

Study of extrusion, microstructure and mechanical properties of 5CrNiMo alloy reinforced with WC particles

Xianzhang Feng¹, Junwei Cheng², Xinfang Zhang²

¹School of Aerospace Engineering, Zhengzhou University of Aeronautics,
450046 Zhengzhou, Henan, P.R. China

²School of Materials Science and Engineering, Zhengzhou University of
Aeronautics, 450046 Zhengzhou, Henan, P.R. China

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In order to solve the problems of high toughness, poor thermal strength and low working temperature of 5CrNiMo, the influence of additives on the properties of 5CrNiMo (hot working die steel, which has high toughness, poor thermal strength and low operating temperature) has been studied. A compound composed of tungsten and carbon, with the molecular formula WC was added to 5CrNiMo and most of the WC particles were dissolved in the high temperature molten steel. During the eutectic reaction, the element W precipitates in the form of Fe_3W_3C . The matrix has a fine-grained pearlite structure in which a large amount of carbide particles are released *in situ*. The object of study is a guide rod with a hollow shaft made of 5CrNiMo reinforced with WC particles. The direct extrusion process is analyzed and calculated, and a simulated extrusion process is calculated to analyze the stress, deformation and damage of the metal during the forming process. The parts go through a heat treatment process of spheroidal annealing at 950°C and tempering at 600°C. Studies have shown that a large amount of carbides dissolve, a large amount of bainites are formed in the structure, and the effect of dispersion strengthening is achieved. The strength and hardness of the material is improved.

Keywords: heat treatment, microstructure, tempering, extrusion, working procedure.

Дослідження екструзії, мікроструктури та механічних властивостей сплаву 5CrNiMo, армованого частинками WC. Xianzhang Feng, Junwei Cheng, Xinfang Zhang

Проведено дослідження впливу домішок на властивості 5CrNiMo (штампова сталь для гарячої обробки, яка має високу ударну в'язкість, погану термічну міцність і низьку робочу температуру). WC додавали в 5CrNiMo, і більшість частинок WC розчинялася у високотемпературної розплавленої сталі. Елемент W випадає в осад у формі Fe_3W_3C в ході евтектичної реакції. Матриця має дрібнозернисту перлітну структуру, в якій виділяється велика кількість карбідних частинок *in situ*. Напрямний стрижень з порожнім валом з 5CrNiMo, армованого частинками WC, є об'єктом дослідження. Процес прямої екструзії проаналізовано та розраховано, також розрахованій імітований процес екструзії для аналізу напруги, деформації та пошкодження металу у процесі формування. Деталі проходять процес термічної обробки у вигляді сфероїдального відпала при 950°C та відпустки при 600°C. Дослідження показали, що велика кількість карбідів розчиняється, у структурі утворюється велика кількість бейнітів, досягається ефект дисперсійного зміщення. Міцність і твердість матеріалу покращуються.

1. Introduction

5CrNiMo has almost the same mechanical properties at room temperature and 500–600°C. When heated to 500°C, the hardness of HB300 can still be maintained. Since the steel contains molybdenum, it is not sensitive to temper brittleness. After cooling slowly from 600°C, the impact toughness decreased only slightly. This kind of steel has a tendency to form white spots. Due to the presence of various unfavorable factors, the hydrogen content of the steel may be high, so we need to study a new process to overcome the shortcomings of 5CrNiMo hot-worked die steel in application [1–6]. Large-scale die forging is the main production mode of load-bearing structural parts in the aerospace industry, and its production process is one of the important signs of the development of high-tech manufacturing industry. A large forging die is the main component of the cost and production cycle of large forgings. Since the die bears a huge load in using, it is prone to fracture, damage and deterioration of surface quality due to the friction between the to-be-formed body and the die itself [7].

The working conditions of a large-scale die for forging are harsh, and the quality requirements of cavity are high. At present, 5CrNiMo forgings are mainly produced by quenching and tempering heat treatment. Although 5CrNiMo has good hot processability, with an increase in die size, the internal quality control of the die becomes more and more difficult, and the distribution area of residual stress after quenching becomes more and more prominent, which makes the production cost of large-scale die forging increase and the production cycle lengthen, and becomes one of the main bottlenecks restricting the development of large-scale die forgings [8–9].

The main chemical composition of 5CrNiMo steel is shown in Table 1.

Its performance mainly includes

1) When the carbon content in 5CrNiMo steel is kept at 0.40 %–0.60 %, it can obtain high strength, strong thermal fatigue resistance, certain hardness and wear resistance, good toughness and thermal conductivity.

2) Adding Cr, Ni and Mo elements to 5CrNiMo steel mainly improves the hardenability of steel, especially when they act together.

3) In addition to the elements Ni, Cr and Mo, Fe_3C can be dissolved in 5CrNiMo steel to form $(\text{Fe}, \text{Cr}, \text{Mo})_3\text{C}$, which can improve its hardness and wear resistance.

4) The Mo element in 5CrNiMo steel can reduce tempering brittleness and grain size.

5) The combined action of Cr and Ni elements imparts antioxidant and corrosion resistance to the newly obtained product.

6) When 5CrNiMo steel is quenched, Cr, Ni and Mo are dissolved in austenite to improve the hardenability of the steel. After quenching, the three elements are dissolved in the matrix, strengthen the matrix and improve the stability of the matrix during tempering. In addition to Ni still present in the matrix structure during tempering, Cr and Mo are precipitated as $(\text{Fe}, \text{Cr}, \text{Mo})_3\text{C}$ carbides.

The precipitation and aggregation of carbides require higher tempering temperature of and longer time, to obtain thermal or wear resistance of the steel. Steel with precipitated carbide $(\text{Fe}, \text{Cr}, \text{Mo})_3\text{C}$ and a small amount of the Mo element that did not dissolve during quenching is suitable for the manufacture of all types of large and medium (side length 400 mm) hammer forging dies with complex shapes for large impact loads at low working temperature. It is used for the manufacture of components of simple shapes. The general manufacturing process adopts a vacuum refining process to ensure the purity of steel. Large-scale professional heat treatment can achieve the best steel pre-hardening effect with uniform hardness distribution. The steel is easy to form white spots, so it is necessary to strictly control the smelting process and the cooling system after forging and rolling [11–12].

To obtain thin-walled hollow components with excellent mechanical properties, this work uses a technological method for obtaining 5CrNiMo reinforced with WC particles. To achieve the goal of reducing the amount of cutting and saving raw materials, the cold extrusion process is adopted, and the corresponding heat treatment is

Table 1. Chemical composition of 5CrNiModie steel (wt %)

C	Mo	Si	Mn	S	P	Cr	Ni	Cu
0.50–0.60	0.15–0.30	≤0.40	0.50–0.80	≤0.030	≤0.030	0.50–0.80	1.40–1.80	≤0.30

Table 2. Common lubrication methods

Extrusion material	Lubricant composition
Fine aluminum 1074A	Zinc stearate, manganese stearate powder, civil soap powder, etc.
Alloy steel	Phosphating+saponification, adding molybdenum disulfide into water, vaseline and resin for lubrication, or using high-viscosity and high-sulfur oil, tallow, vegetable oil, etc.

used to improve the mechanical strength and toughness of the components.

2. Forming analysis

2.1 Process analysis

The shape of this component is complicated, with threads and holes in the upper part, threads in the lower part, and through holes in the whole component. It can be produced by mechanical processing, but it is required for mass production, and the mechanical processing method will produce a large amount of waste materials with slow efficiency, resulting in higher production costs. If the extrusion molding scheme is adopted, the production efficiency and material utilization rate can be effectively improved, and the production cost can be reduced.

According to the component drawing, the difference between M16's external thread and external diameter 18 is only 2 mm, and M22's external diameter 30 is only 8 mm. If it is extruded in one step as shown in the drawing, the punch wall of the die is only 1 mm and 4 mm, which will be easily damaged under the action of large extrusion force, and can be uniformly processed into 18 mm and 30 mm external diameters.

The commonly used blanking methods in extrusion include hot-rolled bar cutting, cold-drawn bar shearing and smooth blanking of sheet metal. Among them, cold-drawn bar cutting is the fastest and most economical method of blank making (the material utilization rate can reach 95 %–100 %), and the cut portion of the blank is of good quality and produces little waste. After the bar-shaped blank is obtained by cold cutting, the cross section is generally rough, so, a flat die should be used for alignment. In addition, in order to facilitate the entry of the rod into the blank, an 8.1 mm hole should be drilled in the blank. Surface treatment and lubrication are essential in extrusion forming processes. As a result of processing the blank, it is possible to reduce the unit extrusion force and frictional deformation resistance, improve the

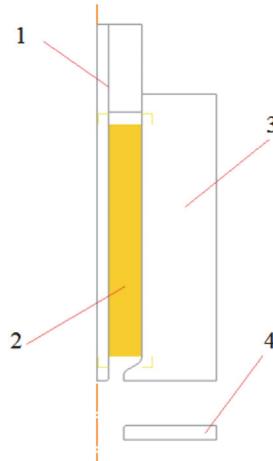


Fig. 1. Finite element model of hook plate. 1 — Punch and mandrel, 2 — blank, 3 — female die, 4 — guide sleeve.

surface quality of the extruded parts, and extend the service life of the extrusion head. Common lubrication methods are shown in Table 2.

2.2 Extrusion model

In order to determine the mechanical behavior of 5CrNiMo alloy reinforced with WC during extrusion, the corresponding extrusion model should be established. It provides the function of creating a simple model and establishes a simple mold structure by inputting coordinates. To reduce the amount of computation, only half of the mold elements are modeled, a symmetry plane is set to receive all data, and some minor geometric elements are ignored, as shown in Fig. 1.

2.3 Forming process

Based on the model given in Fig. 1, we analyzed the extrusion process of 5CrNiMo alloy reinforced with WC, established the law of stress distribution in it and studied the mechanical properties.

For the numerical simulation of the blank forming process, the die is simplified, and the concave-convex die is set as a rigid body without any deformation. In the simulation process, only the blank is deformed, and the blank is set as a plastic body. In the

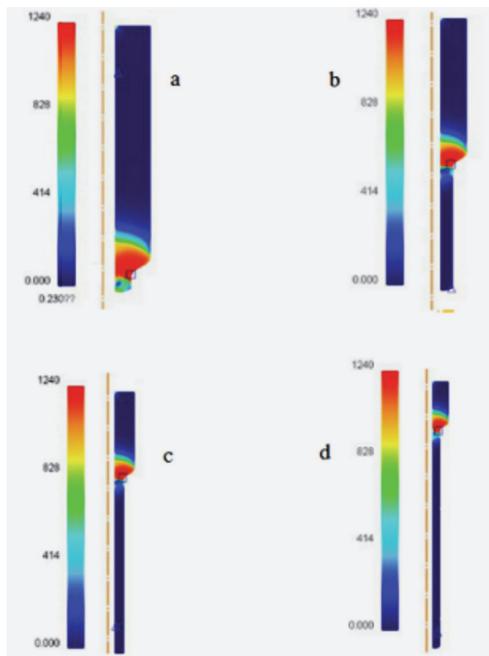


Fig. 2. Stress distribution diagram of forming process: a — step 100, b — step 250, c — step 400, d — step 500.

extrusion process, the female die is fixed and the male die moves, and the press speed is set to the conventional speed of 10 mm/s. The blank is divided into sections using a conditional grid. According to the design calculation, the simulated moving distance of the punch is set to 55 mm, and the step is 0.1 mm/step, which runs for 550 steps in total and is saved every 10 steps. The punch and the mandrel are integrated design, and the punch and the mandrel move together. According to the calculation results, the stress state of the mandrel and the damage distribution of the extrusion parts obtained from the simulation results are shown in Fig. 2.

According to the simulation process diagram and the final result, it can be seen that the fillet transition part of the part is smooth and full, and the forming quality is high. Using the measuring tools provided by the software, it was found that the length of the bottom exceeds the required size of the part.

2.4 Damage analysis

Based on the model given in Fig. 1, the damage analysis of 5CrNiMo alloy reinforced with WC in the extrusion process was carried out, the velocity vector diagram was analyzed, and the material damage in the extrusion process was studied. Based on the

safety of the material forming process, the appropriate extrusion process is provided.

During the extrusion process, the blank at the top of the working belt is slightly damaged, and the damage mainly occurs at the working belt, so the extruded part below the working belt is in a damaged state. The damage is related to factors such as stress amplitude, loading stress, maximum stress, loading frequency, structure size, etc. The stress concentration at the working zone leads to a large degree of damage, and in addition, the metal experiences a strong fluidity due to the smaller structure size.

The damage forming process and velocity diagram are shown in Fig. 3.

The diameter of the die cavity is almost twice that of the working belt. According to the principle of a certain volume, the square of the flow speed of the blank in the cavity is proportional to the square of the flow speed in the working belt. When the metal is extruded, the speed and direction change, and the change in speed must be affected by a force. Where the speed changes drastically, the stress is also greatest.

3. Experimental

The wire cutting machine is mainly used to cut bulk raw materials into pieces, so as to facilitate sample grinding and testing. Scanning electron microscopy (SEM) uses the interaction between electrons and substances to obtain information of various physical and chemical properties of the tested sample, such as morphology, composition, crystal structure, electronic structure and internal electric or magnetic field, etc. X-ray diffractometry uses the diffraction principle to study crystal structure, texture and stress of materials, as well as to perform phase, qualitative and quantitative analysis.

3.1 Organizational analysis

After quenching at 950°C and tempering at 600°C, carbide in steel can be spheroidized and spherical pearlite structure can be obtained by chemical annealing. The microstructure becomes denser and finer, various structural defects and internal stress are effectively eliminated, the hardness is reduced, and the mechanical properties of steel are improved by refining grain. The OM photo is shown in Fig. 4.

An enlarged metallographic image of the composite structure after spheroidizing annealing was obtained using an optical micro-

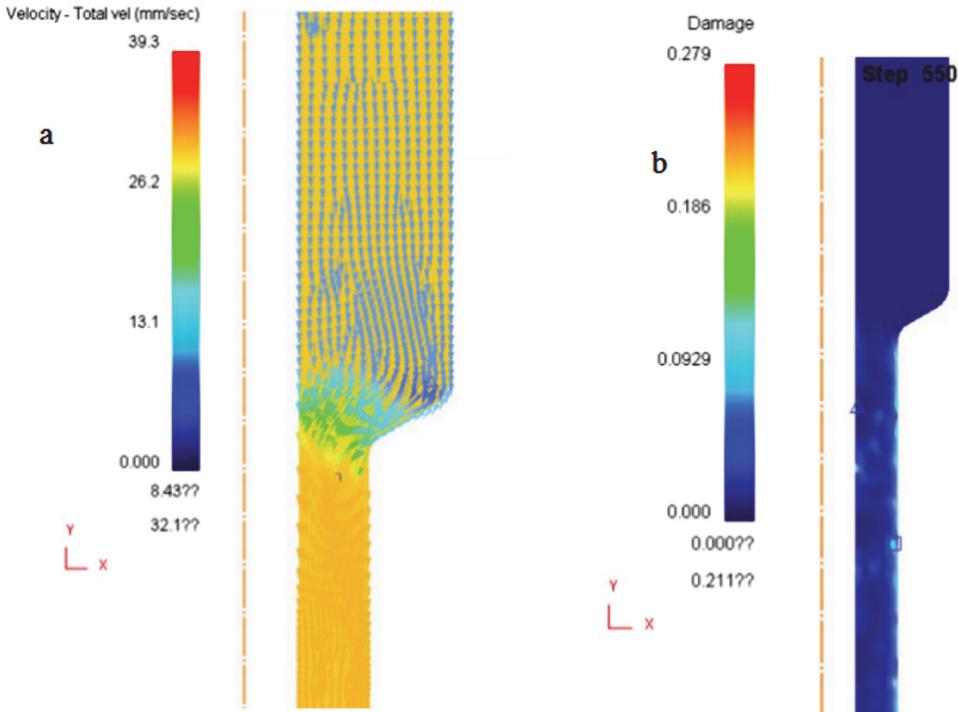


Fig. 3. Damage forming process and velocity diagram: a — metal fluidity, b — damage.

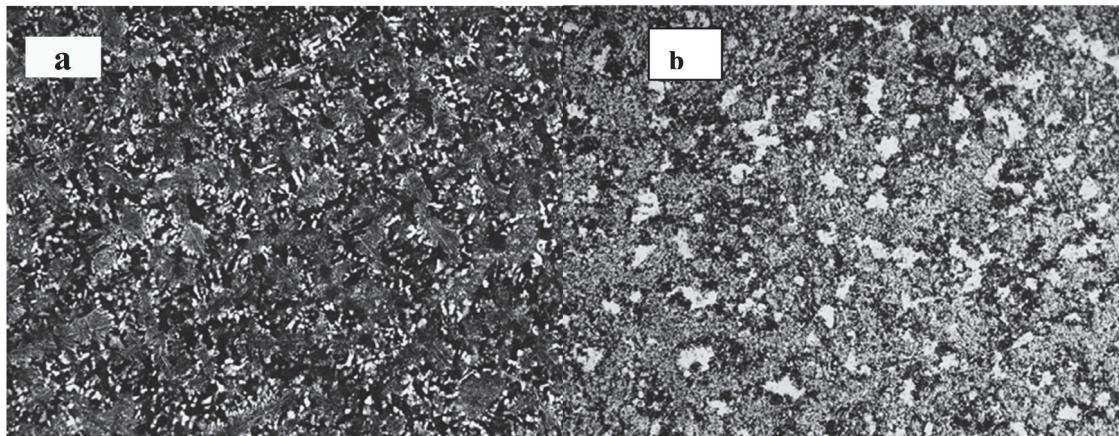


Fig. 4. Metallographic photos; magnification: a — $\times 100$, b — $\times 200$.

scope. It can be seen from the figure that ferrite and cementite are distributed in a spherical shape, that is, spherical pearlite. White WC particles are uniformly distributed in the matrix, which improves the strength and toughness of the material.

During the tempering process, segregation of carbon atoms, martensite decomposition, transformation of residual austenite, formation of cementite, restoration of recrystallization of the α -phase, as well as aggregation and growth of cementite occur.

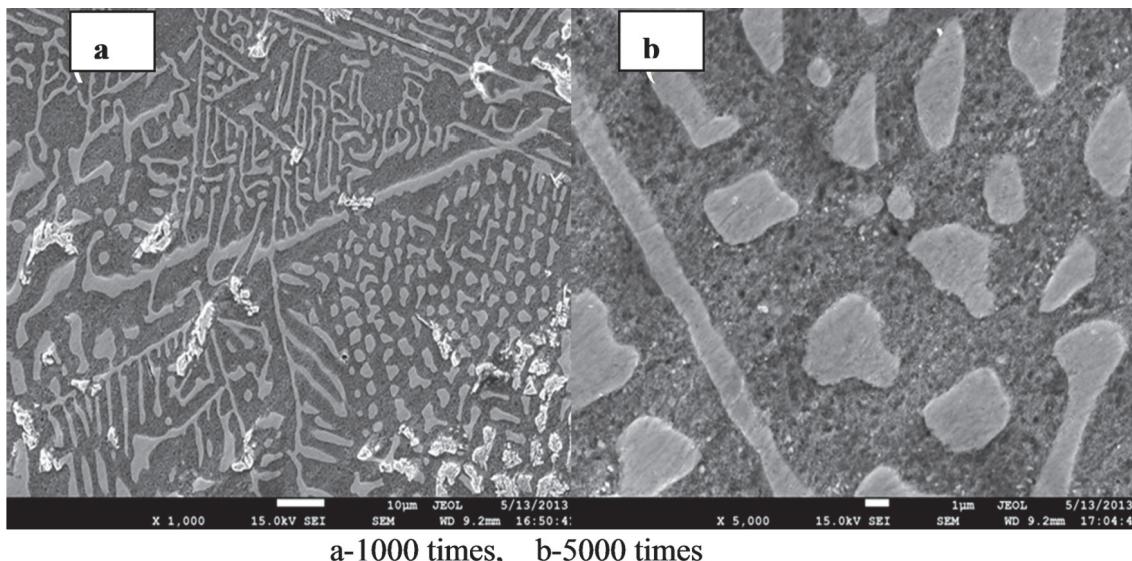
Finally, flake martensite is obtained; cementite aggregates and spheroidizes in martensite; the carbides formed by Cr, Mo, Ni and other alloys rapidly approach the crystal, resulting in precipitation hardening, so that the strength and hardness of the material reach a precise level.

Using a scanning electron microscope, it can be observed that fine WC particles are distributed in the matrix, and the SEM images are shown in Fig. 5.

After spheroidizing annealing, the hardness of the composite is 44. The hardness of

Table 3. The key parameters of friction and wear test

Test force, N	Time, s	Speed, r/min	Test revolution, r/min	Temperature, °C	Friction, N
200	300	200	1000	0	6.525



a-1000 times, b-5000 times

Fig. 5. SEM images; magnification: a — ×1000, b — 5000.

the sample decreases, the cutting ability improves; to reduce deformation and cracking after hardening, preparation for subsequent hardening is carried out. Spheroidizing annealing is suitable for carbon steel and alloy tool steel with carbon content (mass fraction) greater than 0.8 %. With a scanning electron microscope, the distribution of fine WC particles in the matrix can be observed.

3.2 XRD analysis

After quenching at 950°C and tempering at 600°C, the results of XRD analysis of the test specimen are shown in Fig. 6.

After tempering at 600°C, the tested compounds are FeC, WC, Fe₇C₃, Fe₃W₃C, and Fe₃Mo₃C. Compared with those of the previous annealing and quenching, the types of compounds have changed greatly, the alloy carbides disappeared, and a large number of alloy atoms appeared.

3.3 Wear analysis

Related parameters for friction test are shown in Table 3.

The friction force distribution law is shown in Fig. 7.

After quenching at 950°C and tempering at 600°C, the friction force of the sample remained constant without large fluctuations, but compared with the level before quenching, the friction force decreased to the level of 6N; this indicates that hardening reduced the frictional force of the mate-

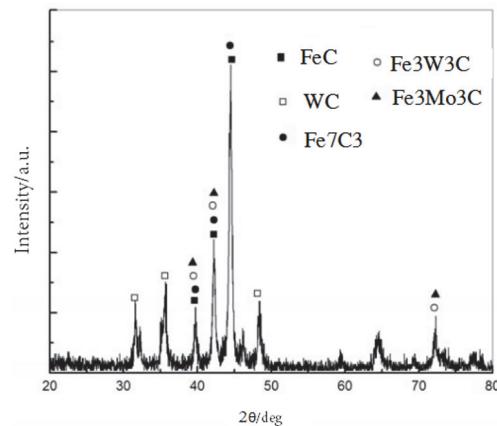


Fig. 6. XRD spectra.

rial, and the reduction of the frictional force increased the wear resistance of the material. As for die steel, high wear resistance can reduce die wear, thereby extending die life.

4. Conclusion

In this paper, the 5CrNiMo composite reinforced by WC was studied. In order to improve the microstructure and properties of thin-walled parts after forming, the formed parts are heat-treated. The metallographic structure, cross-section morphology, hardness and wear resistance charac-

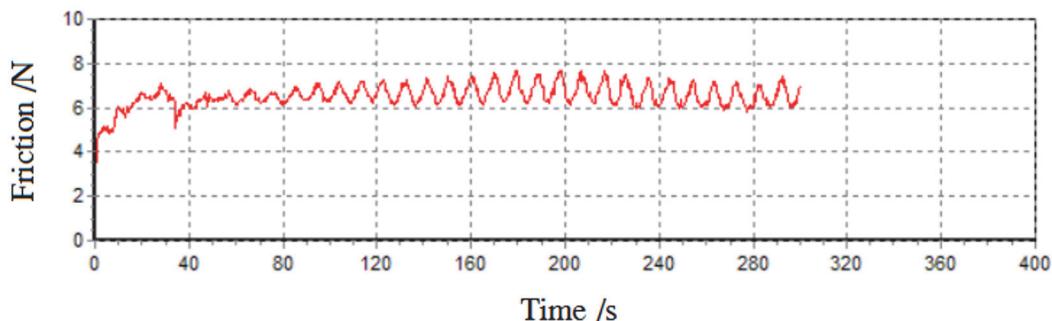


Fig. 7. Friction force distribution curve.

teristics were studied after spheroidizing annealing, quenching and tempering at different temperatures. By comparison, the most favorable heat treatment process was selected.

The results show that the best results on hardness, microstructure and properties of steel were obtained by combining the heat treatment of quenching at 950°C and tempering at 600°C. After the heat treatment process, lath or flake martensite is finally obtained, cementite aggregates and spheroidizes in martensite, and carbides formed by Cr, Mo, Ni and other alloy atoms are uniformly dispersed in the crystal, resulting in dispersion strengthening, which meets the industrial requirements.

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