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**COLD FORMING OF AlCu4MgSi ALLOY BY ORBITAL FORGING**

**KSZTAŁTOWANIE NA ZIMNO STOPU AlCu4MgSi POPRZEZ PRASOWANIE OBWIEDNIOWE**

The article presents selected theoretical and experimental test results for cold forming of AlCu4MgSi aluminum alloy conducted on an oscillating die press PXW-100AAb. Cylindrical samples of aluminum alloy used in the tests were the **T42** ones subjected to the process of natural ageing as well as the ones in transient **W** temper obtained by solution treatment. The experimental tests were supplemented with a numerical analysis based on the FEM. It was assumed in the calculations that a rigid-plastic material model, with thermal phenomena taken into account, and, additionally, the Cockcroft-Latham material cracking model would be used. The obtained test results proved that additional heat treatment preceding cold forming allows for increasing the limit strain.

*Keywords:* orbital forging, AlCu4MgSi alloy, experiment, FEM, damage

W artykule przedstawiono wybrane wyniki badań teoretycznych i doświadczalnych dotyczących kształtowania na zimno stopu aluminium AlCu4MgSi, przy użyciu prasy z wahającą matrycą PXW-100AAb. Próbki cylindryczne wykonane są ze stopu aluminium w stanie naturalnym **T42** oraz w stanie przejściowym **W**, który uzyskano przez obróbkę przesycania. Badania doświadczalne uzupełniono o analizę numeryczną bazującą na MES. Obliczenia wykonano zakładając model materiałowy sztywno-plastyczny z uwzględnieniem zjawisk termicznych, gdzie dodatkowo zastosowano model pęknięcia materiału Cockrofta-Lathama. Uzyskane wyniki badań wykazały, że dodatkowa obróbka cieplna wsadu, poprzedzająca jego plastyczne kształtowanie na zimno pozwala zwiększyć zakres dopuszczalnych odkształceń.

**1. Introduction**

The orbital forging technology allows for manufacturing flat products, for example plates or flange bolts. This metal forming method is characterized by a swinging movement of the tool which presses only a small part of the product surface. Owing to that, orbital forging forces can be 5-10 times lower compared to the ones occurring in conventional upset forging. Given that orbital forging is a very time-consuming process and the product unfortunately needs to be cold formed [1, 2].

The article presents selected theoretical and experimental test results for orbital forging of aluminum alloys

that are difficult to deform. The aim of the tests was to determine an acceptable strain range. One of the materials used was AlCu4MgSi aluminum alloy [3], the chemical composition of which is given in Table 1. The main limitation on cold forming of this alloy in **T42** temper (i.e. solution heat-treated and naturally aged) is a rapid occurrence of cracks. One of the ways to improve formability of the alloy is to employ solution heat treatment. The alloy thus reaches a softened, transient **W** temper. After a short time lapse (approx. one hour) following the heat treatment, the alloy properties begin to return to the original state, which is desirable in terms of subsequent product use.

TABLE 1

Chemical constitution of AlCu4MgSi alloy according to ISO, wt%.

Cu	Mg	Si	Mn	Fe	Cr	Zn, Zr+Ti	Al
3.5÷ 4.5	0.40÷1.0	0.2÷0.8	0.40÷1.0	max0.7	max0.1	max .0.25	balance

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## 2. Experimental tests

The experimental tests were conducted in the Metal Forming Laboratory at Lublin University of Technology. The orbital forging process, whose scheme is presented in Figure 1, was conducted by means of a specially designed PXW-100AAb press. It was assumed that the upper die moves in an orbital manner according to the around-a-circle scheme. The process parameters were as follows: die deflection angle  $\gamma = 2^\circ$ , orbital movement velocity  $\omega = 150$  rpm, linear velocity of the lower die with ejector  $v_m = 4.1 \text{ mm}\cdot\text{s}^{-1}$ . The workpiece was being subjected to upsetting at constant velocity  $v_m$  until the orbital forging force reached the desired maximum value of 588 kN. Once such value was reached, the lower die velocity  $v_m$  was automatically being decreased in such a way so that the forging process could be conducted at the constant force value  $F_{max}$ . The original measurements of the samples were: diameter  $d_0 = 20$  mm and height of the part put to upsetting  $h_0 = 20$  mm. As a result of the orbital forging process, a forging with the flange of

height  $h_1$  was formed. The mean true strain value  $\varepsilon$  was calculated as:

$$\varepsilon = \ln(h_1/h_0). \quad (1)$$

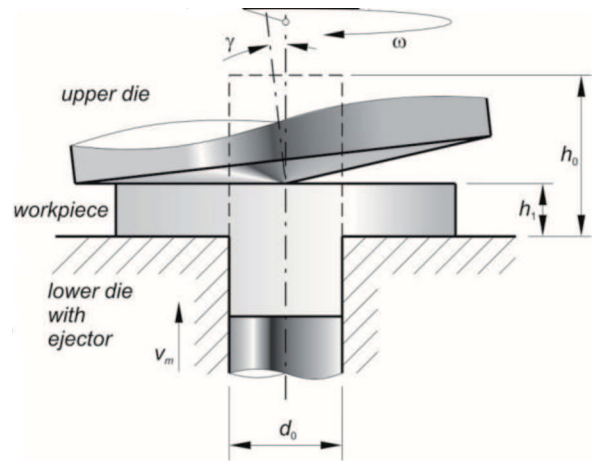


Fig. 1. Scheme of orbital forging process of forging with flange, where:  $d_0$  – original sample diameter,  $h_0$  – original height of the upset forged part of a sample,  $h_1$  – flange thickness,  $v_m$  – lower die velocity,  $\gamma$  – deflection angle,  $\omega$  – upper die orbital velocity

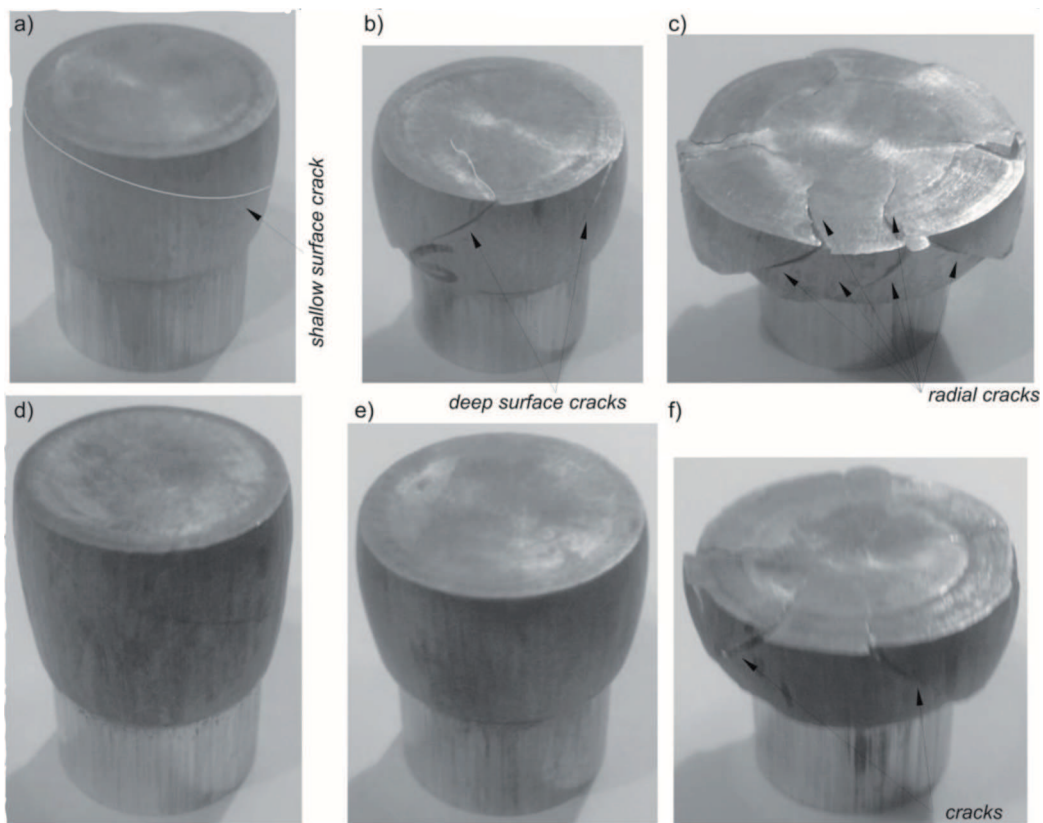


Fig. 2. Shapes of forgings made of AlCu4MgSi alloy in T42 temper (a, b, c) and in solution heat-treated state; values of mean strain  $\varepsilon$  being: -0.38 (a), -0.50 (b), -0.98 (c), -0.37 (d), -0.48 (e), -0.76 (f)

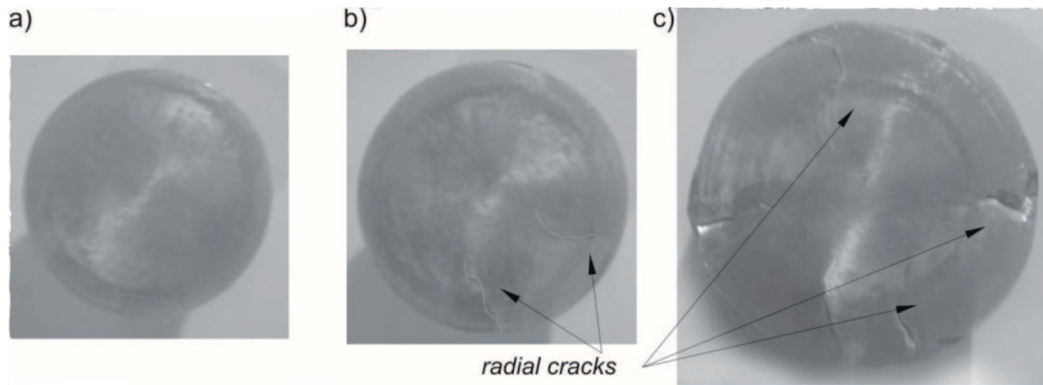


Fig. 3. Frontal surface of forging made of AlCu4MgSi alloy in T42 temper and radial cracks which occur there, values of mean strain  $\varepsilon$  being: -0.38 (a), -0.50 (b), -0.98 (c)

Shapes of sample forgings with different strain values are presented in Figure 2. As proved by the tests, it is impossible to obtain the desired flange height  $h_1$  of 6 mm (Fig. 2c) for forgings made of AlCu4MgSi aluminium alloy. As for products made of aluminum alloy in T42 temper, the first cracks, or shallow scratches on the lateral surface of the forging (Fig. 2a), occur sporadically already at the value of strain  $\varepsilon$  ranging between  $-0.38 \div 0.36$ . Once strain exceeds the value of  $\varepsilon = -0.42$ , surface scratches turn into characteristic deep cracks, inclined towards the main axis of the forging at the angle of  $45^\circ$ . Those cracks then extend to become additional radial cracks visible on the frontal surface of a forging (Figs. 2b and 3). Obtaining the strain value of  $\varepsilon = -0.70 \div 0.68$  may finally result in flange chipping as is shown in Figure 4. The shape of the fracture formed shows that material cracking is preceded by plastic strains. It means that modelling of the analyzed process can be conducted by means of a numerical simulation (e.g. the finite element method – FEM), where the Cockcroft-Latham model [4] is employed as a criterion for predicting crack occurrences on the forging.

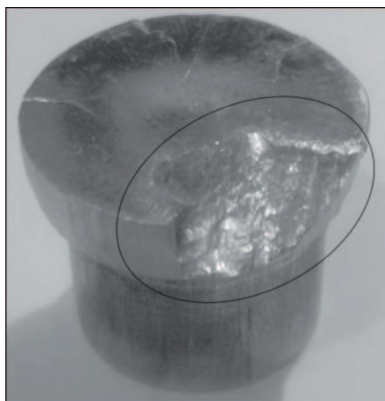


Fig. 4. Fracture resulting from chipping of material in T42 temper; at mean strain value of  $\varepsilon = -0.68$

The aim of the second stage of the experimental tests was to determine the impact of preliminary heat treatment of AlCu4MgSi alloy on the range of acceptable strain in the analyzed process. To make the alloy reach W (softened) temper, solution heat-treatment was employed. It involved heating the samples at the temperature of  $495^{+5}^\circ\text{C}$  for  $35^{+10}$  minutes in an electric chamber furnace which was operated electronically. After the heating, the samples were hardened in water at the temperature ranging between  $15 \div 35^\circ\text{C}$ . In order to prevent material surface from oxidation during heating, the samples were placed in special containers made of aluminium foil. As a result, the semi-finished products were effectively isolated from the electric furnace atmosphere. Moreover, thanks to that solution, neither protective atmospheres nor special heating conditions (e.g. salt baths or shielding gases), which are expensive and harmful to the natural environment, had to be employed. The material condition obtained thereby was not however stable, whereas the orbital forging process had to be completed within approx. 40 minutes after the completion of hardening process.

The obtained forgings made of alloy in W temper are illustrated in Figures 2d÷f. Table 2 presents evaluation of the forging condition in terms of material cracking, depending on the condition of AlCu4MgSi alloy and on the value of mean strain  $\varepsilon$ . The tests show that in the case of forgings made of the alloy in W temper, the first shallow cracks as scratches on the lateral surface occur when strain reaches the value of  $\varepsilon = -0.48 \div 0.42$ . It was additionally observed that material subjected to heat treatment in the way described above is not prone to chipping as far the analyzed strain value  $\varepsilon$  is concerned.

TABLE 2

Assessment of forging condition as for material cracking, depending on AlCu4MgSi alloy temper and on absolute value of mean true strain  $\epsilon$

temper designation	absolute values of mean true strain $\epsilon$						
	$\leq 0,30$	0,36	0,42	0,50	0,62	0,76	$\geq 0,80$
T42	0	0/1	0/1	1/2	2	2/3	2/3
W	0	0	0/1	0/1	1	1/2	2

Details: **0** – no cracks, **1** – shallow cracks on lateral surface of flange, **2** – deep lateral and radial cracks, **3** – very deep cracks and material chipping

On the basis of the conducted experimental tests, a FEM model for the orbital forging process of forgings made of AlCu4MgSi alloy in softened condition was developed. The process simulation was conducted using DeForm-3D, while the calculations were based on the rigid-plastic model, with thermal phenomena taken into account, the constant friction model, and the Cockroft-Latham damage model. The material data were obtained from separate plastometric research works [5, 6,7].

Figure 5 presents selected numerical simulation results which show the distribution of the calculated Cockroft-Latham function values for the forging surface. The maximum values are located on the lateral surface of a forging and on the external perimeter of the material-upper die contact surface. The area of maximum values of the damage function corresponds to the area where the cracks occurred in the experimental forging. Figure 6 presents a diagram which shows changes in maximum damage function values in the function of changes in mean strain  $\epsilon$ . The values were calculated for the central zone of the lateral surface of a forging. The

lines of minimum and maximum values of the damage function marked in the diagram determine the range of the values measured on the forging perimeter for a given phase of the orbital forging process.

It was assumed that once the damage function reached its first limit value, cracks would occur simultaneously. Comparing the calculations with the experimental test results, the following can be observed in Figure 6:

- point A shows the moment when the first cracks occur on the lateral surface of a forging;
- point B shows the moment when deep cracks occur on the lateral surface of a forging; those cracks then extend to become radial cracks on the frontal surface.

Analyzing the theoretical and experimental test results, it can furthermore be claimed that the limit value of the Cockroft-Latham integral is of approx. 0.1 for cold orbital forging of AlCu4MgSi alloy in softened condition. This means that the above value is reached in the FEM simulation exactly at the moment when material cracking begins.

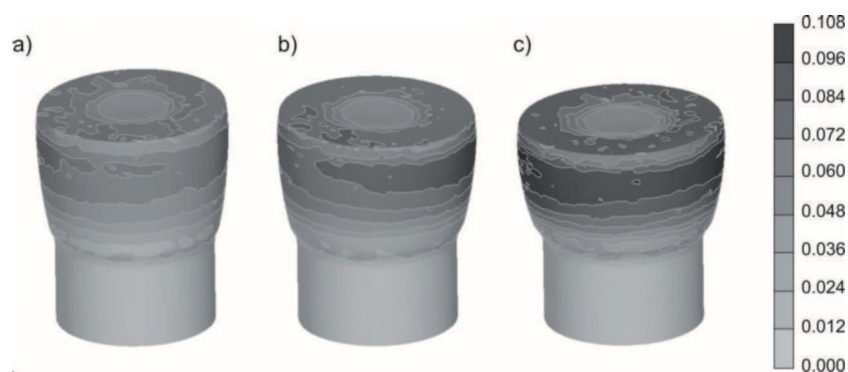


Fig. 5. Cockroft-Latham damage function distribution calculated in FEM simulation, with values of mean strain  $\epsilon$  being: -0.36 (a), -0.43 (b) and -0.52 (c)

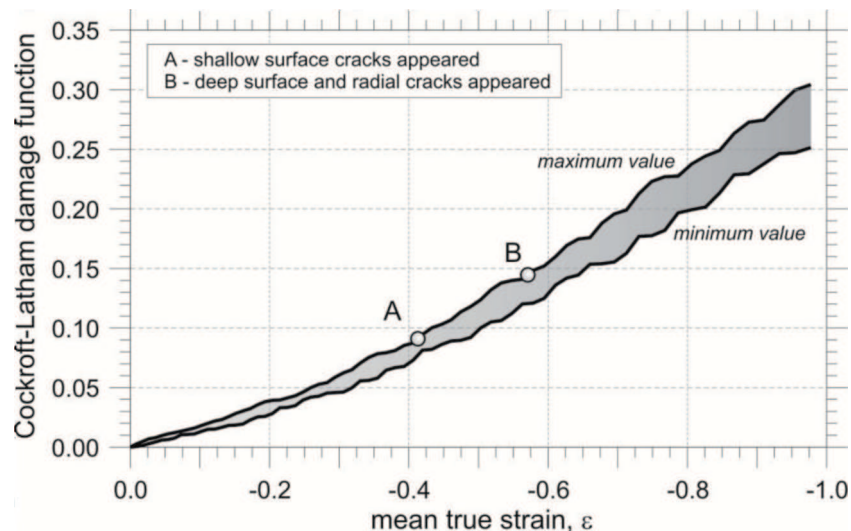


Fig. 6. Range of Cockcroft-Latham damage function values obtained in FEM simulations and calculated for flange lateral surface in the middle of thickness  $h_1$ , where: points A and B show when particular kinds of cracks appear on experimental forgings

### 3. Conclusions

### REFERENCES

On the basis of the presented theoretical and experimental test results, the following observations can be made:

- as a result of preliminary solution heat-treatment, the acceptable strain range during orbital forging of Al-Cu4MgSi alloy in unstable **W** temper increases by 18÷33%, compared to the strain range for forgings made of this alloy in T42 temper;
- in cold forming, material cracking is preceded by plastic strains;
- a comparison of the FEM simulation results with the experimental tests results allows for estimating the limit value of the Cockcroft-Latham function, which indicates the moment when the material cracking phenomenon begins to occur.

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