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THE PORTEVIN-LE CHÂTELIER EFFECT IN A RHEOCAST Al-Si-Cu ALLOY

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Abstract

The plastic instability phenomenon Portevin-Le Châtelier effect (PLC) was investigated in a Rheocast Al-Si-Cu alloy. The effect of strain rate under as-cast, solution treated and water quenched as well as artificially aged conditions was studied. Tensile tests were conducted at room temperature at different strain rates ranging from 10-5 to 10-1 (1/s). The nature and type of PLC effect were identified and analyzed. The results showed that the PLC effect changed with strain rate. Heat treatment of the material, widened the range of strain rates exhibiting PLC as well as changed the nature of the PLC effect.

Introduction

The Portevin-Le Châtelier (PLC) effect is a plastic instability in stress / strain behavior resulting in localized deformation in a moving deformation band. PLC manifests itself as serrations or steps in the plastic region of the stress strain curve [1, 2]. The PLC effect reduces ductility but increases the strength of the material [3]. There are two main appearances of the PLC effect on the stress-strain curves depending on which type of machine that was being used. The grain orientation influences the deformation bands and in polycrystalline materials deformation may propagate around the grains rather than through them [4].

There are three different types of PLC deformation band behaviors, type A, B and C. The definitions of the different types are;

- Type A, continuous band propagation of the whole length of sample, occurs at high strain rates [5,6]. Generally this type of serration has its top above the curve and its lowest point under the curve [7].
- Type B, intermediate (between type A and C) band propagation and strain rate [5,6]. This type of serration has its highest and lowest point in the same way as type A [7]. Compared to type A, type B will exhibit more serrations in the region where the band propagates. Similar to type A it will have the same distinct start and stop of a band propagation [2].
- Type C, occurs at low strain rates with random and more frequent nucleation of bands. Serrations with some plasticity with reload [2,5,6]. For type C the serration only occurs as a stress drop and has its highest on the curve and the lowest under the curve [7].

In types A and B there is a nucleation of a new band for every sharp serration. Type C is following more random patterns. For every new nucleation of a type C band there will be a sharp serration. Since the nucleation is random and occur more often for type C bands the sharp serration will occur more regularly [2].

A material can experience all types of the PLC effect depending on strain rate or temperature. The appearance of PLC effect can also change with different heat treatment. The material can have type A behavior but with decreased strain rate it will first change to type B and then if the strain rate keeps decreasing it will change to type C behavior. The material will experience the same transformation with increased test temperature [2,5].

Critical strain is the strain for onset of the PLC effect. There are three different types of behavior of critical strain vs. strain rate. The "normal" behavior is when the critical strain increases with strain rate and the opposite behavior is called "inverse". The third behavior is the occurrence of both "normal" and "inverse" [6]. In type A deformation behavior it is typical for the critical strain to behave in a "normal" way while type C will demonstrates "inverse" behavior. Type B will experience both "normal" and "invers" behavior [7]. The band strain behaves in the same way as the critical strain. In low stress range the band strain decreases with an increasing stress rate and in high stress ranges the invers behavior will occur [8]

Dynamic Strain Aging (DSA) is the most common explanation of the PLC effect. As a dislocation encounters an obstacle the solute atoms will be are concentrated in the matrix surrounding the around the obstacle further adding to the dislocation pinning force This pinning force is related to the stress amplitude of the serration and will increase with increased strain. The solute atoms diffuse as Schottky defects pairs, making vacancies a driving force for DSA. [1,2,6.9]. In Al-Si alloys the equilibrium vacancy concentration increases with increased amounts of dissolved Si atom [10,11]:

Negative strain rate sensitivity is a phenomena associated with DSA [12]. Strain rate sensitivity is a phenomenon where the stress flow is increased when the strain rate is increased. At a given temperature and strain the amount of stress will be higher for a higher strain rate [13]. The negative strain rate sensitivity is the reversed behavior, when the strain rate is decreased a higher strain is needed. This phenomenon is connected to the PLC effect and when the strain rate sensitivity turns negative the PLC effect starts [12].

The PLC effect in aluminum alloys depends on material composition and treatment. The most widely used main alloying elements investigated are Mg, Zn, Cu and Si. Depending on the concentration of these elements, the experienced PLC effect will vary [14]. Consistent with DSA, the solute atoms in aluminum alloys are responsible for the unstable flow and the PLC effect is increased with the increase of alloying elements [3]. This is true for a certain range of a concentration of elements depending on the alloy, treatments and test conditions [6,14]

The aim of the current study is to elucidate the occurrence of PLC in Rheocast Al-Si-Cu alloys in various conditions.

Experimental

Sample manufacturing

The material investigatedwas a Rheocast Al-alloy with composition shown in table 1. Samples were prepared from a Rheocast telecom component. The process used was the RheoMetal™ process set up in a standard High Pressure Die Casting (HPDC) manufacturing cell

Table 1. Alloy composition Alloy6 is Low Si, Alloy 1 is Medium Si and Alloy 3 is High Si

ID	Si (wt.%)	Cu (wt.%)	Mg (wt.%)	Fe (wt.%)	Mn (wt.%)	Zn (wt.%)
1	1.763	0.7	0.023	0.667	0.285	0.114
3	2.02	0.826	0.0227	0.785	0.334	0.099
6	1.428	0.63	0.03	0.658	0.281	0.107

Mechanical testing

The samples were tested in a tensile machine at constant cross-head speed. The tensile tests are conducted on a Zwick / Roell Z100 tensile machine at constant cross head speed. Elongation was measured by a Zink Clip-on extensometer. The samples were prepared according to ASTM B557 [15].

Heat treatment

JMatPro™ [16] was used to establish the heat treatment temperatures. Solution treatment at 400°C was chosen to dissolve the Cu bearing phase and ageing at 150°C was chosen as the Cu bearing phase showed maximum fraction. The aged samples were solution treated prior to aging. The duration for both solution treatment and aging was 24 hours in an effort to come close to equilibrium. The dissolved amount of Si could be considered constant for all heat treatments based on the JMatPro™ analysis.

Results and discussion

Occurrence of PLC

Not all samples exhibited clear PLC effects under all conditions. The type and occurrence of the PLC effect are summarized in table 2. Mixed mode behavior with Type A and B were found under several conditions. A serrated patter was also found at high strain rate in the as cast condition but did not display the characteristic stress drop necessary for Type C and it was thus not conclusive that Type C was found. It should here be noted that the solution treatment appears to stabilize Type A, suggesting that Si in solution promotes Type A, Figure 1. This also implies that Si would make the material prone to display Type B. The findings are also consistent with literature as Type B appears at lower strain rates. [2,5].

Negative strain rate sensitivity was present in composition 1 and 6 but not in composition 3. This indicated that the strain rate response was connected to alloy composition. The largest negative strain rate sensitivity was found in Alloy 6 with the lowest amount of alloying elements. Composition 3 has the highest amount of alloying elements but did not display a negative strain rate sensitivity. According to the literature the negative strain rate sensitivity should be more prominent with a stronger DSA effect [12]. The occurrence of the PLC effect for the different alloys are collated in table 3.

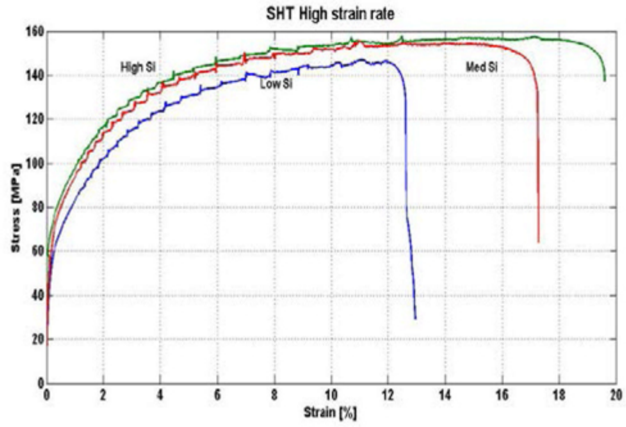

Figure 1. Illustration of the PLC effect at the three different Si-levels in soulution treated condition

Table 2. Illustrations of how the PLC effect was changing type with strain rate and states. "-"indicates that no sample were tested under that particular condition.

Strain rate (1/s) / State	10^{-5}	$5*10^{-5}$	10^{-4}	10^{-3}	10^{-2}	10^{-1}
As-cast	Ser-rations	A and B	A	A	Ser-rations	No PLC
Solution treated	B	-	A/B	A	-	No PLC
Aged	A and B	-	A	A	-	No PLC

Table 3. The PLC effect as a function of strain rates and composition. A bar is marking that no test had been conducted.

Strain rate (1/s) / Comp.	10^{-5}	$5*10^{-5}$	10^{-4}	10^{-3}	10^{-2}	10^{-1}
1	B	B	-	A	-	-
3	A and B	-	A	A	-	-
6	Ser-rations	A	A/B	A	Ser-rations	No PLC

The amount of solute atoms was largest in the as-cast state and there was almost no solute atoms in the aged treated samples, assuming that the temperatures and times applied in the heat treatment cycles have been enough to dissolve, homogenize and precipitate the Cu-bearing phases. This should have given the largest negative strain rate sensitivity in the as-cast samples. Between the different compositions there was not any significant difference in solute atoms. It was only in the solution treated samples that a difference in solute atoms could be seen between compositions and the largest amount belonged to composition 3. If the amount of solute atoms would be the driving force behind the DSA mechanism in the Rheocast material, the negative strain rate sensitivity should have been greatest for composition 3 of the solution treated samples.

The increase of solute atoms should make it easier to pin down dislocations and give a negative contribution to the strain rate sensitivity. Since the results from the negative strain rate sensitivity investigations was conflicting with the DSA mechanism an investigation of the vacancy concentration was conducted. The vacancy concentration increases the diffusivity which could lead to more effective hindering of the dislocations. Since the Rheocast material did not show negative strain rate sensitivity in composition 3, but in the other compositions, the vacancy concentrations for the different compositions was investigated. It should also be noted that increased amounts of dissolved Si increases the amount of vacancies [10]. This means that the largest amount of solute atoms and the fastest diffusivity both were found in composition 3.

Analysis of the nature of the PLC effect

In this section the samples tested with a strain rate below 10^{-4} 1/s will be referred to as Low strain rate samples showing a mixed mode behavior and samples teste at 10^{-3} 1/s will be referred to as High strain rate samples.

In order to investigate the nature of the PLC effect it is important to understand the pinning force and the energies associated with actually passing the obstacles. Two different measures were taken to assess this. The largest difference between the maxima and the minima in a band used to investigate the magnitude of the dislocation pinning force. Similarly, the total area of deviation from the local ideal stress strain curve for a single PLC event was seen as a measure of the total energy associated with the work to pass the obstacles. It should here be noted that it is the absolute value of the energy that was taken as a measure including both positive and negative deviation from the ideal line.

The pining force in the As-cast state passes through a maximum with increasing strain, Figure 2a, associated with Type A, whilst at low strain rate this maxima is not seen. A low strain rate also appears to be associated with a slightly lower pinning force as well, Figure 2b. There is no clear relation between the pinning force and the amount of Si nor between the types as the Medium Si displays Type B and Low Si displays Type A at low strain rate.

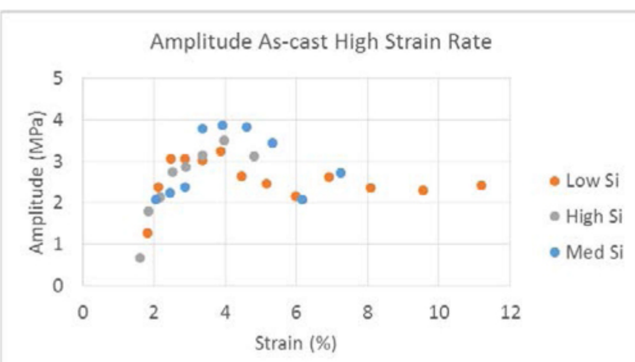

Figure 2a. Maximum peak to peak amplitude in the as-cast state at a strain rate of 10^{-3} 1/s.

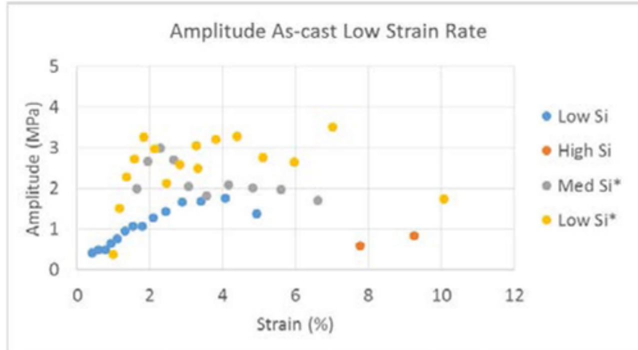

Figure 2b. Maximum peak to peak amplitude in the as-cast state at a strain rate of 10^{-5} 1/s and 5 10^{-5} 1/s (*).

Doing a solution treatment of the material completely changes the nature of the pinning force. At high strain rate, the material exhibited Type A PLC effect and the pinning force increased with increased strain Figure 3a. The difference between the as-cast state and the heat treated state is the amount of Cu dissolved in the matrix phase. This effect is not seen at low strain rate where the pinning fore displays a maximum again with increasing strain. This suggests that Cu has a strong deformation rate effect on the DSA mechanism. Extrapolating data for diffusivities down to room temperature shows that the diffusivity of Si is more than 80 times higher than that of Cu [17].

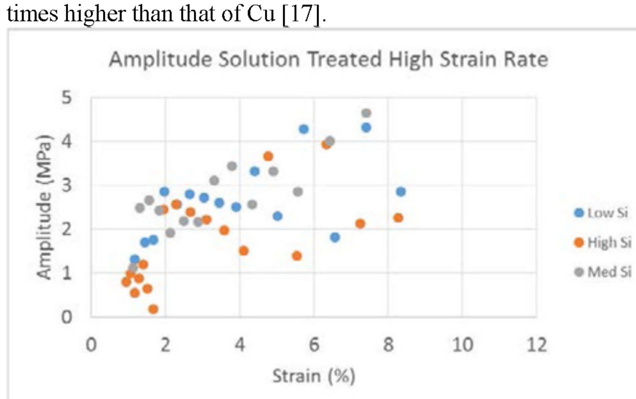

Figure 3a. Maximum peak to peak amplitude in the solution treated state at a strain rate of 10^{-3} 1/s.

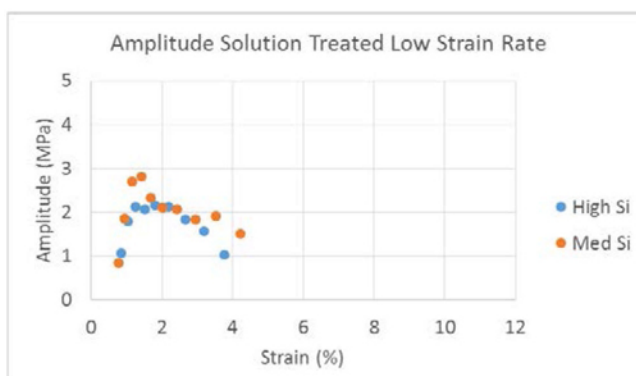

Figure 3b. Maximum peak to peak amplitude in the solution treated state at a strain rate of 10^{-5} 1/s.

The aging treatment will precipitate minor amounts of Cu bearing phases. There was no strong effect confirming this fact. The as-cast state did show the highest strength. This was also reflected in the Amplitude suggesting a more or less unaltered pinning force between the solution treated and the aged stated, Figure 4a and 3b for high and low strain rate respectively.

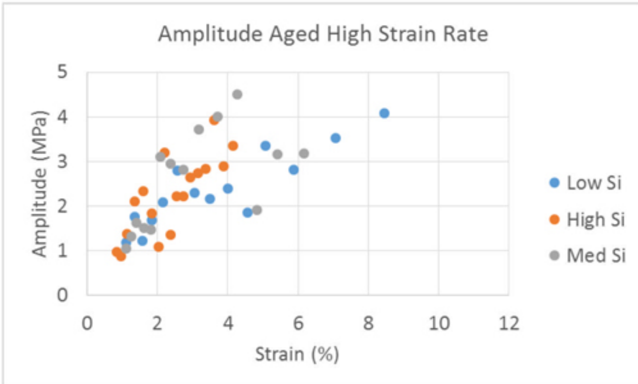

Figure 4a. Maximum peak to peak amplitude in the aged state at a strain rate of 10^{-3} 1/s.

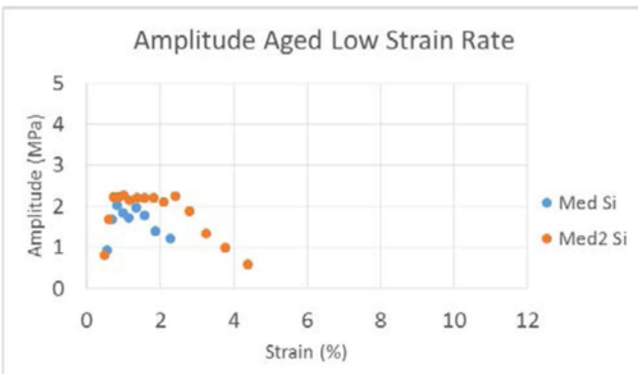

Figure 4b. Maximum peak to peak amplitude in the aged state at a strain rate of 10^{-5} 1/s and 5 10^{-5} 1/s (2).

Taking the energy or work to overcome the obstacles adds the strain accumulation associated with the PLC effect in addition to the actual amplitude discussed ab. In the as cast state for high strain rate the energy shows the same pattern as for the amplitude but the separation between the alloys is greater, Figure 5a. For low strain rate the scatter appears less. The minimum energy for the high strain rate corresponds to the energy level that develops in the low strain rate samples.

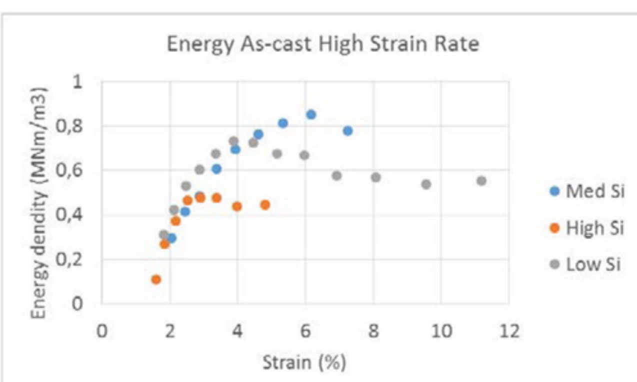

Figure 5a. Energy release associated with the PLC effect in the as-cast state at a strain rate of 10^{-3} 1/s.

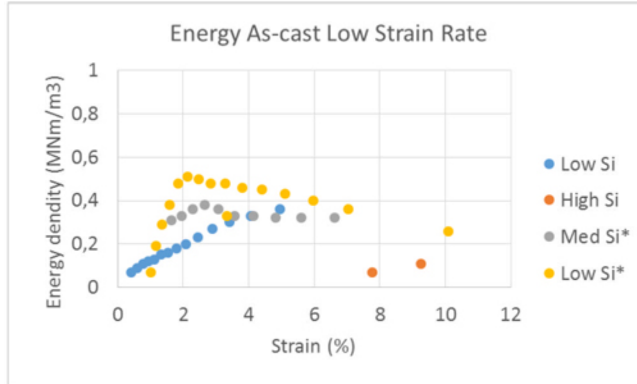

Figure 5b. Energy release associated with the PLC effect in the as-cast state at a strain rate of 10^{-5} 1/s and 5 10^{-5} 1/s (*).

Heat treatment gave an increasing pinning force at high strain rate but for the energy approach a constant steady energy level is seen in the range 1.2-0.4 MNm/m^3 for Type A, Figure 6a. The same level was reached for low strain rate testing, Figure 6b.

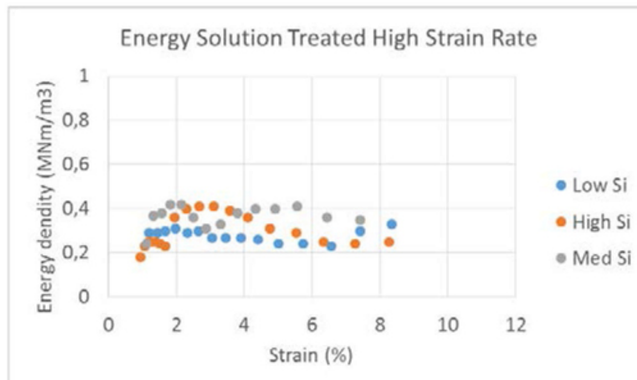

Figure 6a. Energy release associated with the PLC effect in the solution treated state at a strain rate of 10^{-3} 1/s.

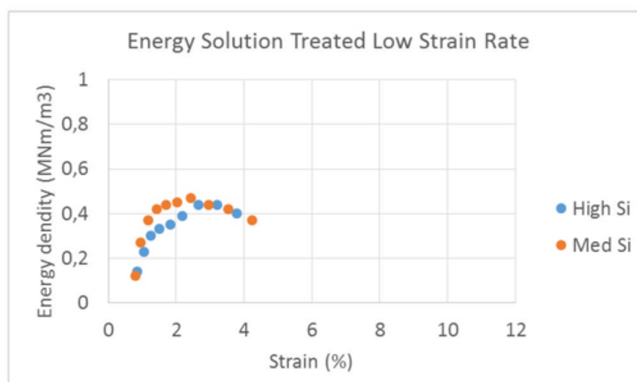

Figure 6b. Energy release associated with the PLC effect in the solution treated state at a strain rate of 10^{-5} 1/s and 5 10^{-5} 1/s (*).

The amplitude or pinning force was more or less unaltered between the solution treated and the aged conditions but the energy measure reveals a different pattern. In the solution treated state at high train rate the energy was independent of strain. This was not the case for the aged condition where the energy increased with strain, Figure 7a. In addition to this, the actual energy levels were almost returned to the high levels of the as cast state, Figure 5a. At low strain rate, the appearance of the energy levels, in both the solution treated and the aged conditions, were similar, Figure 6b and 6b respectively. This again suggests that Cu has a deformation rate sensitivity effect.

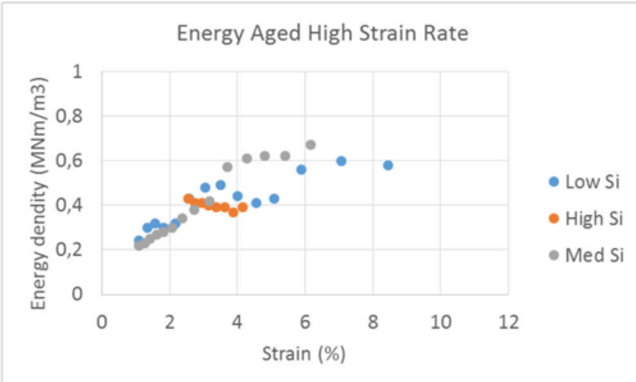

Figure 7a. Energy release associated with the PLC effect in the aged state at a strain rate of 10^{-5} 1/s.

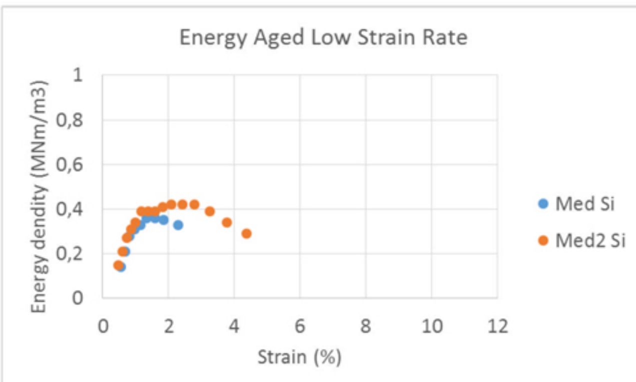

Figure 7b. Energy release associated with the PLC effect in the aged state at a strain rate of 10^{-5} 1/s and 5 10^{-5} 1/s (2).

Based on the JMatPro^{TM} equilibrium calculations, it is suggested that aged samples have Al_2Cu precipitates. It is also suggested that this phase was precipitated during casting and that the solution treatment dissolved this phase. The increase in energy to overcome obstacles may originate from the precipitates suggesting a complex interaction between precipitates and the DSA mechanism where particles add to the work in the PLC related steps and serrations but not to the amplitude or pinning force.

Conclusions

The fact that PLC can occur in Rheocast aluminium alloys in the as-cast condition is an interesting finding by itself, not previously reported.

The actual events in the material clearly illustrate that there is an interaction between the DSA mechanism and particle precipitated. For Cu in particular this has consequences for the deformation rate dependence of the PLC effect.

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