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NUMERICAL INVESTIGATION OF STRESS AND STRAIN DISTRIBUTION IN EQUAL CHANNEL ANGULAR EXTRUSION OF AL 6063 ALLOY

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ABSTRACT

This research work is aimed at studying the stress and strain distribution in the Equal Channel Angular Extrusion of Al 6063. Equal Channel Angular Extrusion (ECAE) processes enable material achieve nanoscale ultra-fine grain size without altering the physical properties. Automatic Dynamic Incremental Nonlinear Analysis (ADINA) which is a Finite Element Analysis (FEA) based solution was used to determine the stress and strain distribution in the material subjected to a single ECAE process. The model ECAE die and Al 6063 billet was developed with ADINA, the ECAE process were simulated and the data from the application was analysed. The result from the simulation showed that after a pass of ECAE of Al 6063, the average effective stress and strain were 203.08 MPa and 0.67 respectively and were highest at the inner part of the billet. Also, the average effective stress and strain were 178.02 MPa and 0.59 respectively at the mid part of the billet and the average effective stress and strain of 178.37 MPa and 0.58 respectively were lowest at the outer part of the billet. The results showing higher stress and strain distribution in the billet part closest to the die inner corner confirms that ECAE process for Al 6063 was inhomogeneous and it is an effective method in increasing the yield strength of Al 6063 alloy.

Keywords: Equal channel angular extrusion (ECAE), Simulation, ADINA, Al 6063, Stress, Strain

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1. INTRODUCTION

Al 6063 alloy has found application in standard architectural shapes and works, custom solid shapes, heat sinks, and seamless and structural tubes and pipes. In the heat treated condition, Al 6063 alloy provides good resistance to general corrosion (including resistance to stress-corrosion cracking) [1]. It is easily welded or brazed by various commercial methods with the caution that direct contact by dissimilar metals can cause galvanic corrosion.

Numerous techniques have been developed in order to achieve improved mechanical properties of materials such as Al 6063 alloy by reducing the grain sizes to ultra-fine nanoscale without changing the physical structure of the materials. Among the numerous techniques, one of the effective methods of obtaining materials with high strength and toughness is Equal Channel Angular Extrusion (ECAE) [2].Because of the widespread use of Al 6063 alloys, it is important to simulate to understand the stress and strain distribution behaviour in Al 6063 when exposed to ECAE.

ECAE was originally developed by V. M. Segal [2-3]. In the ECAE process, a work-piece is pushed through a die of two channels, the two channels have equal cross-sections and the two channels meet at an angle. ECAE is an effective method to produce a large amount of simple shear deformation in a material by passing it around a corner of two intersecting channels with equal cross-sections. A schematic diagram of ECAE showing its geometry is shown in Figure 1 where P symbolizes the deformation force.

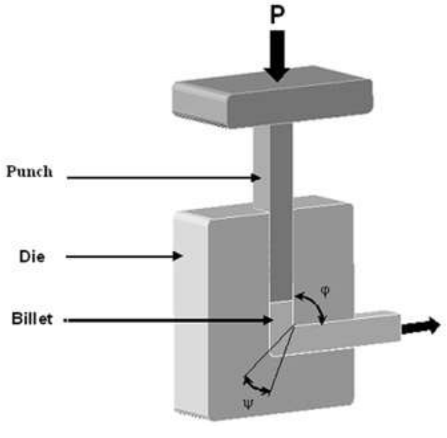


Figure 1 Schematic diagram of an ECAE die showing the inner die angle (∅) and the outer die angle (ψ) [4]

The properties of materials processed by ECAE are strongly dependant on the plastic deformation behaviour during pressing [5-6]. These properties are governed mainly by die geometry (the inner die angle ∅ and outer die angle ψ), material properties like strength and hardening behaviour and process variables such as lubrication and deformation speed [7]. The deformation of the work piece in ECAE is accomplished by a simple shear which is taking place in a thin layer at the crossing plane of the equal channels [8].

The total strain ε of work-piece in N passes through the die is given by equations 1 [9]:

$$\varepsilon_N = \frac{N}{\sqrt{3}}\left[2ctg\left(\frac{\emptyset}{2} + \frac{\psi}{2}\right) + \psi cosec\,\left(\frac{\emptyset}{2} + \frac{\psi}{2}\right)\right] \tag{1}$$

For average strain rate the following relation is derived:

$$\dot{\varepsilon} = \frac{1}{\sqrt{3}}\left[2ctg\left(\frac{\emptyset}{2} + \frac{\psi}{2}\right) + \psi cosec\,\left(\frac{\emptyset}{2} + \frac{\psi}{2}\right)\frac{v\sqrt{2}}{w\psi}\right] \tag{2}$$

Where w [mm] is a diameter or width of the work-piece and v [mm/s] is the punch speed. $\emptyset$ is the inner angle of the die and ψ is the outer angle of the die.

In the vertical channel, the billet moves as a rigid body while all deformation is localized in the small area around the channel’s meeting line. The metal is subjected to a simple shear strain under relative low pressure compared to the traditional extrusion process [10].

ECAE is supported by the principle of Grain-boundary strengthening. Grain-boundary strengthening is a method of strengthening materials by changing their average crystallite (grain) size. Grain-boundary strengthening is based on the opinion that grain boundaries hinders dislocation movement and that the number of dislocations within a grain have an effect on how easily dislocations can traverse grain boundaries and travel from one grain to another grain. So, by changing grain size one can influence dislocation movement and yield strength. For example, heat treatment after plastic deformation and changing the rate of solidification are ways to alter grain size [11].

A fine-grained material (one that has small grains) is harder and stronger than one that is coarsely grained, since the fine-grained material has a larger amount of grain boundary area to hinder dislocation motion. For many materials, the yield strength σ_y varies with grain size according to the Hall-Petch equation.

$$\sigma_y = \sigma_0 + k_y d^{-1/2} \tag{3}$$

In this expression, d is the average grain diameter, and σ_0 and k_y are constants for a particular material. It should be noted that this equation is not valid for both very large or coarse grain and extremely fine grain polycrystalline materials [12]

Extrusion by ECAE method enables obtaining of a fine-grain structure in larger volumes. During the last two decades, ECAE has progressed from being a relatively minor metal processing technique to becoming a well-established and recognized procedure for achieving very significant grain refinement specially with the realization that ultrafine grained materials offers potential advantages in improving strength and toughness in metals and alloys [13].

At present, ECAE is the best developed of all severe plastic deformation (SPD) processing techniques [13-15]. A major advantage achieved in ECAE is that the material cross section is unchanged during the ECAE process, which means that the material can be extruded repeatedly to attain a high total strain [16-17]. Bulk materials can be processed in ECAE, which also gives this process an industrial significance. Furthermore, the fundamental principles of ECAE, dealing with the mechanics of metal flow and the microstructural evolution, provide useful tools that can be utilized both in the development of new SPD methods and in the future exploitations of some of the existing but underdeveloped SPD techniques. Although the mechanical and physical properties of all crystalline materials are determined by several factors, the average grain size of the material generally plays a very significant, and often a dominant, role.

It is difficult to directly measure strain and its distribution in the sample during ECAE process. However, the deformation, strain distribution and stress state in the material during ECAE can be estimated (even at each point) by FEA numerical simulation. Thus, the understanding of the phenomena associated with the stress and strain development is very important for a sound ECAE process design of materials such as Al 6063.

The ADINA system has been found useful in simulating the ECAE of Al 6063 alloy process because of its reliability. The ADINA System offers a one-system program for comprehensive finite element analyses (FEA) of structures, fluids, heat transfer, electromagnetic and multiphysics. ADINA is commercial finite element software which is developed and distributed worldwide by ADINA R&D, Inc [18]. Finite element method (FEM) is a numerical method that can be used excellently in the description of the deformation behaviour during different deformation processes such as ECAE [19].

The finite element analysis (FEA), is based on the idea of building a complicated object with simple blocks, or, dividing a complicated object into small and manageable pieces. Application of this simple idea can be found everywhere in everyday life, as well as in engineering [20]. The division into elements may partly correspond to natural subdivisions of the structure. FEA is the most widely applied computer simulation method in engineering.

The use of finite element analysis (FEA) for simulation possesses in technology is currently increasing mainly because of its speed, accuracy and cost effectiveness. Numerical solutions to very complicated stress problems can be obtained routinely using FEA, thus the need to simulate the ECAE process so as to understand the stress and strain distribution in Aluminum 6063 alloys during the process. The diversity of element types, material models, formulations and solvers available in most of the commercial and non-commercial finite element codes, makes FEA suitable for investigating the ECAE process of materials such as Al 6063 [21].

2. METHODOLOGY

The simulation of Equal Channel Angular Extrusion was done using a Finite Element Analysis (FEA) based application - the Automatic Dynamic Incremental Nonlinear Analysis (ADINA®) software.

Preprocessing: The ADINA® environment for the ECAE model was created with the ADINA® user interphase (AUI) version 8.6 (900 nodes) on a personal computer. The "ADINA® structure" program module was used.

The geometry of the die and billet used for the ECAE experiment was plotted on an X-Y scale graph so as to obtain the points and lines needed for the model. The geometry of these points and lines which made up the die of 90^o inner angle (∅) and billet were then defined in the AUI. The model was then developed.

The properties (Young Modulus, Initial yield stress) of unextruded Al 6063 were gotten experimentally and recorded in the model. The Poisson's ratio was obtained from literature.

These properties were fed into the model so as to use them in defining the properties of the billet in the model. The billet's Young's Modulus is 4704.27 Mpa, Poisson ratio is 0.33, yield stress is 92.00 MPa and the strain hardening modulus of 1768.52 MPa.

1. The die was defined as a rigid material.
2. In the simulation, the following assumptions were made:
3. The material was initially homogeneous.
4. The material is bilinear elastoplastic material (a material with both elastic and plastic behaviours).
5. The von Mises flow rule is used to construct the constitutive relation.
6. There is no friction between the surface of the material and the die wall due to the use of lubricant in the ECAE [2-3].

The model was meshed by dividing it into little sub problems that can be formulated easily. The billet was meshed by dividing the vertical and horizontal geometry into 30 and 4 elements respectively. A total of 120 elements were used. The contact planes were also meshed with 3 nodes per segment. The total number of nodes used was 579. Size of the mesh fineness chosen was such that distortion or divergence in elements during simulation was avoided. The meshing was done in such a way that the mesh density is not too low or too high.

Load was set on the billet in the die in form of displacement downwards in the vertical direction. The ram speed used was constant at 0.02 mm/s.

Formed bodies are in contact condition with dies or tools during forming process, therefore the lines, points and edges in the geometry whereby contacts between the die and the billet will occur during the ECAE process were defined. The billet was then pushed through the die once.

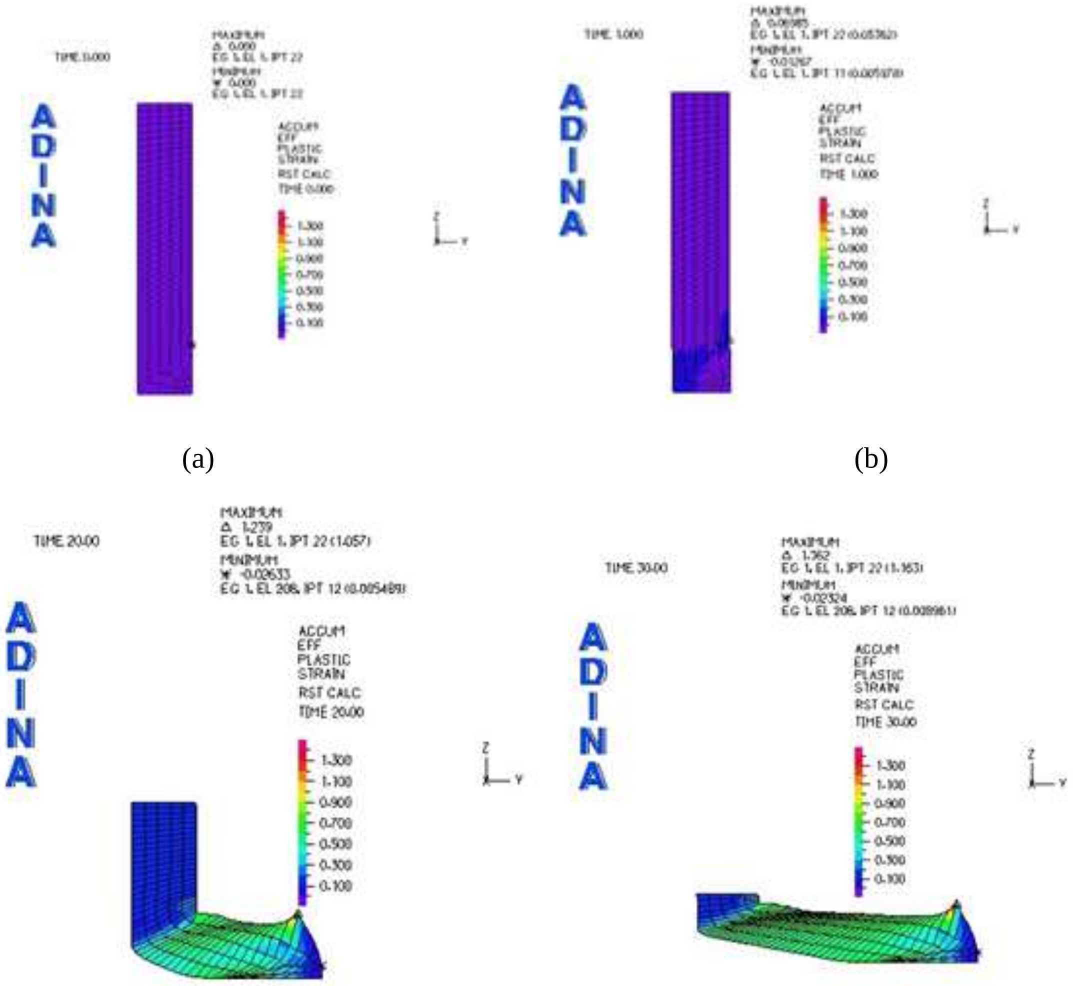
Analysis: The data earlier captured in the preprocessing stage was now used as the input code for ADINA® processor. The ADINA® processor then solved the nonlinear problem at every node during the deformation process. The analysis was done by the ADINA® software. Effective strains (ε_N) were automatically calculated using Equation 1 above.

Post processing: The program module was then changed to post processing module whereby the ECAE process was played and the final extrusion result was displayed on the screen. A snapshot was done and this was saved accordingly. The billets properties at the different nodes in the inner (billet part close to the inner sharp corner of the die), middle (billet part in the middle of the billet) and outer part (billet part close to the outer corner of the die) of the billets were recorded and studied for further analysis and inferences.

3. RESULTS AND DISCUSSION

Figures 2 and 3 show the results from ADINA® showing the distributions of equivalent plastic deformation (stresses and strains) after the ECAE process.

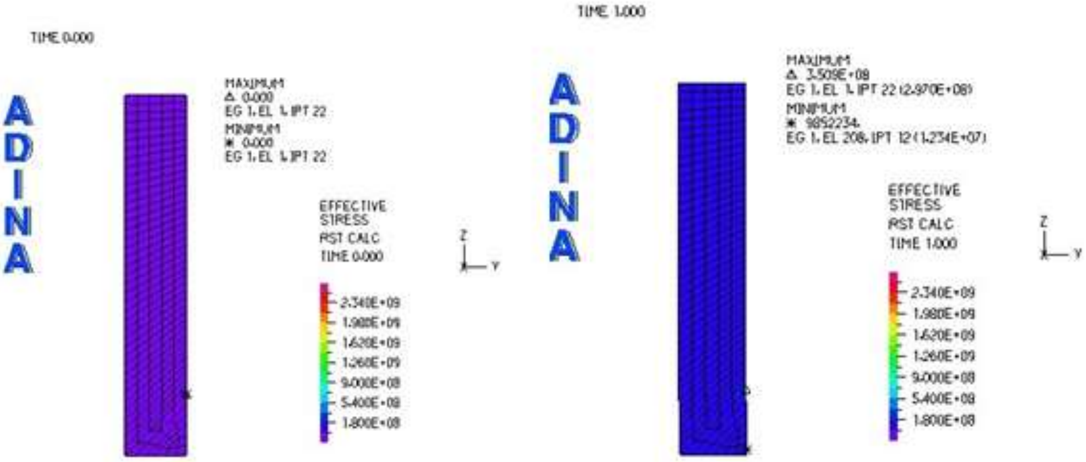
It was observed that plastic deformation is non-uniformly distributed along the cross-section and also the length of specimen. Along the work-piece length, the plastic deformation is divided into three deformation areas which are the head, the body and the tail of the billet. The head was where non-uniformity of plastic deformation is caused by non-uniformly material flow during junction from vertical to horizontal canal, the body was where there is steady state of plastic deformation and the tail where the non-uniformity of plastic deformation is related to the uncompleted pressing of specimen during the exit channel. It was noticed that the non-uniformity of plastic deformation concentrated to the bottom part of the work-piece, this supports Lapovok's and Basavaraj et al's findings [22-23] using other softwares which contradicts early believes that ECAE was a uniform deformation process.



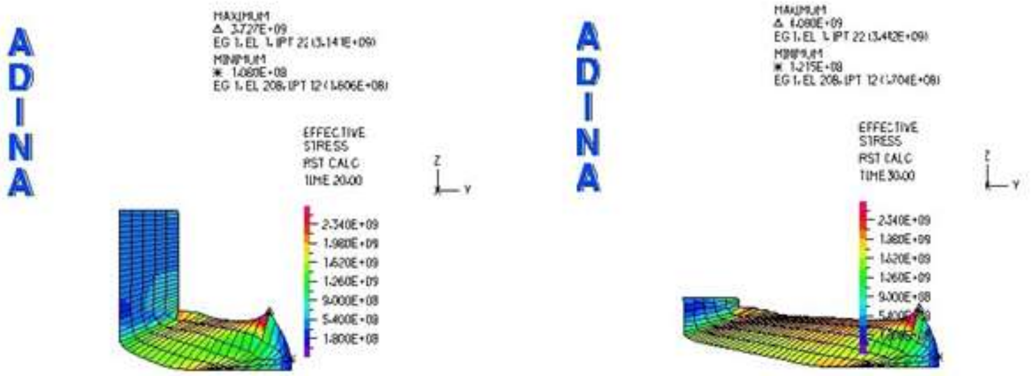
(a) (b)

(c) (d)

Figure 2 Distribution of accumulated effective plastic strain at different times for Ø = 90o(a)Initial stage (b) after 1 second (c) after 20 seconds (d) after 30 seconds



(a) (b)



(c) (d)

Figure 3 Distribution of effective stress at different times for Ø = 90 ° (a) Initial stage (b) after 1 second (c) after 20 seconds (d) After 30 seconds

From Figure 2b and 3b, it was observed that deformation started around the place where the billet makes a contact with the inner corner of the die. Further pushing of the billet leads to growth in the deformation and the formation of uniform band as shown in Figures 2 and 3 (c-d). A dead zone which shows where the material is stress free was noticed at the inner corner that came out first in the exit channel. It was also observed that the shape of each rectangle from the mesh changed to trapezoidal shape at the end of the ECAE.

Table 1 shows the properties of the billet obtained from the simulation and figures 4 and 5 show the effective strain and stress present on the nodes at the end of the ECAE.

Table 1 Properties of the billet obtained from the simulation

Inner Die Angle	Part of billet with respect to the inner angle of the die	Average Effective Stress (Mpa)	Average Accumulated Effective Plastic Strain	Average yield stress (Mpa)
90 °	Inner	203.08	0.67	204.19
	Middle	178.02	0.59	181.22
	Outer	178.37	0.58	178.37

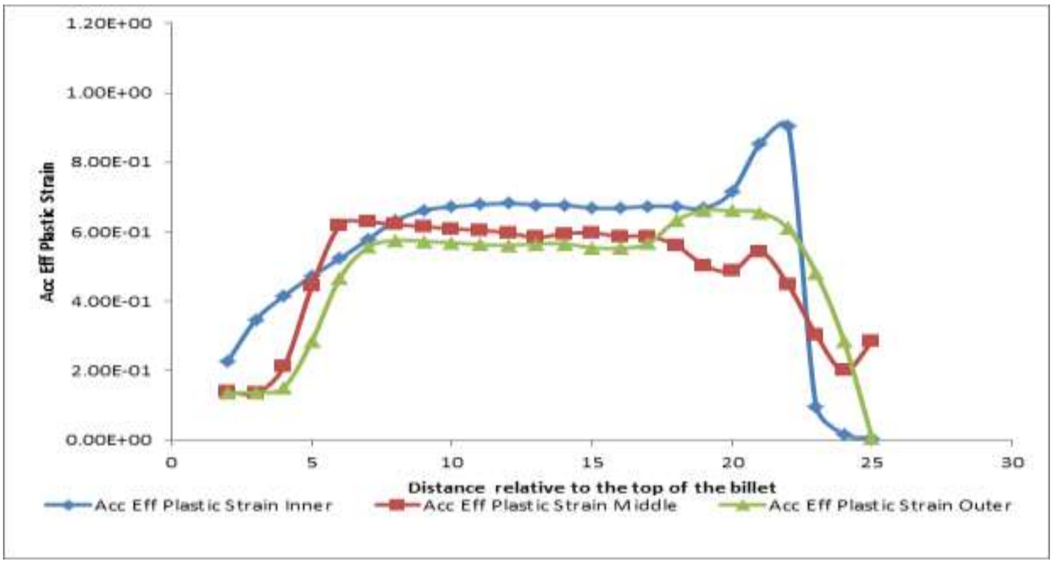


Figure 4 The effective strain present on the nodes at the end of the ECAE

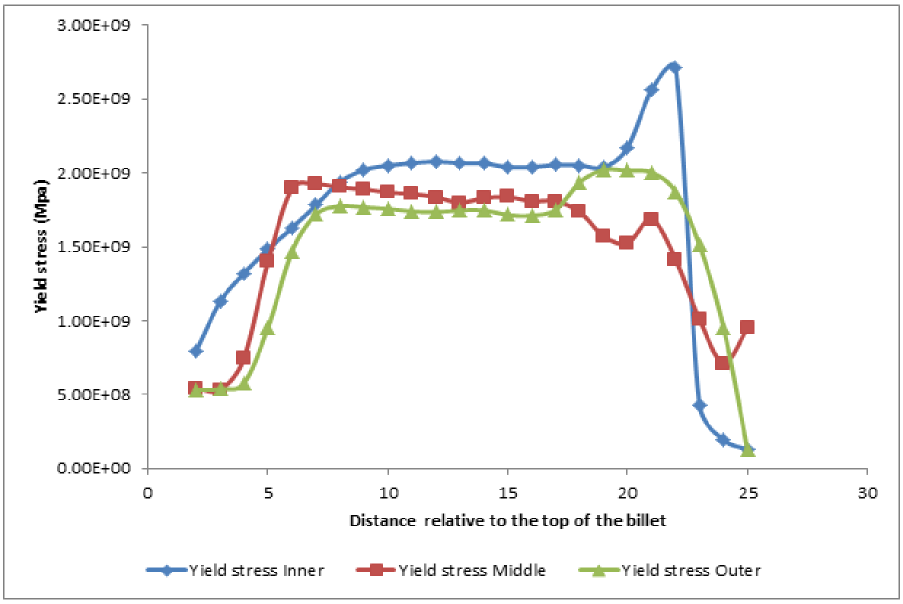


Figure 5 The effective stress present on the nodes at the end of the ECAE

From the simulation, as shown in Figures 4 and 5, the effective plastic strain and stress induced by the ECAE at 90^o and 120^o are not uniform though these were relatively uniform around the core centre of the billet. From obtained results showing the effective plastic stress and strain, it could be seen that there were higher straining and stresses in the points situated in the edge of work-piece passing over the inner die (inner part of the billet) than in the other parts (especially the part contacting the outer part of the die) of the work-piece.

4. CONCLUSION

From the simulation, ECAE process helps to improve the yield strength of Al 6063. Strengthening of material was caused by grains refinement and strain hardening of solid solution.

Also, the horizontal analysis of a billet shows that average effective stress, yield stress and effective plastic strain was maximum at the part of the billet which contacted the sharp inner corner of the die. They decreased towards the part of the billet contacting the outer part of the die. Due to this, the part of the billet closer to the die corner shows more strain and stress being distributed than the billet part close to the outer part of the die.

Moreover, vertical analysis of the billet shows that the first and last part of the billet extruded has the minimum stress and strain distribution. This confirms that deformation via ECAE is a non-uniform (i.e. inhomogeneous) type of deformation.

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