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ARTICLE

Hot Processing Map and Hot Rolling Experiment of Ti-Al Clad Plate

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Abstract: The hot deformation behavior of explosive welded titanium-aluminum (Ti-Al) clad plate was studied by isothermal compression tests at 300~500 °C with strain rates of 0.1~10 s^{-1} on Gleeble 3500 simulated machine. The hot processing map was developed on the basis of experimental data using the principles of dynamic materials model, and the verification experiment of hot rolling process of Ti-Al clad plate was carried out based on the hot processing map. The results show that Ti-Al clad plate is a kind of positive strain rate sensitive material. The efficiency of power dissipation of 0.64~0.72 can be observed at 420~460 °C with strain rate of 1.6~6.3 s^{-1} in the hot processing map, and the process parameters of this region are suitable for the hot rolling of Ti-Al clad plate. After hot rolling, the interfaces of the Ti-Al clad plates are well bonded, and the plates have excellent mechanical property and good sheet metal forming property. The deformation mechanism of Ti-Al clad plate in the hot rolling process is as follows: the Al layer with low deformation resistance and fast flow can produce plastic deformation, and at the same time it can pull the Ti layer together to produce plastic deformation; in this process, the Al layer is hot deformation while the Ti layer is cold deformation.

Key words: Ti-Al clad plate; hot processing map; hot rolling; traction deformation

Titanium has many excellent properties, such as low specific gravity, high specific strength, good corrosion resistance, and high temperature impact resistance. It has been widely used in aviation and aerospace, but it is expensive. Although aluminum has low price, low specific gravity, high specific strength and specific stiffness, its corrosion resistance and high temperature impact resistance are relatively poor, so it cannot be used alone in high temperature and corrosive environment. Titanium-aluminum (Ti-Al) clad material has the characteristics of low specific gravity and high thermal conductivity of aluminum and excellent high temperature resistance and corrosion resistance of titanium. Therefore, Ti-Al clad plate has a very broad development and application prospect in aviation, aerospace and other fields[1,2].

At present, many studies have been conducted on the preparation, microstructure and properties of Ti-Al clad plate. Xia[3] and Henryk[4] studied the microstructure and mechanical properties of the explosive welded Ti-Al clad plate, and found that the explosive welded Ti-Al clad plate has a wavy composite interface. No intermetallic compounds are found at the interface and the diffusion area is very short. The tensile and bending properties of the clad plate are good. Zhang[5] hot rolled the explosive welded Ti-Al clad plate and prepared the Ti-Al clad sheet. Xiao[6] prepared Ti-Al clad plate by differential temperature rolling method. Ti plate and Al plate achieved strong metallurgical combination under high pressure and high temperature. The research of Gao[7] and Lazurenko[8] on the heat treatment process of Ti-Al clad plate showed that the diffusion heat treatment can significantly improve the interface bonding strength of Ti-Al clad plate. Xu[9] and Lee[10] studied the interface structure and properties of Ti-Al clad plate, and found that there are intermediate phases composed of TiAl and $TiAl_2$ at the interface of the clad plate. However, the basic research on the hot deformation behavior of Ti-Al clad plate is still limited. In this work, the hot deformation behavior of Ti-Al clad plate was studied by isothermal compression tests on Gleeble 3500 simulated machine, and the hot processing map was developed on the

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basis of experimental data using the principles of the dynamic materials model, and the verification experiment of hot rolling process of Ti-Al clad plate was carried out based on the hot processing map. All these research work may provide a definite reference for designing hot rolling process of Ti-Al clad plate in industry.

1 Experiment

The hot compression test material was explosive welded Ti-Al clad plate with a thickness of 4.7 mm, in which the titanium plate was TA1 and the aluminum plate was 2A12 aluminum alloy coated with 0.25 mm thick pure Al layer, and its chemical composition is shown in Table 1. After annealing at 450 °C for 4 h, the experimental material was straightened and polished, and then wire cut and circumferential grinding were carried out to produce cylindrical samples of Φ6 mm× 4.5 mm. Two cylindrical samples were combined in the form of Al-Ti-Ti-Al to obtain a hot compression specimen of Φ6 mm× 9 mm, as shown in Fig.1.

Hot compression tests were carried out on a Gleeble-3500 simulator. The experimental temperature was 300, 350, 400, 450 and 500 °C, the strain rate was 0.1, 1, 5 and 10 s^{-1}, and the true strain was 0.7. The sample was heated to the preset temperature at a speed of 10 °C/s and held for 3 min before compression test. Immediately after the compression, the sample was cooled to room temperature by water. The experimental material for hot rolling experiment was explosive welded Ti-Al clad plate with a size of 400 mm×500 mm×4.7 mm.

2 Results and Discussion

2.1 True stress-true strain curves and hot deformation behavior

The data of deformation temperature, strain rate, true strain and flow stress during hot compression deformation of Ti-Al

Table 1 Chemical composition of 2A12 and TAl plate (wt%)

2A12	Si	Fe	Cu	Mn	Mg	Al
	0.14	0.16	4.26	0.67	0.92	Bal.
TA1	Fe	O	N	H	C	Ti
	<0.01	0.050	0.0055	0.0019	0.014	Bal.

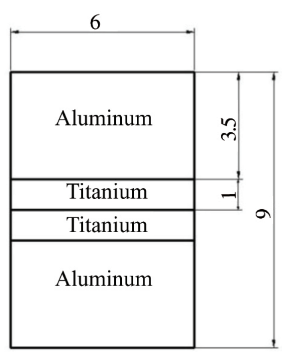

Fig.1 Size of hot compression specimen of Ti-Al clad plate

clad plate were collected by computer, and the true stress versus true strain curves of hot compression deformation of Ti-Al clad plate under different conditions was drawn, as shown in Fig.2. It can be seen that the deformation resistance of Ti-Al clad plate is relatively small on the whole. When the strain rate is 1 s^{-1} and the deformation temperature is 450 °C, the deformation resistance is about 90 MPa.

It can also be seen from Fig.2 that the flow stress of Ti-Al clad plate is greatly affected by strain rate and deformation temperature. The flow stress increases with the increase of strain rate and decreases with the increase of deformation temperature, which indicates that the Ti-Al clad plate is a kind of positive strain rate sensitive material.

2.2 Hot processing map of Ti-Al clad plate

The value of flow stress at a strain of 0.5 was collected from the true stress versus true strain curves (Fig.2), and the relation between lgσ and lg$\dot{\varepsilon}$ was fitted by cubic function at a certain temperature, as shown in Eq.(1). The values of a, b, c and d can be calculated by the experimental data and regression analysis. Using Eq. (2), the strain rate sensitivity parameter m at a certain temperature was obtained. According to Eq. (3), the efficiency of power dissipation η can be obtained, and the power dissipation map can be developed by the method of interpolation, as shown in Fig.3a. Using Eq.(4), the values of $\xi(\dot{\varepsilon})$ were obtained, and the flow instability map can be developed by the method of interpolation, as shown in Fig. 3b. By superimposing of flow instability map on the power dissipation map, hot processing map is developed and shown in Fig.4.

$$\lg\sigma=a+b\lg\dot{\varepsilon}+c(\lg\dot{\varepsilon})^2+d(\lg\dot{\varepsilon})^3 \quad (1)$$

$$m=\frac{\partial(\lg\sigma)}{\partial(\lg\dot{\varepsilon})}=b+2c\lg\dot{\varepsilon}+3d(\lg\dot{\varepsilon})^2 \quad (2)$$

$$\eta=\frac{2m}{m+1} \quad (3)$$

$$\xi(\dot{\varepsilon})=\frac{\partial\lg\frac{m}{m+1}}{\partial\lg\dot{\varepsilon}}+m=\frac{2c+6d(\lg\dot{\varepsilon})}{m(m+1)\ln 10}+m<0 \quad (4)$$

In the hot processing map, the contour numbers represent percentage of efficiency of power dissipation and the shaded domain indicates the region of flow instability (the valves of ξ are negative). The map exhibits a small region of flow instability and a region of peak efficiency of power dissipation. The region of flow instability is mainly distributed in the temperature range of 470~500 °C and the strain rate range of 1~10 s^{-1}. The region of peak efficiency of power dissipation occurs in the temperature range of 420~460 °C and strain rate range of 1.6~6.3 s^{-1}, with an efficiency of power dissipation of 0.64~0.72. According to the hot processing map, the region suitable for the hot deformation of Ti-Al clad plate is in the temperature range of 420~460 °C and strain rate range of 1.6~6.3 s^{-1}.

2.3 Hot rolling of Ti-Al clad plate

2.3.1 Hot rolling process of Ti-Al clad plate

According to the experimental results of hot compression test, the preheating temperature of hot rolled billet of Ti-Al

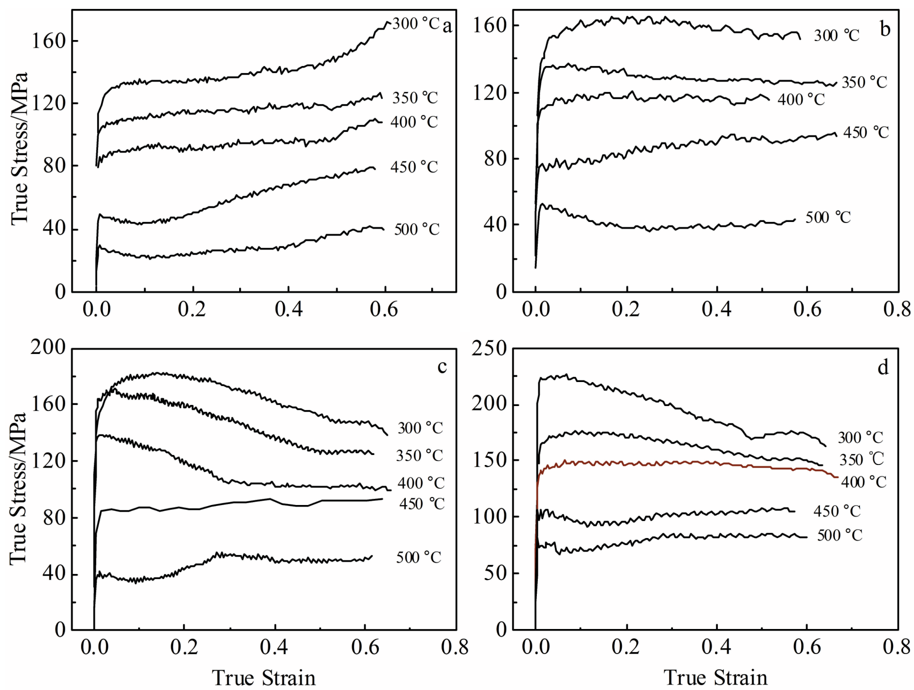

Fig.2 True stress-strain curves of Ti-Al clad plate obtained from hot compression test at different preset temperatures and strain rates: (a) $\dot{\varepsilon}$=0.1 s^{-1}, (b) $\dot{\varepsilon}$=1 s^{-1}, (c) $\dot{\varepsilon}$=5 s^{-1}, and (d) $\dot{\varepsilon}$=10 s^{-1}

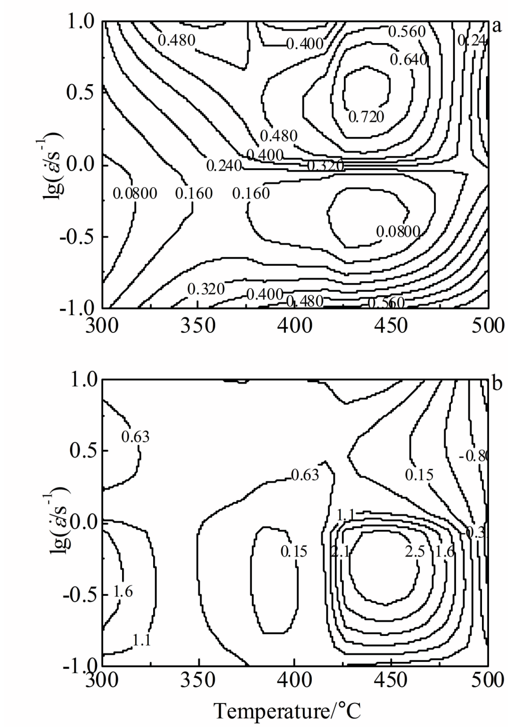

Fig.3 Power dissipation efficiency map (a) and instability map (b) of Ti-Al clad plate obtained at a strain of 0.5

clad plate is 450~460 °C (as it takes time for the billet to transfer from the heating furnace to the rolling mill, and there is a temperature drop for the billet, so the upper limit of preheating temperature is chosen), and the average strain rate is 3~4.5 s^{-1}. The hot rolling process parameters of Ti-Al clad

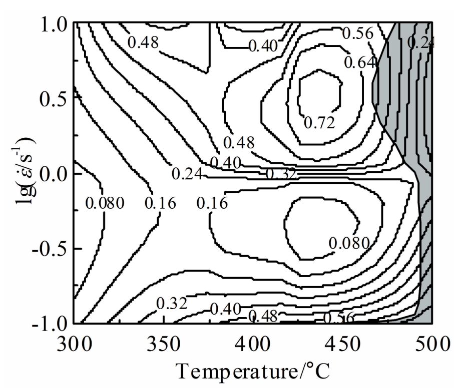

Fig.4 Hot processing map of Ti-Al clad plate obtained at a strain of 0.5

plate are shown in Table 2.

Under the above conditions, the Ti-Al clad plate with a thickness of 1.8 mm was successfully rolled, and the rolled plate has no cracks and good surface quality, as shown in Fig.5. Fig.6 shows the EDS composition line scanning of the composite interface of rolled plate on the scanning electron

Table 2 Hot rolling process parameters of Ti-Al clad plate

Form of billet	Preheating temperature of billet/°C	Thickness of rolled plate/ mm
Two explosive welded Ti-Al clad plates are symmetrically assembled (with Ti layer inside and Al layer outside)	450～460	9.4→5→3.6

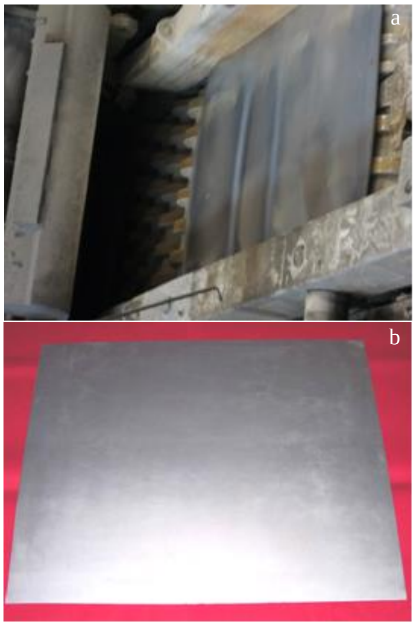

Fig.5 Hot rolled Ti-Al clad plate: (a) hot rolled plate, (b) plate after levelling

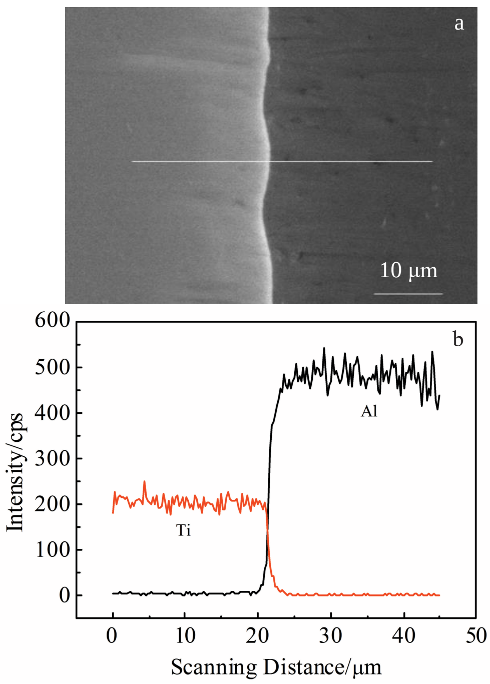

Fig.6 SEM image (a) and EDS line scanning results (b) of interface of Ti-Al clad plate

microscope. It can be seen that the atomic diffusion layer thickness of Ti element in the aluminum layer is about 2.5 μm, and the diffusion layer thickness of Al element in the titanium layer is about 1.5 μm, and the titanium-aluminum interface forms a good metallurgical bonding due to the mutual diffusion between atoms. Fig.7 shows the longitudinal section microstructure of the rolled plate. It can also be seen that the interface of the explosive welded Ti-Al clad plate is well

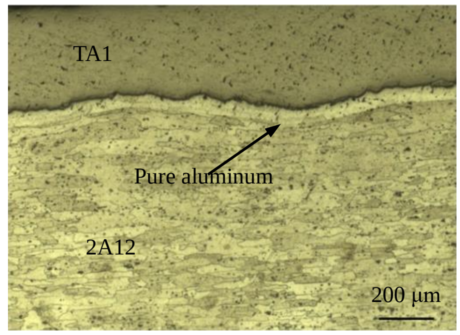

Fig.7 OM microstructure of longitudinal section for Ti-Al clad plate

bonded after hot rolling, and the grain structure of 2A12 is fine and uniform.

2.3.2 Deformation mechanism of Ti-Al clad plate during hot rolling

In the rolling process of Ti-Al clad plate, because the deformation resistance of Al layer is less than that of Ti layer, plastic deformation of Al layer will occur first as shown in Fig. 8. However, due to the constraint effect of explosive welding interface, the Ti layer also needs to deform together with the Al layer; otherwise the bonding interface between them will crack. Therefore, the deformation mechanism of Ti-Al clad plate in the hot rolling process is as follows: the Al layer with low deformation resistance and fast flow can produce plastic deformation, and at the same time it can pull the Ti layer together to produce plastic deformation.

Fig. 8 shows the stress-strain curves of TA1 pure titanium

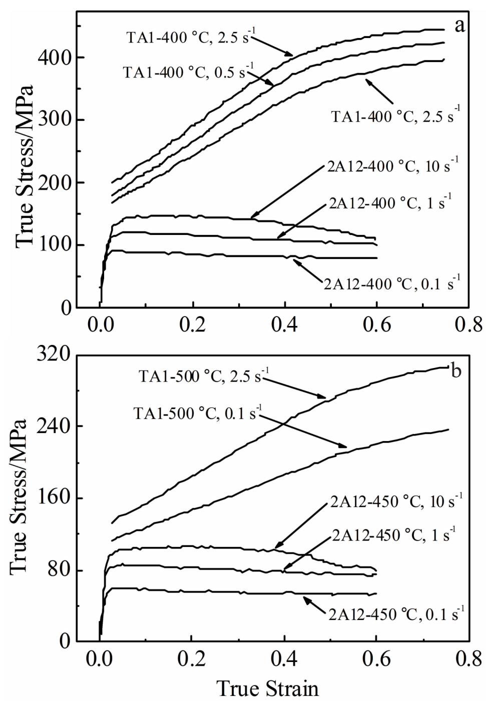

Fig.8 Stress-strain curves of TA1 pure titanium and 2A12 aluminum alloy during compression deformation: (a) 400 °C, (b) 450 °C (2A12) and 500 °C (TA1)

and 2A12 aluminum alloy during compression deformation under different deformation conditions[11,12]. It can be seen that under the selected deformation conditions, the 2A12 aluminum alloy experiences dynamic softening during the deformation process, while the TA1 pure titanium only experiences work hardening. Therefore, when the Ti-Al clad plate is rolled under the process parameters shown in Table 2, the Al layer has dynamic softening during the deformation process, and dynamic recovery or dynamic recrystallization will occur, which is a thermal deformation process. However, only work hardening occurs in the deformation process of Ti layer, which belongs to cold deformation process. Because of the cold deformation of Ti layer under the action of tensile stress, when the deformation degree is too large or the stress concentration occurs, the Ti layer is prone to crack.

2.3.3 Application performance analysis of Ti-Al clad plate

In practical application, the Ti-Al clad plate needs to have excellent mechanical property and good sheet metal forming property, so the mechanical property, bending property, cupping property and drawing property of hot rolled Ti-Al clad plate were tested.

Table 3 shows the mechanical property of rolled plates along the rolling direction of 0°, 45° and 90°, indicating excellent mechanical property. The bending property of the rolled plates is shown in Table 4 and Fig.9. No visible cracks appear when the sample is bent at 90° and 120°, showing good bending property.

According to GB/T 4156-1984, the cupping property of hot rolled Ti-Al clad plate was tested. The cupping test samples are shown in Fig. 10, and the average cupping value is 7.78, which indicates that the hot rolled Ti-Al clad plates have good bulging property. According to GB/T 15825.3-1995, the drawing property of hot rolled Ti-Al clad plate was tested. The drawing test samples are shown in Fig. 11, and the limit drawing coefficient m is 0.508, which indicates that the hot rolled Ti-Al clad plates have good drawing performance.

Table 3 Mechanical property of Ti-Al clad plate in different directions

Sample number	Tensile strength/ MPa	Yield strength/ MPa	Elongation/ %
0°-1	464	325	25
0°-2	462	323	24
45°-1	453	323	33
45°-2	454	325	32.3
90°-1	464	327	28.5
90°-2	463	326	27.5

Table 4 Bending property of Ti-Al clad plate

Sample number	Mandrel diameter/mm	Bending angle/(°)	Description of results
1	4.0	90	No visible crack
2	4.0	90	No visible crack
3	4.0	120	No visible crack
4	4.0	120	No visible crack

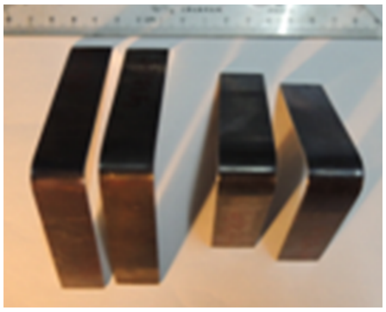

Fig.9 Bending test piece of Ti-Al clad plate

Fig.10 Cupping test piece of Ti-Al clad plate

Fig.11 Drawing test piece of Ti-Al clad plate

The composition distribution of microarea in Fig. 5, microstructure in Fig.6 and the above test results show that the Ti-Al clad plate rolled under the process parameters shown in Table 2 has perfect bonding interface, excellent mechanical property and good sheet metal forming property.

3 Conclusions

1) The flow stress of Ti-Al clad plate increases with the increase of strain rate and decreases with the increase of deformation temperature, indicating that the Ti-Al clad plate is a kind of positive strain rate sensitive material.

2) In the temperature range of 420~460 °C and strain rate of 1.6~6.3 s^{-1}, the efficiency of power dissipation of Ti-Al clad plate during hot deformation is 0.64~0.72, and the process parameters of this region is suitable for the hot rolling of Ti-Al clad plate. The hot rolling experiments of Ti-Al clad plate

show that the clad plates can be successfully rolled under these conditions, and the interfaces of the rolled plates are well bonded, and have excellent mechanical property and good sheet metal forming property.

3) There is a flow instability region in the hot processing map of Ti-Al clad plate which is mainly distributed in the temperature range of 470~500 °C and the strain rate range of 1~10 s^{-1}. This region should be avoided during the hot deformation process of Ti-Al clad plate.

4) The deformation mechanism of Ti-Al clad plate in the hot rolling process is as follows: the Al layer with low deformation resistance and fast flow can produce plastic deformation, and at the same time it can pull the Ti layer together to produce plastic deformation; in this process, the Al layer is hot deformation while the Ti layer is cold deformation.

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钛铝复合板热加工图及热轧实验

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摘　要：采用Gleeble-3500热模拟试验机进行高温等温压缩实验，研究了爆炸焊接钛铝复合板在变形温度为300~500 ℃、应变速率为0.1~10 s^{-1}条件下的热变形行为，利用动态材料模型构建了钛铝复合板热加工图，并基于热加工图进行了钛铝复合板热轧工艺验证实验。结果表明：钛铝复合板属于正应变速率敏感材料；在热加工图中变形温度为420~460 ℃、应变速率为1.6~6.3 s^{-1}时，功率耗散效率达到0.64~0.72，该区域对应的工艺参数适合进行钛铝复合板热轧；热轧后实验板材界面结合良好，具有良好的力学性能和钣金成形性能。钛铝复合板在热轧过程中的变形机制为：变形抗力低、流动快的铝层在自身发生塑性变形的同时牵引着钛层一起发生塑性变形，其中铝层是热变形，钛层为冷变形。

关键词：钛铝复合板；热加工图；热轧；牵引变形

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