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Satbayev University

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INFLUENCE OF THERMOMECHANICAL ROLLING SCHEDULES ON SCREW-SHAPED AND FLAT ROLLS AND NITRIDING SCHEDULES ON THE STRUCTURE AND MECHANICAL PROPERTIES OF P6M5 STEEL CUTTERS

Abstract. The article studies the influence of the number of passes during rolling (cogging) of blank part in helical and smooth rolls on the formation of structures, mechanical and plastic properties of tool steel P6M5 after thermomechanical processing under different modes and low-temperature ion nitriding. It is shown that cogging in helical rolls with twelve passes and one pass in smooth rolls allows to obtain an ultra-fine-grained (UFG) structure in surface zone of the rolled strips. It is established that nitriding of the surface zone with a coarse-grained structure contributes to the surface hardening of the samples, changes in the strength characteristics of steel, and reduces the plastic properties, which is due to the formation of a crushable surface layer on the samples. It is proved that when nitriding workpieces with a UMP structure, a hardened layer is formed that is less prone to brittle fracture. The results of analysis and estimation of the thickness of the nitrided layer after rolling in HR (helical roll) and PR (plain roll) under various thermomechanical conditions and nitriding at a temperature of 500 ° C are presented. It is established that ion nitriding under the selected temperature-strain mode allows almost 2 times to increase the microhardness of the surface during nitriding, and the thickness of the near-surface layer increases under thermomechanical processing of HR with twelve passes.

Key words: steel R6M5, helical and smooth rolls, mechanical properties, ion nitriding, microhardness, structure.

Introduction. To this date, the use of modern methods of modifying structural materials is one of the main ways to increase the durability and reliability of cutting tools of metal-cutting machines in mechanical engineering [1]. This is due to the fact that 85-90% of the tools of metal-cutting machines do not reach the required service life due to surface wear of cutters. Experts know that the cost of repair and maintenance of mechanical engineering parts is several times higher than the cost of originals parts.

It is known [1-3] that nitriding is currently one of the most effective methods of surface modification, which increases the hardness of the surface layers, wear resistance, fatigue and corrosion resistance of machine parts. Therefore, the nitriding process has been widely used in various branches of mechanical engineering, including mechanical processing.

Wear resistance of metal materials is a structure-sensitive characteristic [4-6]. Therefore, it is important to know the rules, describing the interrelationship between initial structure of the surface layer and the structure obtained in the zone of application of the nitrided layer, as well as the tribotechnical rules in interface of rubbing pairs.

The purpose of this work is to develop a new manufacturing technique of cutters to improve the tribotechnical and mechanical characteristics of nitrided structural steels.

Methods and materials. In the work [7], a tool with rolls with helical working surfaces was developed. In these rolls, the helical protrusions and depressions of the upper and lower rolls are located opposite. Helical rolls (HR) are designed to produce semi-finished products with fine-grained structure. The developed tool performs intensive plastic deformation (IPD) without significant changes in the original shape and size of the workpiece.

Series of experiments were conducted in laboratory. As the material of the workpiece, steel P6M5 with a size of 6×150×400 mm was chosen. The tool steel was subjected to thermomechanical rolling according to following modes:

1. Heating to a temperature of 850°C, rolling in smooth rolls (SR) to a thickness of 4.0 mm;

2. Heating to the temperature of 850°C, rolling with four passes in HR to the thickness of 5.8 mm, heating at the temperature of 850°C, rolling with four passes in HR to the thickness of 5.5 mm, heating at the temperature of 850°C, rolling in SR to the thickness of 4.0 mm;

3. Heating to the temperature of 850°C, rolling with four passes in HR to the thickness of 5.8 mm, heating at the temperature of 850°C, rolling with four passes in HR to the thickness of 5.5 mm, heating at the temperature of 850°C, rolling with four passes in HR to the thickness of 5.0 mm, heating at the temperature of 850°C, rolling in SR to the thickness of 4.0 mm;

4. Heating to the temperature of 850°C, rolling with four passes in HR to the thickness of 5.8 mm, heating at the temperature of 850°C, rolling with four passes in HR to the thickness of 5.5 mm, heating at the temperature of 850°C, rolling in SR to the thickness of 4.0 mm. Annealing of rolled samples at temperatures of 900, 1000 and 1100°C with an exposure time of 2 hours.

5. Heating to the temperature of 850°C, rolling with four passes in HR to the thickness of 5.8 mm, heating at the temperature of 850°C, rolling with four passes in HR to the thickness of 5.5 mm, heating at the temperature of 850°C, rolling with four passes in HR to the thickness of 5.0 mm, heating at a temperature of 850°C, rolling in SR to the thickness of 4.0 mm. Annealing of rolled samples at temperatures of 900, 1000 and 1100°C with an exposure time of 2 hours.

After rolling the samples according to modes 1, 2 and 3, they were quenched at 1200°C and a single released at 560°C.

To study the effect of the nitriding process on the mechanical properties and wear resistance of the cutters, samples with dimensions of 50×20×4 mm were cut out of the blanks. After grinding and electrolytic polishing, the cut samples were subjected to low-temperature ion nitriding at the temperature of 520°C in JON-600 unit. Herewith, the following process parameters were used: vacuum pressure (reactive atmosphere) p = 150 Pa, time t = 10 hours, the composition of the reaction atmosphere is a mixture consisting of 90% N_2, 5% Ar and 5% H_2, the flow rate of gaseous media was as follows: 900 ml/min N_2 + 50 ml/min Ar + 50 ml/min H_2.

The hardness was studied in the cross-sections of the selected zones by the Rockwell method according to SS (State standard) 9015, and the micro-hardness was measured using the PMT-3 micro-hardness meter according to the standard method [2].

Metallographic analysis was carried out using an energy-dispersion spectrometer JNCAENERGY (England), installed on an electron probe micro-analyzer JEOL (Geol) at an accelerating voltage of 25 kV. The magnification range of the JEOL device is from 40 to 40,000 units. The structural features of the samples were also studied using an electron transmission microscope (TEM) JEM-2100CX at accelerating voltages of 200 kV. To identify the structure of the steel, micrographic specimen was etched in a solution of 5% HNO_3 and 95% C_2H_5OH.

Determination of the main mechanical characteristics and the nature of their changes during thermomechanical rolling and nitriding was carried out on a universal Instron machine at room temperature according to SS 1497-84.

Abrasive wear test was carried out using the T-05 tribotester under dry friction conditions according to the “shaft – liner” scheme. The T-05 tester is equipped with the Spider 8 control unit and Catman Express 3.0 computer program. During the tests, the friction force F, the temperature of the sample, and the mutual displacement of the friction pair h caused by the wear of the sample were continuously recorded. All experiments were performed at a constant load of 18,615 N and rotation speed of 150 rpm. The counter-sample was a roller having a diameter of 35 mm, made of VK8 alloy with a hardness of 87-90 HRC. To measure the mass loss of the samples, RADWAG analytical balance of the WPA 40/160/C/1 type with a scale of 0.01 mg was used.

Results and discussion. Analysis of the microstructure of the strips rolled according to mode 1 showed that in the longitudinal section along the rolling direction, the presence of coarse lines and carbide banding is observed. The microstructure contains large, medium, and small inclusions of carbides. This orientation of the carbide phases along the rolling direction leads to anisotropy of the properties, uneven volume changes during quenching, and an increase in the level of thermal stresses caused by phase hardening. Accordingly, this structural inhomogeneity negatively affects the wear resistance of the tool.

It should be noted that the strips of steel P6M5 rolled according to mode 1 have a differently-grained structure. This structure consisted of relatively large non-recrystallized grains with an average size of ~ 86 microns in longitudinal and ~35 microns in transverse directions. Small grains with a size of ~7-12 microns were located along the boundaries of large grains.

The study of this microstructure after quenching at the temperature of 1200°C and tempering at 560°C shows that during this heat treatment, the retained austenite turns into martensite supersaturated with carbon and alloying components, and also in soluble relatively large-sized carbide is released. All this leads to an increase in hardness. Bright fields representing retained austenite are practically absent. The hardness from the sample's surface was 60-62 HRC.

The study of the structural state of the P6M5 steel strips rolled according to modes 2 and 3 shows that the fine-grained structure is formed in the surface zone of the blank section. At the same time, the density of intragranular dislocations increases. It should be noted that rolling in the second mode led to the formation of a fine-grained structure in P6M5 steel. The average grain size in the peripheral zone of the workpiece reached 2-6 microns, and in the central zone-12-19 microns. When deformed according to the third mode, an ultrafine-grained (UFG) structure was formed along the entire longitudinal and cross sections of the workpiece. It is worth noting that in the central zone of the blank, the more coarse-grained structure still preserved. Thus, as a result of the passage of softening processes in the metal of the blank, a recrystallization UFG structure was formed. In the surface zone of the rolled strips, a structure with average grain size of about 0.6 – 0.9 microns was formed, and in the central zone -3-5 microns.

Based on the obtained data, it can be noted that during rolling in HR, the action of alternating deformation mechanisms provides fragmentation and reorientation of the crystal lattice. At the same time, large-angle boundaries are formed on the peripheral zones of the workpiece with a high density.

The analysis of the phase state of samples deformed according to modes 2 and 3 showed that a uniform distribution of carbide inclusions is observed in the surface zone, i.e. there is no banding and striation. In the central zone of the sample, the carbide inclusions are slightly stretched in the rolling direction. It should be noted that in the surface zone of the sample, the carbide inclusions are mainly distributed along the grain boundaries. At the same time, there is a partial crushing of large carbides. The average size of carbides in this zone, when rolling in modes 2 and 3, respectively, was 2.4 – 2.6 and 1.1 – 1.3 microns.

Further metallographic studies have shown that after annealing in steel P6M5, the above-described minor structural non-homogeneity persists. At the same time, the average grain size of the strips rolled according to mode 4 increases to the size of 9.3, 12.7 and 16.4 microns, respectively, at the annealing temperature of 900, 1000 and 1100°C. The similar increase in grain sizes is observed when rolling strips according to mode 5. In this case, the average grain size grew to a size of 5.7, 9.1, and 12.2 microns, at an annealing temperature of 900, 1000, and 1100°C. The average density of carbides in the sections of the rolled strips, respectively, was: when rolling in mode 4: 1.3 million pieces/mm^2; when rolling in mode 5:1.8 million pieces/mm^2. At the same time, the average diameter of the carbide particles, when rolling according to mode 4 and 5, was 3.16 and 1.61 microns, respectively.

Quenching and tempering at temperatures of 1200°C and 560°C respectively, samples rolled according to modes 2 and 3, led to an increase in the size of carbide particles due to their coagulation. At the same time, the average diameter of the carbide particles, respectively, was 6.43 and 3.84 microns. However, their number decreased due to the effect of braking processes on the release of carbide particles from the solid solution. The effect of the braking processes on the release of carbide particles from the solid solution is associated with shock cooling of the rolled strips. It should be noted that in the longitudinal and cross-sections of the strips rolled according to modes 2 and 3, the density of carbide particles decreased, respectively, by 1.9-2.1 and 1.2-1.6 times. The hardness of the strips rolled in modes 2 and 3, respectively, was 62-64 HRC and 65-68 HRC.

Thus, it is established that quenching at the temperature of 1200°C of strips rolled according to mode 3 leads to an increase in the hardness of P6M5 steel (by no more than 5 HRC) compared to the hardness of strips rolled according to modes 1 and 2. Studies of samples made of P6M5 steel have shown that, according to the thermomechanical modes 1, 2 and 3, the rolled strips have a hardness that does not contradict the previously obtained results [3, 8, 9].

The analysis of the influence of the degree of deformation, i.e. the number of passes, at the temperature of thermomechanical processing of 850 C, on the strength of steel P6M5 showed, that with an increase in the number of passes when rolling strips in HR in modes 2-5, a steady increase in the strength of steel is observed, which reaches its maximum in the fourth pass. Further increasing of the number of passes to eight and twelve initiates the softening process. At the same time, it should be noted that the fulfillment of rolling in HR and

SR according to the thermomechanical rolling mode 3 in the deformation temperature range of 800 – 900°C and subsequent quenching makes it possible to obtain products with an increased tensile strength. Thus, the strength increases for P6M5 steel under the thermomechanical rolling mode 3 and quenching was 14% (compared to the processing mode 1).

Thereby, rolling the strips according to the thermomechanical mode 2 and 3 contributed to the formation of a high-strength state with low plasticity (Table 1). Strip annealing, treated according to modes 4 and 5 at a temperature of 900, 1000 and 1100°C contributes to the relaxation of the structure. This led to the decrease in strength properties. Analysis of the flow curves of samples rolled in thermomechanical modes 1-5 shows that with the increase in the grain size, the yield stress and strength, as well as the plasticity of the samples, decrease.

Table 1 Characteristics of P6M5 steel before and after nitriding

Processing type	$\sigma_{0.2}$, MPa	$\Delta\sigma_{0.2}$*	$\sigma_в$, MPa	δ, %	k_δ**
Mode 1	3156	0,06	3268	8.3	0,11
Mode 1 and nitriding	3346		3448	7.4	
Mode 2	3293	-	3456	8.6	-
Mode 3	3565	0,08	3717	9.8	0,07
Mode 3 and nitriding	3621		3718	9.1	
Mode 4	1531	-	2242	47.7	-
Mode 5	1438	-	2723	53.2	-
*$\Delta\sigma_{0,2}=(\sigma_{0.2(N)}-\sigma_{0.2})/\sigma_{0,2}$; *N* – indicates states with a nitrided layer;					
**$K_\delta=(\delta-\delta_N)/\delta$ - embrittlement coefficient.					

On the basis of the conducted studies, we concluded that the thermomechanical rolling mode 3 and the subsequent quenching and tempering of samples at temperatures of 1200°C and 560°C respectively is optimal in the preparation of tool blanks for low-temperature nitriding. In order to confirm the conclusions, metallographic analysis of the structure and micro-hardness of the nitrided samples were performed.

Analysis of the structure of the bands rolled under thermomechanical modes 1 and 3 and subjected to ion nitriding in a glow discharge shows the presence of a dark (highly etched) diffusion zone, which is an α-phase-nitrogenous ferrite with a BCC lattice and a small release of nitride compounds [10]. The study of the microstructure shows that the transition from the nitrided layer to the base (matrix) of the material is smooth, which is one of the main requirements for the microstructure of nitrided steel. The analysis of the structure of the samples rolled according to the thermomechanical mode 3, quenched and ion nitrided in the glow discharge showed more developed dark diffusion zone, compared to the samples rolled according to the thermomechanical mode 1.

For samples deformed according to mode 1, nitrided at 10 h exposure, the microhardness increases near the surface to 14-16 GPa, and the depth of the nitrided layer having a microhardness of 7-9 GPa is 15-35 microns. The decrease in microhardness occurs smoothly, which indicates to a slight diffusion of nitrogen atoms to a depth of several tens of micrometers.

The relatively high surface hardness of the samples treated according to mode 1 can be explained by significant rate of nitride formation in the stressed surface layer of steel obtained during quenching. In our opinion, during ion nitriding of samples made according to mode 1, high surface defects and coarse-grained structure prevent penetration of nitrogen deep into the sample and formation of the nitride phase.

When nitriding for 10 hours of samples rolled according to mode 3, there is a decrease in micro-hardness to almost 11-12 GPa at the depth of up to 20 microns from the surface and its slower decline deathward of the sample. The depth of the nitrided layer (with micro-hardness of 7-9 GPa) is 70-90 microns, which indicates the increase in the rate of nitrogen diffusion to 10 microns/h. In this rolling mode, the structure formed by the UFG leads to an increase in the rate of nitrogen diffusion deep into the sample and the formation of solid ε-phase (Fe_xN), i.e., a nitride of variable composition with a hexagonal tightly packed lattice of metal atoms [10, 11].

The study of polished sections showed that the nitrided layers of the samples have different color from the main material. In our opinion, the reason for this is the active etching of the nitrided layer. Consequently, nitride-containing phases formed during nitriding reduce the corrosion resistance of the material.

The analysis of the obtained data shows that ion nitriding contributes to the surface hardening of the samples, formation of crushable layer on the surface of steel samples. In the presence of the nitrided layer, the samples are deformed viscously (matrix), and the surface nitrided layer is destroyed cleavagely. In this case, the surface layer of nitrided samples made according to mode 1 cracks quickly from the very beginning of deformation. This leads to the formation of rough transverse cracks from the beginning of the sample testing. In samples treated according to mode 3, the process of cracking and fragmentation of the surface of the samples is slow and accompanies the entire process of plastic flow. Ion nitriding in modes 1 and 3 causes hardening of the samples (Table 1).The value$\Delta\sigma_{0,2is}$ 0.06 and 0.08, respectively. The nature of the flow curves changes slightly during nitriding, but the stretching of the samples before destruction decreases measurably. The increase in the grain size and the formation of high-strength states of small thickness (mode 1) leads to the increase in embrittlement coefficient k_δ (Table 1).

Thus, ion nitriding contributes to the change in strength characteristics, reduces the plastic properties of P6M5 steel, which is due to the formation of a brittle surface layer on the samples. However, samples made according to the third thermomechanical rolling mode and nitrided according to the above modes show a lower tendency to the brittle fracture.

Further, the tribotechnical properties of samples made of P6M5 steel, made according to the 1st and 3rd thermomechanical rolling modes were investigated. The analysis of the obtained data showed that the main mechanism of wear of the tested steel is abrasive wear with small traces of plastic flow of the material.

When testing the abrasive wear of samples made of P6M5 steel rolled according to mode 1 and nitrided on the glow discharge, the sample temperature at the beginning of the test increased from 25 to 51°C, and then dropped to 33°C. Meanwhile, the displacement of the abrasive pair reached 235 microns. During the control of the wear resistance of these samples, the shift of the abrasive pairs first occurred gradually, with a sharp shift occurring after 380 s. This sudden increase in the displacement of the friction pairs is due to the rapid cleaning of the surface of the tested samples from the nitrided layer.

Abrasion tests of samples made of P6M5 steel rolled according to mode 3 and nitrided in the glow mode according to the above modes resulted in an increase in the sample temperature from 26 to 66°C, and then decreased to 51°C. At the same time, the displacement of the abrasive pair consisting of a counter-sample and P6M5 steel was ~ 131 microns. During the control of the wear resistance of the hardened samples, sharp displacement of the abrasive pairs occurred after 1850 s.

Decrease in the friction force that occurs during the abrasive wear test of all tested samples made of P6M5 steel subjected to the nitriding process indicates the decrease in the coefficient of friction of the nitrided layer. At the initial stage of the test, the friction force in all tested materials was 17 N, and then after a certain time (see above) it decreased to 7 N and remained at this level constant until the end of the test.

The process of nitriding in the glow discharge allowed increasing the abrasion resistance. This is evidenced by measurements of mass losses of samples. The sample rolled according to mode 1 had the greatest mass loss during the abrasive wear test (more than 45 mg). Measurements of mass losses of samples rolled according to mode 3 and further subjected to nitriding in glow discharge showed significant decrease in these values (0.12 mg of its mass). Nitriding in the glow discharge also had a positive effect on reducing the coefficient of friction. For the P6M5 steel sample, the coefficient of friction decreased from 0.668 in the initial state to 0.124 in the nitrided state.

Thus, the nitriding process makes it possible to significantly increase the wear resistance and reduce the coefficient of friction of the steel. This improvement in wear resistance and coefficient of friction is due not only to the formation of the nitride layer, but also to the formation of chromium nitride in it. It is known that chromium nitride, in addition to the significant increase in hardness, also contributes to the increase in the wear resistance of steels.

Conclusions. 1.In this paper, we estimate the microhardness of the modified layer of steel P6M5, rolled with different thermomechanical modes in HR and SR and nitrided at 500°C.

2. It is proved that the use of SPD and nitriding in the glow discharge increases the wear resistance and improves the cutting properties of metal-cutting tools.

3. It is shown that the nitrided layer deposited on the surface of the sample with the UFG structure helps to reduce the coefficient of friction and, consequently, to improve the chip removal from the cutting edge of the metal-cutting tool.

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БҰРАНДАЛЫ ЖӘНЕ ЖАЗЫҚ ПІШІНБІЛІКТЕРДЕ ИЛЕМДЕУДІҢ ТЕРМОМЕХАНИКАЛЫҚ РЕЖІМДЕРІНІҢ ЖӘНЕ АЗОТТАУДЫҢ РЕЖІМДЕРІНІҢ Р6М5 БОЛАТЫНАН ЖАСАЛҒАН КЕСКІШТІҢ ҚҰРЫЛЫМЫ МЕН МЕХАНИКАЛЫҚ ҚАСИЕТІНЕ ӘСЕРІ

Аннотация. Мақалада, Р6М5 аспаптық болаттан жасалған дайындаманы бұрандалы және тегіс пішінбіліктерде илемдеген кезде, өту санының айтылған болаттың құрылымының қалыптасуына, механикалық және пластикалық қасиеттеріне қалай әсер ететіндігі зерттелген. Бұндай зерттеу әртүрлі режимдермен термомеханикалық өңдеуден және төменгі температурада иондық азоттаудан кейін жүргізілген. Бұрандалы пішінбілікте (БП) он екі өту және тегіс пішінбілікте (ГП) бір өтумен илемдеген кезде жолақтардың беткі аймағында ультраұсақтүйіршікті (УҰТ) құрылымды алуға мүмкіндік бар екені жұмыста көрсетілген. Ірі түйіршікті құрылымы бар дайындаманың беткі аймағын азоттау, болаттан жасалғанүлгілердің беткі қабытының беріктенуіне, беріктік сипаттамаларының өзгеруіне ықпал жасайтындығы және пластикалық қасиеттерінің төмендейтіндігі мақалада анықталды. Осындай өзгерістер үлгілерде сынғыш беткі қабаттың пайда болуымен байланыстырылған. УҰТ құрылымы бар дайындамаларды азоттаған кезде қатайған қабат тез бұзылмауға бейім болмайтындығы дәлелденді. 500ºС температурада азоттау және әртүрлі термомеханикалық режимдермен БП және ЖП-те илемдеуден кейін азотталған қабаттың қалыңдығы талданған және бағалау нәтижелері жұмыста келтірілген. Таңдалған температура-деформация режимінде иондық азоттау беттің микроқаттылығын 2 есе арттыруға мүмкіндік беретіндігі мақалада анықталған. Он екі өтіммен БП дайындаманы термомеханикалық өңдеп, кейінірек оны азотаған кезде беткі қабаттың қалыңдығы артатындығы мақалады дәлелденген.

Түйінді сөздер: Р6М5 болаты, бұрандалы және жазық пішінбілік, механикалық қасиет, ионды азоттау, микроқаттылық, құрылым.

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ВЛИЯНИЕ ТЕРМОМЕХАНИЧЕСКИХ РЕЖИМОВ ПРОКАТКИ В ВИНТООБРАЗНЫХ И ГЛАДКИХ ВАЛКАХ И РЕЖИМОВ АЗОТИРОВАНИЯ НА СТРУКТУРУ И МЕХАНИЧЕСКИЕ СВОЙСТВА РЕЗЦОВ ИЗ СТАЛИ Р6М5

Аннотация. В статье изучено влияние количества проходов при прокатке заготовки в винтообразных и гладких валках на формирование структур, механические и пластические свойства инструментальной стали Р6М5 после термомеханической обработки в разных режимах и низкотемпературного ионного азотирования. Показано, что прокатка в винтообразных валках (ВВ) двенадцатью проходами и одним проходом в гладких валках (ГВ) позволяет получить ультра мелкозернистую (УМЗ) структуру в поверхностной зоне прокатываемых полос. Установлено, что азотирование поверхностной зоны с крупнозернистой структурой способствует поверхностному упрочнению образцов, изменению прочностных характеристик стали, снижает пластические свойства, что обусловлено образованием хрупкого поверхностного слоя на образцах. Доказано, что при азотировании заготовок с УМЗ структурой образуется упрочненный слой меньше склонный к хрупкому разрушению. Представлены результаты анализа и оценки толщины азотированного слоя после прокатки в ВВ и ГВ с различными термомеханическими режимами и азотирования при температуре 500ºС. Установлено, что ионное азотирование при выбранном температурно-деформационном режиме позволяет почти в 2 раза повысить микротвёрдость поверхности при азотирования, а толщина приповерхностного слоя увеличивается при термомеханической обработке в ВВ с двенадцатью проходами.

Ключевые слова: сталь Р6М5, винтообразные и гладкие валки, механические свойства, ионное азотирование, микротвёрдость, структура.

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