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A Study on the Fault Diagnosis of the 3-D Roll Shape in Cold Rolling

Chang Woo Lee
Department of Mechanical Engineering, Konkuk University,
1 Hwayang-Dong, Gwangjin-Gu, Seoul 143-701, Korea
Hyun Kyoo Kang
Department of Mechanical Engineering, Konkuk University,
1 Hwayang-Dong, Gwangjin-Gu, Seoul 143-701, Korea
Kee Hyun Shin*
Department of Mechanical and Aerospace Engineering, Konkuk University,
1 Hwayang-Dong, Gwangjin-Gu, Seoul 143-701, Korea

The metal processing system usually consists of various components such as motors, work rolls, backup rolls, idle rolls, sensors, etc. Even a simple fault in a single component in the system may cause a serious damage on the final product. It is, therefore, necessary to diagnose the faults of the components to detect and prevent a system failure. Especially, the defects in a work roll are critical to the quality of strip. In this study, a new 3-D diagnosis method was developed for roll shape defects in rolling processes. The new method was induced from analyzing the rolling mechanism by using a rolling force model, a tension model, the Hitchcock's equation, and measurement of the strip thickness, etc. Computer simulation shows that the proposed method is very useful in the diagnosis of the 3-D roll shape.

Key Words : 3-D Roll Shape Fault, Deformed Roll Radius, Diagnosis, Parameters Sensitive Analysis, Rolling Force, Transverse Strip Tension, Work Roll

Nomenclature

A : Cross-sectional area of strip
E : Modulus of elasticity
L : Length of strip span
h_{i0}: Steady-state value of strip thickness
H_i: Change in strip thickness from a steady-state operating value
h_i : Strip thickness $(=h_{i0}+H_i)$
t_{i0} : Steady-state value of strip tension
T_i: Change in strip tension from a steady-state operating value
t_i : Strip tension $(=t_{i0}+T_i)$
v_{i0}: Steady-state operating value of strip speed
V_i: Change in strip speed from a steady-state operating value
v_i : Strip speed $(=v_{i0}+V_i)$
ε_i : Strain of strip
P : Rolling pressure
R : Radius of work roll
R': Radius of deformed work roll
$f(arb)$: Rolling force function
B : Strip width
K : Mill constant
σ_i : Stress of strip
$\bar{K}$: Mean constrained compressive yield strength

1. Introduction

The continuous processing systems such as cold rolling system generally consist of various components like driven rolls, idle rolls, sensors.

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* Corresponding Author,
E-mail : khshin@konkuk.ac.kr
TEL : +82-2-450-3072; **FAX** : +82-2-447-5886
Department of Mechanical and Aerospace Engineering, Konkuk University, 1 Hwayang-Dong, Gwangjin-Gu, Seoul 143-701, Korea. (Manuscript **Received** May 11, 2004; **Revised** August 27, 2004)

In the rolling system, a work roll shape fault may cause a serious damage on the final products. Therefore, it is important to monitor the process systems and diagnose the component faults and draw up a scheme in order to minimize degradation of product quality and economic loss. For example, in steel rolling, the eccentricity of work roll or backup roll has a fatal influence on gauge control (Laila Salah et al., 2002). A 2-D diagnosis technique of the eccentricity of the roll has been reported by the using frequency analysis (Tahk and Shin, 2002). Various eccentricity compensation methods to control the tension and the strip thickness for the system with roll eccentricity have been proposed (Ginzberg, 1993; Kugi et al., 2000; Shin, 2003).

In this paper, a new diagnosis algorithm is suggested to identify the defective work rolls on the basis of correlations among strip shape, rolling mechanism, and system operating information. By using this algorithm, the defective work roll can be identified in the cold rolling system. From the results of computer simulation, it is verified that the proposed diagnosis algorithm of 3-D roll shape detected the fault successfully.

2. Mathematical Models

2.1 Tension model

The automatic control system in a cold rolling system generally consists of the three major control systems: a roll gap control, a roll speed control, and a strip tension control system. These control systems heavily interact each other (Ginzberg, 1993). The thickness of the strip can be changed by roll gap control, but can not be controlled precisely without controlling the tension of the strip. It is also reported that the effect of roll gap control on the strip thickness can be cancelled out due to the interaction between strip tension and strip thickness (Shin et al., 1998). But, authors could not find literature on the mathematical model that fully describes interaction among the roll gap, the roll speed, and the strip tension.

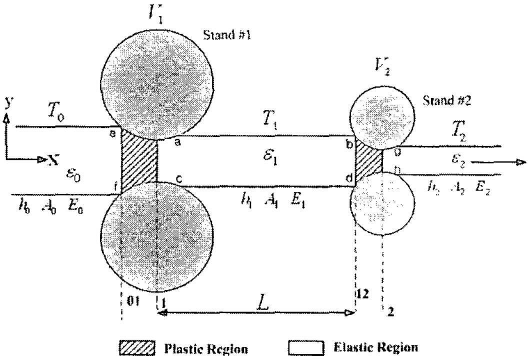

Fig. 1 Rolling of a strip between two stands

Consider a metal strip with tension between two stands as shown in Fig. 1. The strip is transported from left to right and rolled to change its thickness from h_0 to h_1. In the plastic and the elastic regions, the law of conservation of mass, stress-strain relationship, and Hooke's law are used to derive a mathematical model which describes a dynamic relationship among the strip tension, the roll speed, and the strip thickness as shown in Eq. (1) (Shin, 2000).

$$\begin{aligned}\frac{d}{dt}[T_1(t)]=&-\frac{v_{20}}{L}T_1(t)+\frac{v_{10}}{L}\frac{A_1E_1}{A_0E_0}T_0(t)\\&+\frac{A_1E_1}{L}\left(\frac{V_2(t)\,h_{20}+v_{20}H_2-v_{120}H_1}{h_{10}}-V_1(t)\right)\end{aligned}\tag{1}$$

Eq. (1) shows that the tension of a strip between two stands is very sensitive not only to the speed changes but also to the thickness changes of strip at each rolling stand.

2.2 Rolling model

Figure 2 shows a rolling process in which the strip thickness is reduced from h_{i-1} to h_i. The relationship between original work roll radius and deformed work roll radius is shown in Fig. 3. The rolling process can be represented as following Eqs. (2) and (3) (Robert, 1978).

$$P=\bar{K}\left(1-\frac{\sigma_{i-1}}{\bar{K}}\right)\sqrt{R'(h_{i-1}-h_i)}\,f(arb)\tag{2}$$

$$R'=R\left(1+\frac{cP}{B(h_{i-1}-h_i)}\right)\tag{3}$$

Eq. (2) and (3) express respectively the rolling

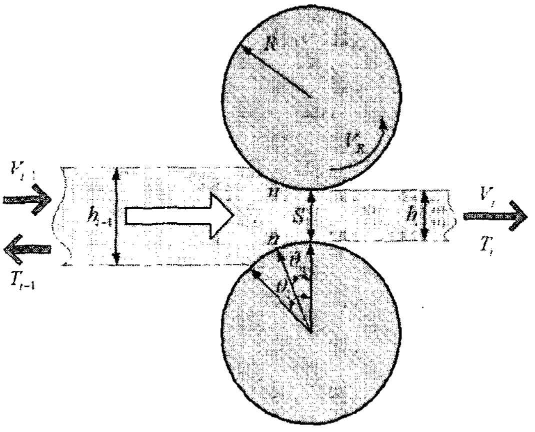

Fig. 2 Rolling of strip in single stand

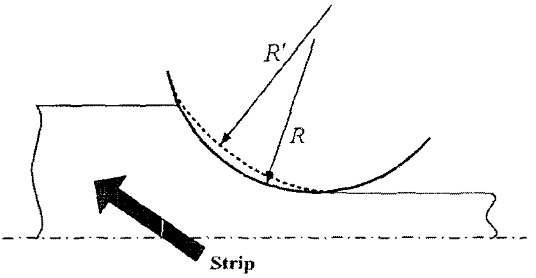

Fig. 3 Schematic of elastic deformation of a work roll

force and the radius of deformed roll. Thus the rolling force is calculated as the product of a mean constrained compressive yield strength, the length of the arc of contact, a rolling force function, thickness reduction, and strip stress. Eqs. (1) and (2) must be solved simultaneously to calculate the strip tension, rolling force, and deformed roll radius because these two equations are coupled.

3. The Proposed Fault Diagnosis Algorithm of the 3-D Roll Shape

3.1 Finite strip element method

Modern strip mills generally roll the strip with large width. In order to overcome the difficulty of solving the problem of the large strip width and the shortcoming of a great deal of computation, the authors used the finite strip element method. As shown in Fig. 4, total strip is assumed to be linearly composed of several elements. It is also assumed that there are no steady state thickness errors in each segment. The same finite element method is also applied to roll shape in width direction for the analysis of the 3-D roll shape fault, as shown in Fig. 5. It is assumed that there are no steady state radius errors of roll in each element.

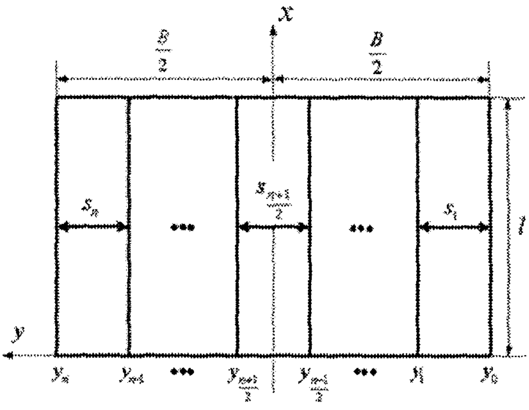

Fig. 4 Finite element division of a strip

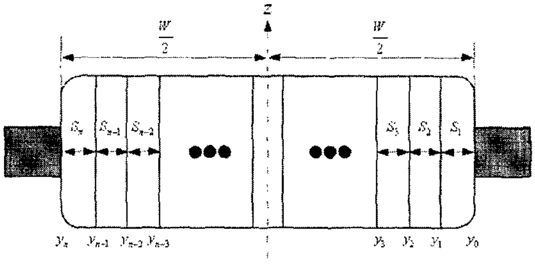

Fig. 5 Finite element division of a roll

3.2 Parameter analysis

Eqs. (1), (2), and (3) have strong correlations, thus they must be computed simultaneously. But it needs very long computation time because of many coupled parameters in these equations. So it is necessary to find the major factors which affect on the 3-D roll shape analysis. Figure 6 shows that the change in the value of rolling force function is very small as the delivery strip thickness varies. Therefore, it could be assumed to be constant in the region of small thickness variation. The same conclusion could be made for the deformed roll radius as shown in Fig. 7. But rolling pressure is very sensitive to the variation of delivery strip thickness (Fig. 8). From this parameter sensitivity analysis, we assumed that rolling force function and deformed roll radius are constant, and rolling pressure is a variable during computer simulation.

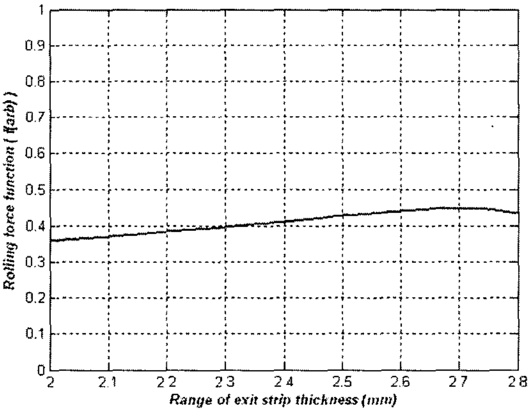

Fig. 6 Rolling force function variation

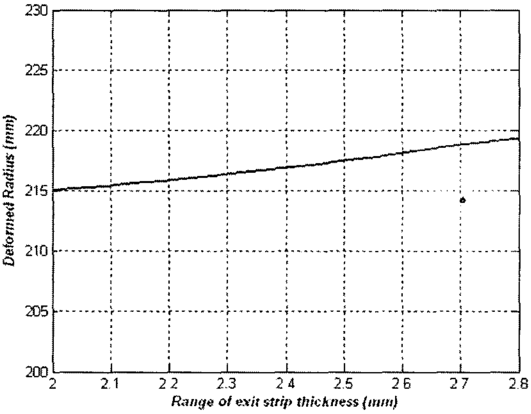

Fig. 7 Deformed roll radius variation

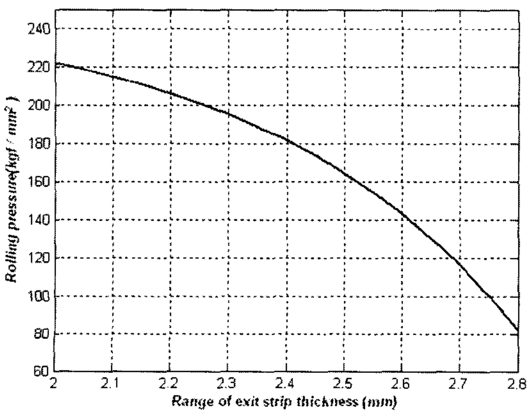

Fig. 8 Rolling pressure variation

3.3 The proposed diagnosis algorithm

It is assumed that the roll gap is controlled within the allowable bound and there are no faults in the entry and delivery strip thickness measurement. The fault diagnosis algorithm for 3-D roll shape can be outlined as follows and the flowchart of that is shown in Fig. 9.

Diagnosis algorithm

Step 1 (Thickness measurement):

The entry and the delivery strip thickness are taken from gauge meters in each stand.

Step 2 (Calculation input parameters):

The tension and the velocity values of each strip element are calculated by Eq. (1) and the law of the conservation of mass within a span respectively.

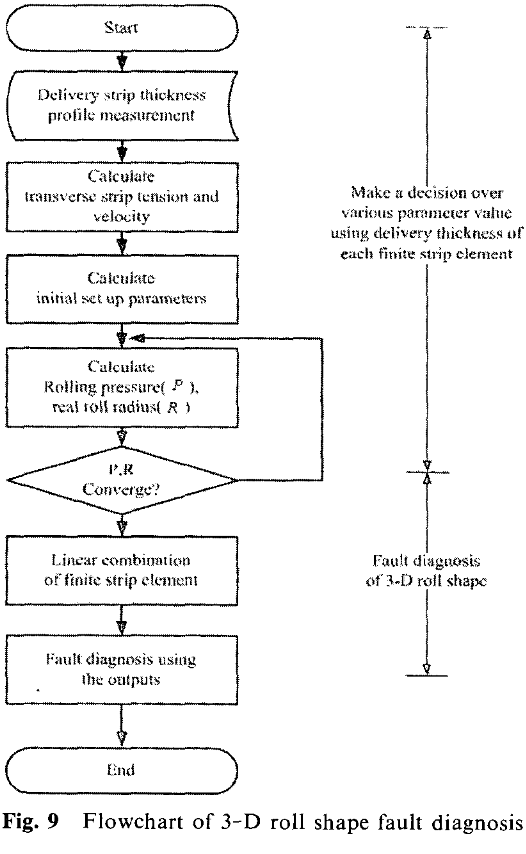

Fig. 9 Flowchart of 3-D roll shape fault diagnosis

Step 3 (Initial values):

In order to calculate the mathematical models as shown in Eqs. (1), (2), and (3) simultaneously, find out the set-up values.

Step 4 (Calculation of features):

By using Eqs. (2) and (3), the calculations of roll radius and rolling pressure in each strip element are repeatedly executed until they converge.

Step 5 (Linear combination):

By using the results obtained from step 3, the total 3-D roll shape is reconstituted.

Step 6 (Fault diagnosis) :

Fault diagnosis of the 3-D roll shape is carried out using the outputs from step 4.

4. Diagnosis Algorithm Verification

4.1 Parameter values and system condition for numerical simulation

A series of numerical simulations for a simplified rolling system (Fig. 10) has been carried out to verify the performance of proposed diagnosis algorithm. It is assumed that this system includes faulty rolls at stand 1. And it is also assumed that a roll has two kinds of faults such as periodic eccentricity in circumferential direction and non-uniform radius in width direction which may be symmetric, asymmetric, and random.

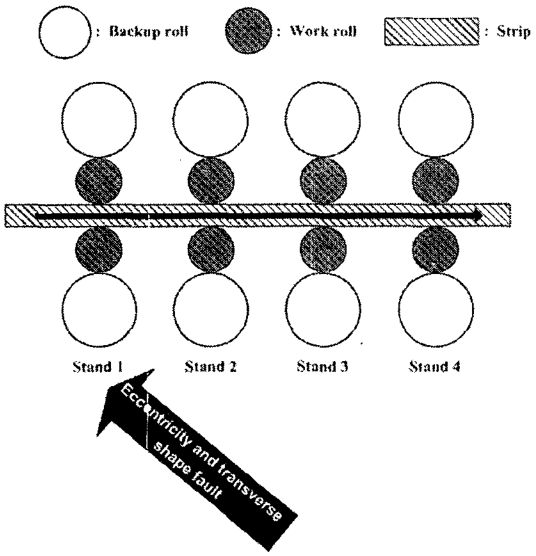

Fig. 10 A simplified cold rolling system

Table 1 shows the reference strip thickness and strip stress of stand 1. Table 2 shows the simulation condition data that are applied to rolling and tension models. A typical strip and cold rolling system operating conditions were used for computer simulation.

4.2 Results and discussions

The transverse thickness of the strip at the entrance of the first stand is assumed to be uniform. The entry and delivery strip thickness obtained from measuring instruments at stand 1 are used to estimate strip stress. In stand 1, it is found out that uneven delivery thickness causes different strip velocity for each finite segment of the strip from the simulation results. The strip stress variation between stand 1 and stand 2 is induced by the strip speed change as shown in Fig. 11. The uneven reduction of the strip in width direction causes inequality in transverse rolling pressure distribution, as shown in Fig. 12. Finally, the diagnosis of 3-D roll shape is carried out by using the information of strip

Table 1 Simulation conditions

	Stand No. 1	Values
Reference strip thickness	Entrance	10 mm
	Exit	7 mm
Reference strip stress	Entrance	149.94 MPa
	Exit	200.9 MPa

Table 2 Rolling system parameters

Simulation parameters	Values
Drive-side mill constant (K_D)	4×10^9 N/m
Work-side mill constant (K_W)	4×10^9 N/m
Work roll radius	210 mm
Distance between stands	6000 mm
Strip width	1280 mm
Poisson's coefficient of strip	0.12
Elastic modulus	0.021 MPa
The number of finite strip element	32
The width of a finite strip element	40 mm

thickness, strip velocity, strip stress, mill operation values, rolling set up parameters, and rolling mechanism. From the simulation results, it is found out that the proposed diagnosis algorithm is successfully able to detect that the work roll in stand 1 has a periodic eccentricity and une-

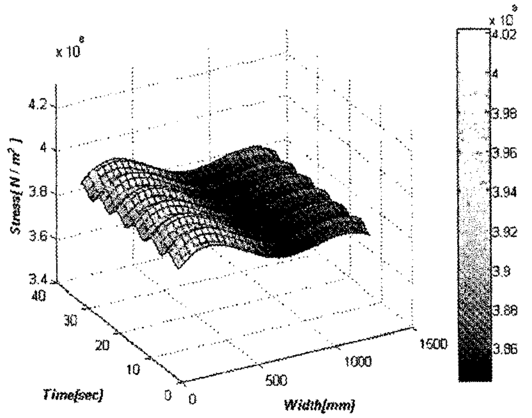

Fig. 11 Stress profile betwen stand 1 and stand 2

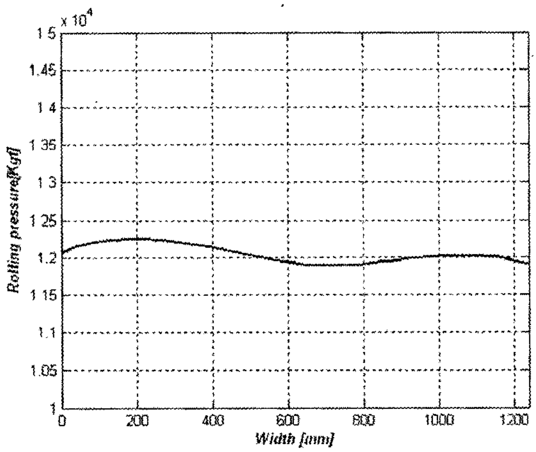

Fig. 12 Transverse rolling pressure in stand 1

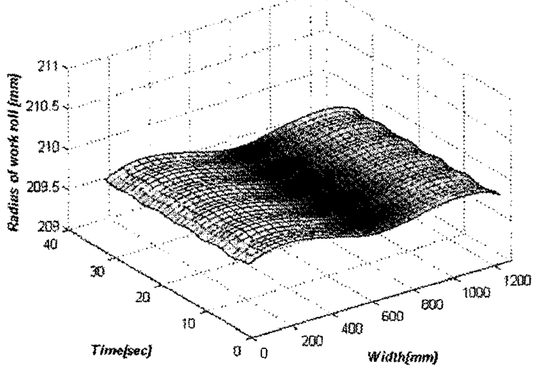

Fig. 13 Radius of the work roll in stand 1

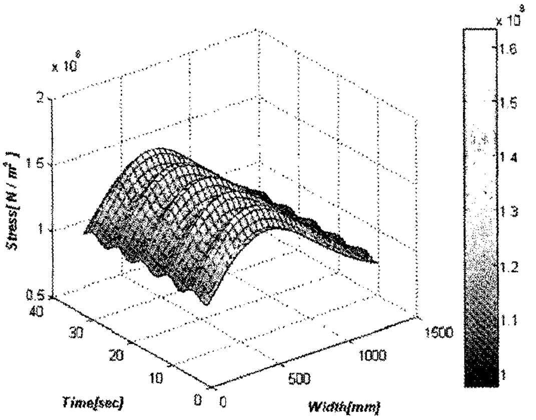

Fig. 14 Front strip stress in stand 1

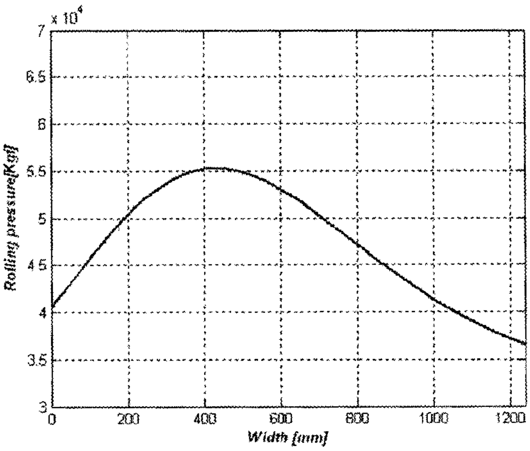

Fig. 15 Transverse rolling pressure in stand 1

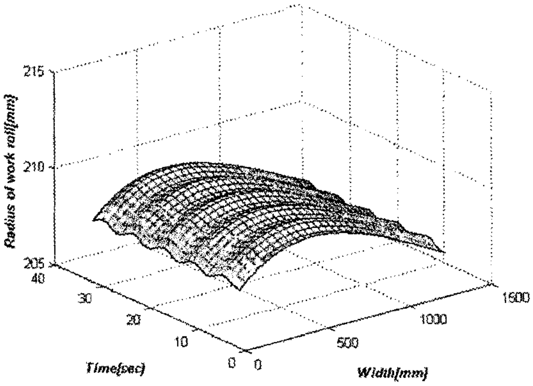

Fig. 16 Radius of the work roll in stand 1

ven transverse radius roll, as shown Fig. 13. The faulty work roll in stand 1 has a 0.0499% maximum roll radius error.

The same procedure of diagnosis as described above is applied to stand 1 with assumption that different delivery strip thickness error in stand 1. A Front strip stress distribution due to delivery thickness error is shown in Fig. 14. The uneven transverse reduction of the strip thickness generates the error of rolling pressure in width direction, as shown Fig. 15. Finally, 3-D roll shape of the faulty roll in stand 1 is obtained by the proposed diagnosis algorithm, as shown in Fig. 16.

5. Conclusions

A new diagnosis algorithm has been proposed to predict the fault of the 3-D roll shape. The finite strip element method has been used to reduce the computation time and to analyze the behavior of total material for large dimensional problem. For the purpose of effective calculation, the parameter sensitivity analysis has been executed.

A series of numerical simulations were carried out for several conditions of work roll to verify the performance of the proposed diagnosis algorithm. The main results of this study are summarized as follows :

(1) The main factors for fault diagnosis of 3-D roll shape are defined.

(2) A new diagnosis algorithm is proposed for the estimation of the 3-D roll shape using the measured strip thickness, the correlation of a tension model, a rolling model, and the rolling mechanism.

(3) The diagnosis method is very effective in analyzing the work roll shape in a rolling process.

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