THE INFLUENCE OF EXTRUSION DIE ANGLE DURING THE HOT EXTRUSION PROCESS OF AL ALLOYS

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ABSTRACT: One of the most important parameters for the hot extrusion process effecting the deformation force, material flow, microstructural and mechanical properties of the extruded material is the Extrusion Die Angle (EDA). In this investigation, the effects of EDA on load, material flow and microstructure of hot extruded commercially pure aluminum has been studied. The finite element simulation were carried out using Deform 3D. Finite element modeling shows that the values of the equivalent plastic strain and its distribution, flow material and deformation forces depend extremely on deformation temperature, reduction and EDA. To estimate the reliability of the numerical analysis, the FE model was validated using experimental results. The results showed that the lowest extrusion force occurs in an optimum die angle for each reduction. Optimum EDA obtained 16, 18 and 23 degrees at reductions of 50%, 60% and 70%, respectively. Also, material flow, inhomogeneity of microstructure and the equivalent plastic strain increases with increasing of EDA.

KEYWORDS: *Die angle; FEM; Hot extrusion; Material Flow; Microstructure; Reduction.*

1.0 INTRODUCTION

The advantages of aluminum and its alloys make it particularly appropriate for complex extrusion processes. High ductility and the ideal ratio of strength to mass density in aluminum alloy prepare various applications in automotive and aircraft manufacturing, and also in lightweight construction [1]. Nearly 80% of all metals products consisting of aluminum alloy undergo hot forming during some part of their processing history [2]. Hot deformation processes are a fundamental step in the production of engineering parts which require not only dimensional accuracy but also suitable microstructural and mechanical properties with minimization of load and energy. Therefore investigation of materials behavior during hot deformation is very essential.

Hot extrusion is one of the most important processes used to produce aluminum alloys. Minimization of load and energy, deformation homogeneity and controlling of microstructure of the extruded material are considerable aspects in die design process. It is commonly accepted that product properties are strongly correlated to microstructure. So it is of paramount importance to understand the way in which the structure is modified and how the forming parameters (i.e. die geometry, reduction, temperature, etc.) affect these modifications.

Simulation of hot forming processes with application of finite element method (FEM) has been the subject of many recent works. High temperature and large plastic deformations of the extrusion processes have led to developments in the microstructure of the material [3-7].

Joun and Hwang [8] applied a finite-element-based optimal process design technique in steady-state metal forming to die profile design in forward extrusion. They predicted the die profile for minimization of forming energy for various process conditions and materials. Lee et al. [9] designed the optimal die profile for hot rod extrusion that could yield more uniform microstructure. They applied the flexible polyhedron search (FPS) method to obtain the optimal die profile, and to show validity of result of their study, performed a hot extrusion experiment.

Byon and Hwang [10] presented a process optimal design methodology to minimize the punch force in steady-state forming process by using the finite-element method. The influences of die profile on the microstructural changes of the hot extruded sample have not been investigated in the previous researches. In the meantime, the effects of other parameters of hot extrusion process including temperature, friction coefficient, reduction and etc. have been disregarded in the prior investigation.

In this paper, the optimum angle of conical die is achieved using finite-element method for hot extrusion of pure aluminum rod. Also, the simulation results have been verified by experimental data, and finally, microstructural changes have been investigated for different die angles and various hot extrusion conditions.

2.0 MATHEMATICAL MODEL

2.1 Mechanical Model

As shown by Eq. (1) the actual work, W_a, to complete the extrusion process is the sum of the ideal work, W_i, that would be required for the shape change in the absence of friction and inhomogeneous flow, the work against friction between work and tools, W_f, and the work to do redundant or unwanted deformation, W_r [11].

$$W_a + W_i + W_f + W_r \tag{1}$$

Unlike the ideal work, the friction and redundant work depend on die angle. As it is clear from Figure 1, for a given reduction, the contact area between the die and material decreases with increasing die angle; so with a constant coefficient of friction, frictional work decreases while the redundant work term increases with die angle. Therefore, for each reduction, there is an optimum die angle, for which the total work is a minimum [11].

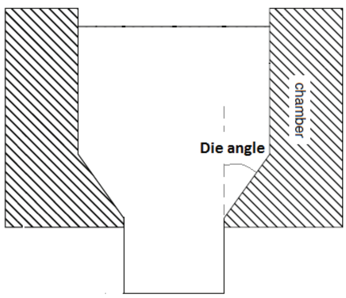


Figure 1: A typical conical die

Generally, the hot deformation behavior of metals and alloys are characterized by stress, strain, strain rate and temperature. The equations covering these values varying in wide ranges are given as [12]:

$$Z = \dot{\varepsilon}\exp(\frac{\Delta H}{RT}) = A(\sinh \alpha\sigma)^n \tag{2}$$

$$\sigma = \frac{1}{\alpha}\left\{\left(\frac{Z}{A}\right)^{1/n} + \left[\left(\frac{Z}{A}\right)^{2/n} + 1\right]^{1/2}\right\} \tag{3}$$

where σ is the flow stress, T is the absolute temperature, Z is the temperature compensated strain rate and commonly known as Zener-Hollomon parameter, A is a constant, n, ε, ΔH and R are the power exponent, the strain rate, the activation energy and the universal gas constant, respectively. The behaviour of an aluminum alloy during extrusion as a thermomechanical process depends on temperature, strain (reduction) and strain rate (ram velocity), as described by Eqs, (2) and (3).

2.2 Microstructural Model

Evolution of microstructural changes during hot extrusion is a very complicated operation. The distribution of microstructure through cross section and along the length of extrusion die varies considerably under normal extrusion conditions. This causes a non-uniform distribution of mechanical properties and hence may necessitate extra post-extrusion operations such as machining away the recrystallised layer.

The relationship between the volume fraction recrystallised and the holding time is generally represented by the JMAK equation clarified by Eq. (4) [13].

$$X_V = 1 - \exp\left\{-0.693\left(\frac{t}{t_{50}}\right)^k\right\} \tag{4}$$

Where X_V represents the static recrystallized volume fraction achieved at the annealing temperature, t is annealing time, k is the Avrami exponent with a commonly reported value of 2, t_{50} is the time to 50% static recrystallization. There are two kinds of models consisting of empirical and physical models for the calculation of t50. The empirical model bypasses the evolution of substructure, and relates the final microstructure with strain, strain rate and temperature by regression of the experimental data. The only advantage of this model is its easy usage.

$$t_{50} = A d_0^a \varepsilon^{b'} Z^c \exp\left(\frac{Q_{rex}}{RT_a}\right) \tag{5}$$

A, a, b′, c are constants, d_0 is the initial grain size, ◎ is the equivalent strain, Q_{rex} is the activation energy for recrystallization, R is the universal gas constant, Ta is the annealing temperature and Z is the Zener-

Hollomon parameter.

For the physical model, t_{50} is calculated based on the stored energy (P_D) and the density of recrystallization nuclei (N_V):

$$t_{50} = \frac{C}{M_{GB} P_D} \left(\frac{1}{N_V} \right)^{1/3} \tag{6}$$

where C/M_{GB} is a calibration constant.
As shown by Eq. (3) the recrystallized grain size is expressed as a function of initial grain size, strain, strain rate, and temperature.

$$d_{rex} = a_2 d_0^{h_2} \varepsilon^{n_2} \dot{\varepsilon}^{m_2} \exp\left(Q_2 / RT \right) + c \tag{7}$$

where a_2, h_2, n_2, c and m_2 are material constants.
The kinetics of grain growth is described by isothermal equation as presented in Eq. (8).

$$d_{gg} = \left[d_{0g}^{m} + a_g t \exp\left(-Q_g / RT \right) \right]^{1/m} \tag{8}$$

where d_{gg} denotes the final grain size after growth and holding time of t, whilst d_{0g} is the grain diameter prior to the holding period, a_g and m are materials constants, and Q_g is activation energy of grain growth.

2.3 Finite Element Modeling

The Finite Element Modeling (FEM) is one of the most precise methods to analyze the forming process, which is usually non-linear, thermomechanical coupled and involves very large deformations. To date, various models have been proposed and integrated into FEM programs to study the load and microstructure response under various forming conditions, and to control the microstructural evolution.

In this work, a 3D model has been constructed to simulate the hot extrusion process for aluminum alloys using finite element program DEFORM™. The billet is assumed to behave as a thermo–elastic viscoplastic material with temperature-dependent elastic modulus and poisson's ratio. The range of temperatures, strains and strain rates experienced by the material during the extrusion process is large, hence it is necessary to define the plastic behavior of the billet as a function of temperature, strain and strain rate. This was done using a hyperbolic sine equation, shown in Eq. (3), which relates the steady state flow stress of the material to the strain rate and temperature under which it is deformed. It is also assumed that the die and stem materials behave as a rigid solid.

The geometry of the billet, stem and die of hot extrusion at the reduction value of 50% shown in Figure 2. The die with a round opening had a bearing length of 2.5 mm.

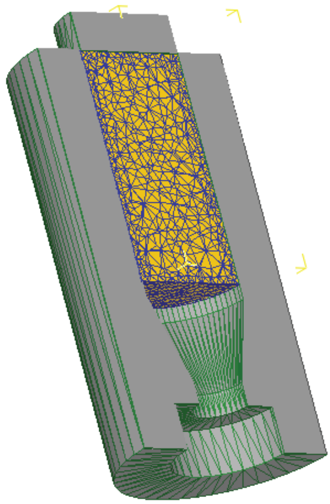


Figure 2: Billet, stem and die in FE model.

The process was carried out at three initial temperatures of 350 ºC, 450 ºC and 550ºC. Also three reductions of 50%, 60% and 70% have been studied. The density of the billet was assumed to be constant at 2710 kgm-3. Coefficient of friction depending on applying lubricant comes from test conditions.

3.0 EXPERIMENTAL PROCEDURE

3.1 Material

The chemical composition of the AA1070 aluminum alloy employed in this work is given in Table 1.

Table 1: Chemical composition of AA1070

%Ga	%Ti	%Cu	%Fe	%Zn	%Si	%Al
0.010	0.0126	0.0102	0.199	0.0102	0.0788	99.7

Aluminum billets were cut from a bar of AA1070 with 16mm in diameter and 30mm in height (that was reduced by wire drawing) to be used for the experiments. Samples were first annealed at 600 ºC with two holding time consisting of 5 and 50 min and then air cooled so that two initial grain sizes of 40 and 200 µm were obtained.

3.2 Equipment and Extrusion die

The schematic diagram of the die-set used in this study is shown in Figure 3. Three conical dies with a half angle of 10, 20 and 30 degrees have been constructed for the reduction of 50%. The die-set consists of die, container, punch, lower and upper shoes and rings. Samples were hot extruded under initial temperatures like FEM program. A5 glass lubricant was applied manually on the surfaces of the billet and die and container.

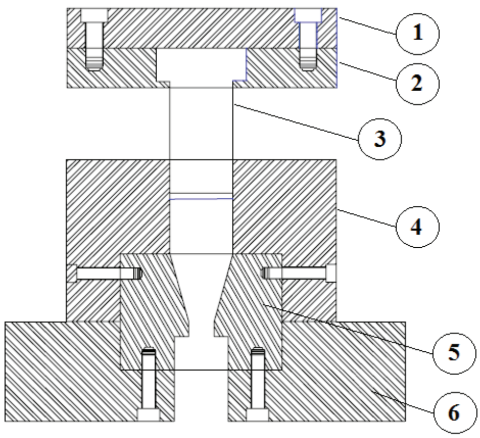
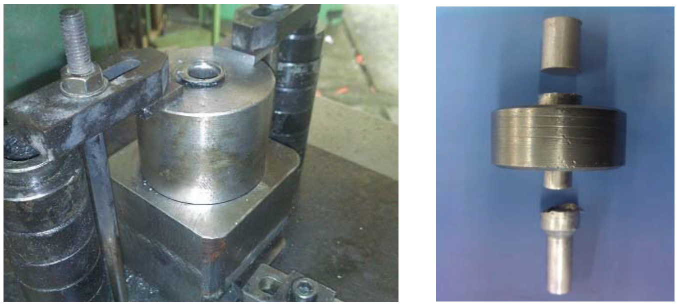


Figure 3: Schematic diagram of the die-set, (1) upper shoe, (2) holder ring, (3) punch, (4) container, (5) die and (6) lower shoe.

The best resolution of microstructures for investigation of microstructural changes and determination of grain sizes of annealed and hot extruded samples is achieved by the examination of electrolytically anodized samples in a polarized light microscope (PLM). Figure 4a illustrates the die set; while Figure 4b shows the specimen before and after the tests.

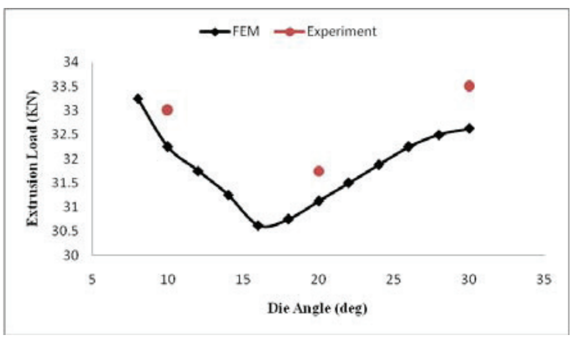


(a) (b)

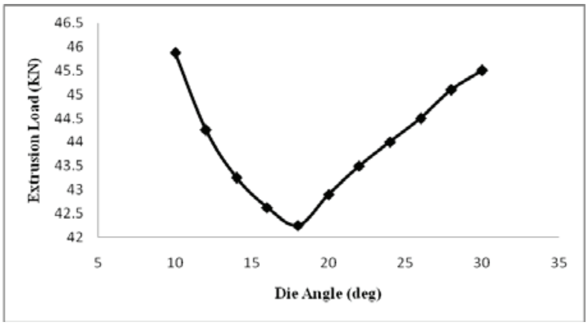
Figure 4: Extrusion condition: (a) die-set and (b) billet and deformed sample

4.0 RESULTS AND DISCUSSION

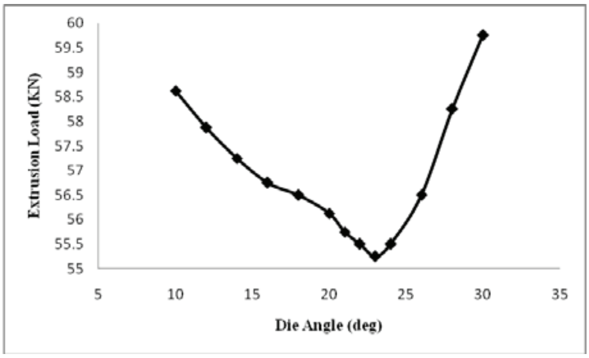
The influence of die angle on maximum extrusion load illustrated in Figure 5, at reduction of 50% and the temperature of 450ºC and punch speed of 50mm/sec. As it is clear from this Figure, there is an optimum die angle, for which the maximum extrusion load is a minimum. Due to the similar condition, except for the die angle, it can be concluded that just the suitability of die angle causes this decreased load. Also, it is obvious from Figure. 5a that the experimental data and simulation results (FEM) have proper accordance at different die angles.



(a)



(b)



(c)

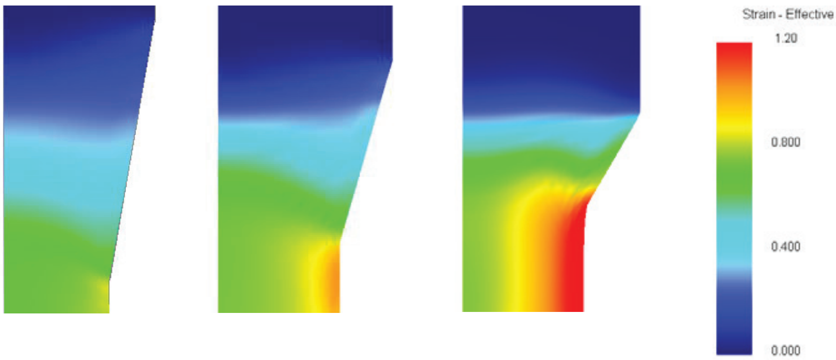
Figure 5: Influence of die angle on the maximum required extrusion load for different value of reduction: (a) 50%, (b) 60%, (c) 70%

The influence of reduction on the amount of required maximum load and optimum die angle resulted from the simulation is presented in Table. 2. It is clear that the amount of reduction can affect on the optimum die angle. In a same condition, the optimums die angle increases with increasing of the reduction amount.

Table 2: Reduction effects on the required maximum load and optimum die angle

Amount of reduction	50%	60%	70%
Required maximum load (kN)	30.62	42.19	55.25
Optimum die angle (deg)	16	18	23

Figure 6 shows distribution of the effective strain at different regions of deformation in the half cross-section of hot extruded billet. As illustrated in this Figure, the effective strain has a non-uniform distribution in the deformation zone.



(a) (b) (c)

Figure 6: Distribution of effective strain for die angle of (a) 10º, (b) 16º and (c) 30º in the deformation zone

As can be seen from Figure 7, the amount of EDA can strongly control the manner of strain distribution and strain inhomogeneity.

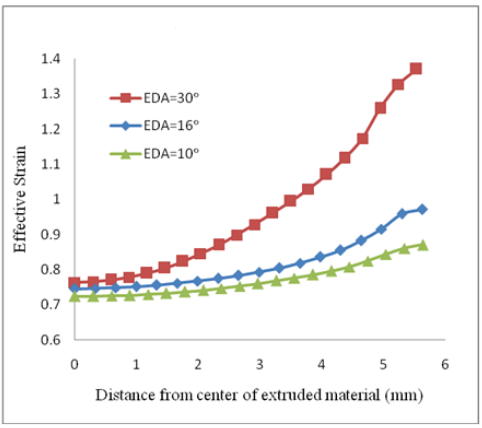


Figure 7: Effects of EDA on the distribution of effective strain at the exit position of deformation zone

The amount of effective strain increases with increasing dies angle. Also, inhomogeneity of the effective strain increases with increasing of distance from the center to the surface of the extruded material.

The effects of deformation temperatures on the maximum required load for different reductions during the hot extrusion process are illustrated in Figure. 8. It is obvious that the alternations and values of the hot extrusion load increases with increasing of reduction values. Meanwhile the values of hot extrusion load decreases with increasing of deformation temperature values.

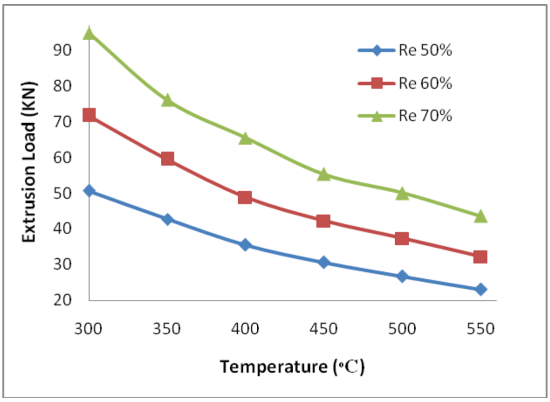


Figure 8: The variation of extrusion load at different deformation temperatures and reductions.

The influences of die angles and friction coefficients on the extrusion load are shown in Figureure 9. It is clear from this Figureure; extrusion load gradually decreases and after that increases with an increase in the die angle. Also, it is obvious that extrusion load increases with increasing of friction between die and workpiece surface.

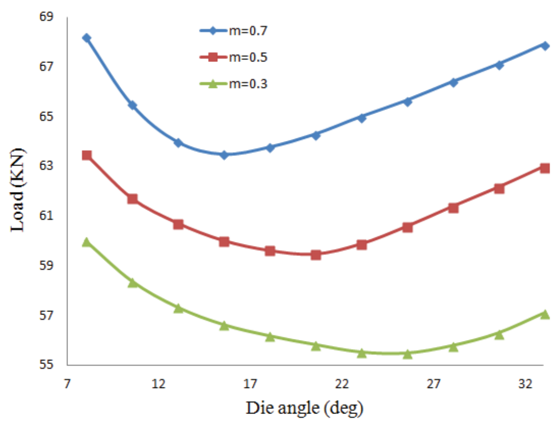
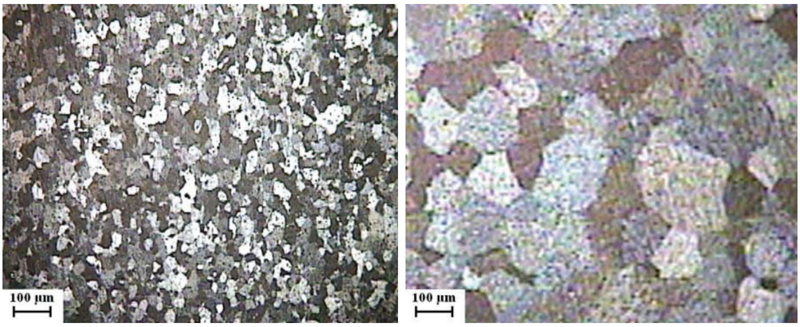


Figure 9: The variation of extrusion load at different friction coefficients and die angles.

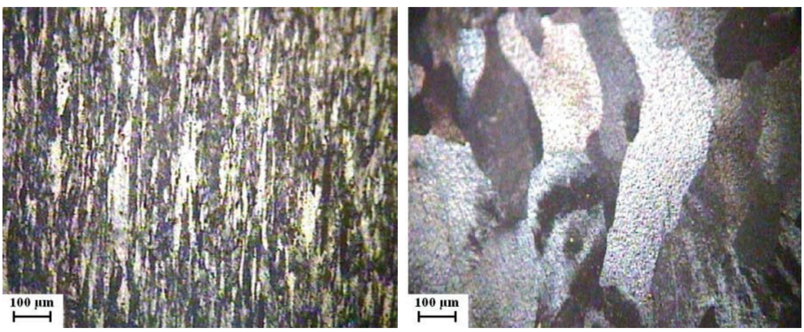
Microstructures of the two samples with initial grain size of 40 and 200 μm before hot extrusion illustrated in Figures 10a and 10b, respectively. To investigate the initial microstructure, the samples are first annealed at 600 ºC with two holding times of 5 and 50 min, and then air cooled, so the grain size of samples obtained are about 40 and 200 μm, respectively.



(a) (b)

Figure 10: Microstructures of samples before hot extrusion at annealing temperature of 600 ºC and holding time of (a) 5 min and (b) 50 min.

Microstructures of samples hot extruded at the temperature of 450ºC are shown in Figure 11. As shown in this Figure, severely elongated grains are observed at hot extruded sample with initial grain size of 200 μm, which suggest that dynamic or static recovery be the main restoration process during or after the hot extrusion.



(a) (b)

Figure 11: Microstructures of samples after hot extrusion with die angle of 20º for two initial grain sizes of (a) 40 μm and (b) 200 μm.

In Figure 12, the influence of die angle on microstructure evaluation is illustrated. Detailed microstructural observation indicates that more homogenous structure in Figure 12(b) is due to the extrusion process with die angle of 20º which is close to the optimum die angle obtained from simulation.

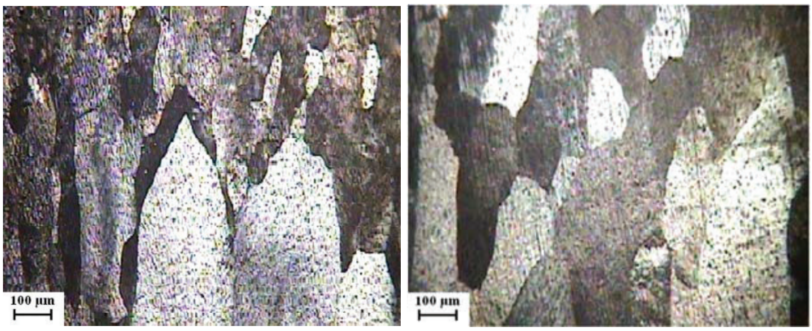


Figure 12: Microstructures of samples after hot extrusion at the temperature of 550 ºC with two die angles of (a) 20º and (b) 30º.

5.0 CONCLUSIONS

In this work, a mathematical model based on the finite element analysis was proposed to predict the optimum die angle during the hot extrusion process of aluminum alloy. Deformation forces, material flow and microstructural evaluation of the hot extruded material affected by Extrusion Die Angle (EDA), were investigated. The results show that at each reduction, there is an optimum die angle providing minimum extrusion load. In the same conditions, optimum die angle increases with increasing the amount of reduction and decreasing friction of die. The results also show that the values of the equivalent plastic strain and its distribution depend extremely on EDA. The equivalent plastic strain increases with increasing of EDA. Investigations show that temperature is one of the most prominent parameters that controls the process.

Finally, microstructural investigations show that EDA and the other processing parameters of hot extrusion have efficient effects on the microstructure of hot extruded sample, as the optimum die angle prepares more homogenous microstructure.

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