of the particle reinforced MMC, no cracks could be detected. For the short fiber reinforced MMC (Figure 3), no cracks were found in the matrix as well as in the surrounding shell material. The ceramic short fibers were broken in 5 – 10 segments with a length of 5 – 15 μm and an orientation trend in the longitudinal direction.

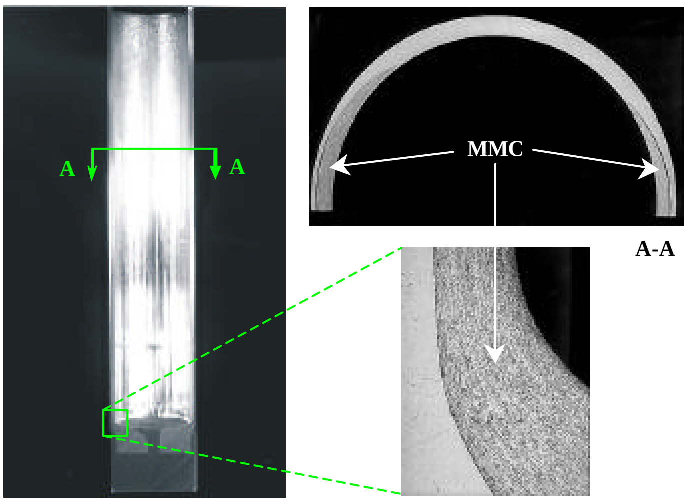

Figure 4: backward co-extrusion of short fiber reinforced MMC in the AA6082 surrounding shell.

Compared to the test conditions during forward extrusion, the deformation rate of $\varphi = 1.6$ was significantly higher for the backward extrusion test. Figure 4 shows a deformed specimen containing two short fiber reinforced MMC inserts. As already observed for forward extrusion, the short alumina fibers have broken in several segments and oriented in longitudinal direction. No cracks were observed in the matrix of both, the short fiber and particle reinforced MMC.

Tensile tests have been carried out with the forward extruded MMC inserts. Table 1 shows these results in comparison to the material properties before forming. It can be observed, that yield strength was increased for more than 100% and ultimate tensile strength between 20 and 60%. At the same time, a significant (50 to 90%) reduction of elongation to failure occurred.

material	parameter	before Cold Forging	after Cold Forging	variation [%]
MMC6061	$R_{p0.2}$ [MPa]	93 ± 7	281 ± 1	+ 202
	R_m [MPa]	180 ± 2	296 ± 1	+ 64
	A_5 [%]	18.6 ± 0.9	1.7 ± 0.1	- 91
MMC6082	$R_{p0.2}$ [MPa]	136 ± 3	271 ± 6	+ 100
	R_m [MPa]	242 ± 1	292 ± 5	+ 21
	A_5 [%]	3.9 ± 0.4	1.9 ± 0.3	- 51

Table 1: mechanical properties of both MMCs before and after cold forward extrusion.

4 THIXOFORGING

4.1 Material

Aluminum alloy AA6061 reinforced with 15% vol. Al_2O_3 particles was tested and compared with the same unreinforced alloy (AA6061).

4.2 Semi-solid forging experiments

The rheological properties of the tested materials were studied by means of backward extrusion using cylindrical specimens (Ø 26 x 35 mm).

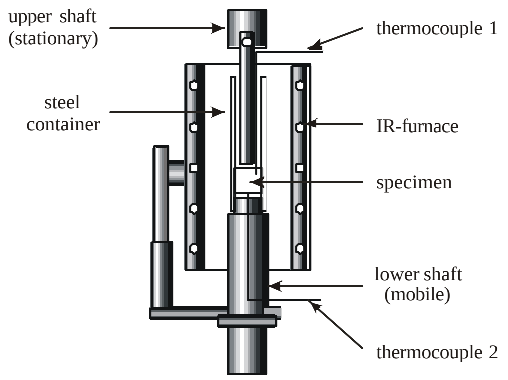

Figure 6: experimental set-up for the backward extrusion in the semi-solid state.

In a first step, the specimen was inserted into steel container and brought on a temperature within the semi-solid interval by an IR-heating furnace, Figure 6. After homogenization, the cylindrical specimen was isothermally backward extruded around the stationary plunger.

The results of former thixoforging experiments have shown, that thixotropic flow behaviour of AA6061 is characteristically developed for fractions of liquid phase f_L between 40 % and 60 % [7]. The flow behaviour of the aforementioned materials has therefore been investigated in function of the liquid fraction in this range and, additionally in function of the punch velocity.

The required forming energy at different liquid fractions for the unreinforced and reinforced aluminium materials is shown in Figure 7. Compared to the unreinforced material, the reinforced specimens show significantly higher forming energy values under the same test conditions. This is due the presence of the ceramic reinforcement, which represent a considerable obstacle to the thixotropic flow of the semi-solid slurry.

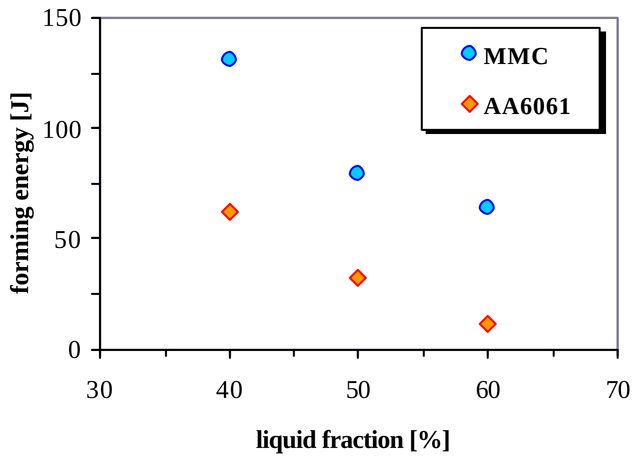

Figure 7: forming energy at different liquid fractions for unreinforced and reinforced aluminum alloy AA6061. Isothermal holding time 5 min. Punch velocity 20 mm/s. Punch displacement 15 mm.

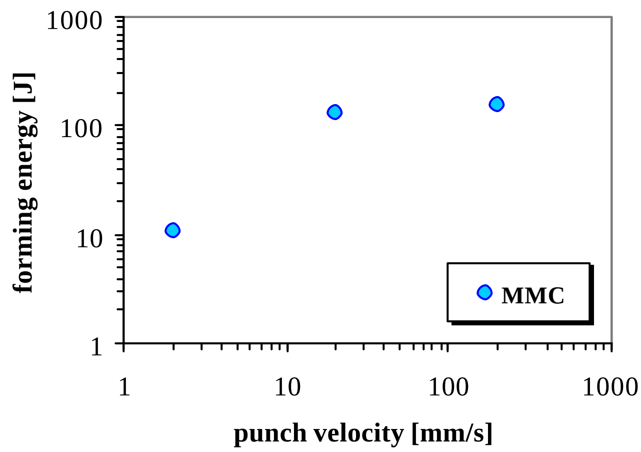

Figure 8: forming energy at different punch velocities for the MMC. Isothermal holding time 5 min. Liquid fraction 40%. Punch displacement 15 mm.

An equivalent phenomenon has been observed by varying the punch velocities between 2 and 200 mm/s, Figure 8. Comparably low forming energies were measured for low punch velocities. A possible explanation for that behaviour can be seen in the only slightly developed physical interactions between particles and liquid phase under this conditions. On the other hand, at high velocities, the particle represent an remarkable obstacle to the material flow and more load is needed.

The metallographic analyses of the deformed MMC specimens also manifest the different forming behavior. The forming parameters correspond directly with the ceramic particle distribution within the specimen, Figure 9. Separation increases with increasing liquid fraction. We assume the shear force exerted on the ceramic particles to be responsible for this fact. For example, by increasing the liquid fraction or decreasing the punch velocity, the shear force decreases, resulting in liquid-particle separation. This is because the ceramic particles need a certain shear force in order to flow, and in case of higher liquid fraction or low punch velocities this limit is not reached. Increasing the punch velocity, the fluid flow and also the shear force increase and the ceramic particles can easily be transported together with the fluid phase.

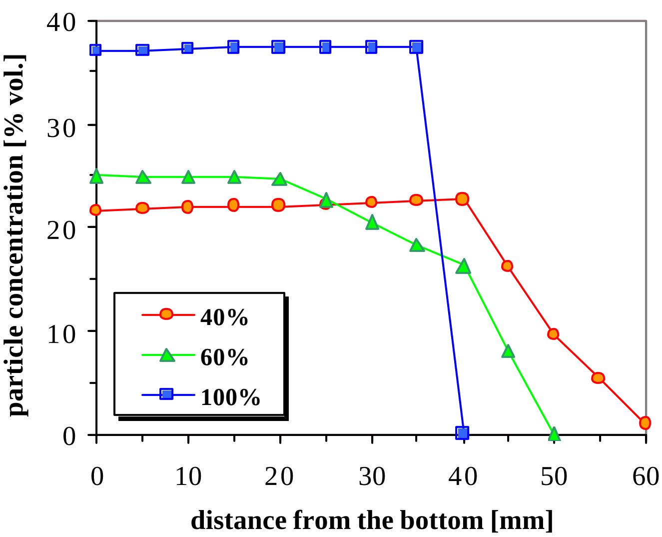

Figure 9: Particle concentration within the backward extruded MMC specimens, at different liquid fractions. Isothermal holding time 5 min. Punch velocity 20 mm/s.

Consequently, in these experiments it was not possible to obtain a regular distribution of reinforcement particles within the specimen under semi-solid conditions. This effect however allows to produce specimens with predefined concentration gradient by varying the process parameters during Thixoforging.

5 CONCLUSIONS

The two variants of forming processes presented in this paper have shown very promising results. It was possible to achieve high deformation for the MMCs without initiation and development of cracks. The semi-solid forging process allowed the production of specimens with a desired ceramic concentration gradient, just by varying the forming parameters.
It can be expected, that a transfer of this approach to other types of brittle materials will lead to an improvement of forming behaviour as well; tests on Mg-alloys are actually under investigation.

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