研究論文

1.0Cr-1.0Mo-0.25V 터어빈 로터강의 열영향부 연화층이 크립 파단 특성에 미치는 영향

- Part I: 크립 파단 수명 -

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Effect of HAZ Softening Zone on Creep Rupture Properties of 1.0Cr-1.0Mo-0.25V Turbine Rotor Steels

- Part I : Creep Rupture Life -

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Key Words : Turbine Rotor Steel (터어빈 로터강), Weld Repair (보수용접), Softening Zone (연화층), Heat Input (열입열량), HAZ (열영향부), Creep Rupture Life (크립 파단수명)

초 록

손상된 ASTM A-470 class 8 고압 증기 터어빈 로터강의 수명 연장을 위해 보수 용접이 행하여졌다. SAW 용접부의 미세경도 측정결과 모재의 경도는 VHN 253이었으나 모재에 근접한 열영향부의 경도는 VHN 227로 떨어졌다. 이와같이 경도가 떨어진 영역을 "연화층"이라 정의하였으며 약 0.5-0.6mm의 크기를 나타내었다. 한편 크립 파단 시험시 파괴는 연화층 부근에서 일어났으며 593℃와 19Ksi (132 Mpa)에서 파단시간은 772.4hr이었다. 연화층의 크기를 줄이기 위해서 MIG 및 TIG 용접이 행하여졌는데 연화층 크기는 MIG의 경우 0.3-0.4mm이고 TIG의 경우에는 입열량의 크기에 따라 0 부터 0.4mm의 크기를 나타내었다. 그러나 크립 파단시간은 연화층 크기가 작어질수록 감소하였다. 특히 TIG 용접부의 경우 크립 파단시간은 입열량과 밀접한 관계를 나타내었는데 입열량이 클수록 파단시간은 길어졌다. 대부분의 파괴는 ICHAZ에서 발생되었으나 입열량이 감소함에 따라 파단부는 CGHAZ으로 이동하였다. 파단면은 tearing과 dimple을 갖는 입내파괴를 나타내었다.

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Abstract

Weld repair of ASTM A-470 class 8 high pressure (HP) steam turbine rotor steel has been performed to extend the service life of older fossil units. Microhardness measurements were conducted across the weldment from unaffected base metal (BM) to weld metal (WM). The hardness of the BM was VHN 253, however it dropped up to VHN 227 at the heat affected zone (HAZ) close to unaffected BM for multipass SAW. This area of hardness drop is called ″ softening zone″ and has a width of 0. 5-0. 6 mm. During creep rupture test, failure occurred around the softening zone and rupture time was 772. 4hr at 19 Ksi (132 Mpa) and 593℃. Multipass MIG and TIG welding have been employed to reduce the softening zone width. The softening zone width for MIG was 0. 3 - 0. 4 mm and for TIG was zero-0. 4 mm depending on heat inputs. However creep rupture time was decreased as softening zone width reduced. Creep rupture time also showed a close relationship with heat inputs in TIG process. The higher heat input, the longer rupture time. Most failure occurred at intercritical HAZ (ICHAZ), however rupture location was shifted to coarse grained HAZ (CGHAZ) as heat input decreased. The rupture surface showed tearing and dimple which indicated transgranular fracture.

1. Introduction

Low alloy ferritic steel, particularly, 1. 0Cr-1. 0Mo-0. 25V steel has been widely used as a rotor steel for many years. This steel is relatively inexpensive, tough, and ductile at low temperatures; retains its strength at elevated temperatures and has good hardenability characteristics. The inlet and exhaust temperatures of a typical fossil HP turbine are around 538℃ which corresponds to a temperature range where creep embrittlement[1, 2], temper embrittlement[3, 4] and low cyclic fatigue[5, 6] are of great concern. Since the steam turbine rotor is among the most critical and highly stressed components, these defects can cause catastrophic rotor bursts.

When a turbine rotor gets severely damaged, the utility must remove the unit from service and replace it with a new one. Normally, it takes 2-3 years to get a new turbine rotor made and put into service. As an alternative method, weld repair of turbine rotors, if feasible, offers opportunity for significant savings to electric utilities and their customers. Such repairs could restore a damaged rotor and return it to service until a new turbine rotor arrives. Usually weld repair of the damaged region is carried out by build up techniques or if necessary, replace the local interstage section with a new forging welded to the old rotor. The repair of steam turbine rotors using welding favors not only cost benefits but also intrinsic risks. Although weld repair is an attractive means, some difficulties may be encountered mainly due to Cr-Mo-V steel weldability. The nominal composition of Cr-Mo-V steels is considered difficult to weld because of their high carbon content, impurities and alloying contents. This alloy was developed to provide optimum high temperature fatigue and creep properties and was not originally intended to be welded. Therefore, close consideration should be given for repair welding to meet the satisfactory service at elevated temperatures.

It has been shown that poor weldability problems can be associated with fabrication and service: Those problems are normally transverse weld metal cracking[7], hot cracking[8] and circumferencial HAZ reheat cracking[9]. Reheat cracking occurs typically at the CGHAZ during stress relief heat treatment[10] or more gradually in service. In Kim s investigation[11], retired rotor steel had coarse prior austenite grains (about 120 ㎛), making this rotor very susceptible to reheat cracking. However, Kim did not find reheat cracking because of the grain refinement that occurred at the CGHAZ due to multipass welding.

Besides the reheat cracking, creep damage is also major interest of repair welding. According to D. J. Gooch[12] circumference cracking in the transition zone between the HAZ and the BM has increased for long term service. This is designated as "type IV" cracking and is considered the major failure mechanism for 2.25Cr-0.5Mo-0.25V, 2.25Cr-1Mo, and other low alloy ferritic steel weldment. Type IV cracking is thought to be primarily a consequence of excessive system stresses, however failure location varies with welding process, heat input and applied creep rupture stress[13]. The objectives of this study are i) to characterize the failure behavior at the HAZ of crosswelds produced with different welding processes and heat inputs, and ii) to determine optimum condition for repair welding of HP steam turbine rotors.

2. Experimental Procedure

Multipass welds were produced on coupons machined from the turbine rotor steel which was retired after 20 years of service. The chemical compositions of the rotor steel are shown in Table 1. Three different welding processes, submerged arc welding (SAW), metal inert gas welding (MIG) and tungsten inert gas welding (TIG) were employed. Preheating was conducted at 200℃ and interpass temperature was maintained between 200-250℃. All weldments were post weld heat treated (PWHT) at 676℃. Table 2 summarizes welding conditions for SAW, MIG and TIG weld. Test specimens were machined for microhardness and creep rupture test after PWHT. Figure 1 shows location of creep rupture test specimens taken and dimensions. Creep rupture tests were performed at 593℃ and 19 Ksi (132 Mpa).

Table 1. Chemical Compositions of the Rotor Steel (wt-%)

C	Mn	P	S	Si	Ni	Cr	Mo	V
0.335	0.850	0.020	0.021	0.248	0.137	1.070	1.170	0.280

Table 2. Summary of Welding Conditions for SAW, MIG and TIG Weld

Weld Type	Current (A)	Voltage (V)	Travel Speed (ipm)	Heat Input (kJ/in)
SAW	575	28	16	60.4
MIG	265	29	9	51
TIG	265	12	4	48
TIG	240	16	4	57.6
TIG	245	10	1.88	78
TIG	250	10.5	1.75	90
TIG	250	10.5	1.5	105
TIG	250	10.5	1.3	120

3. Results and Discussion

Development of Softening Zone at HAZ adjacent to the BM

Microhardness measurements across the HAZ and BM for SAW are observed in Figure 2. The hardness values range from 343 VHN near the fusion line to 227 VHN near the interface between HAZ and BM. The hardness then rapidly increases to 253 VHN at the BM. A 26 VHN drop

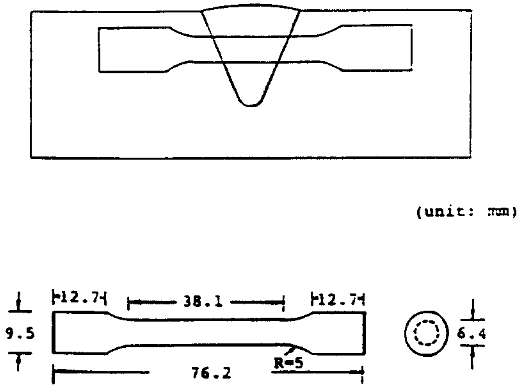


Fig. 1 Location of creep rupture specimens taken and dimensions

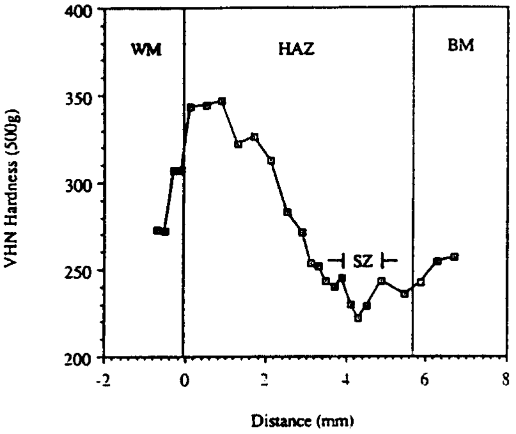


Fig. 2 Microhardness showing cross weldment of SAW process

occurs at HAZ adjacent to the BM and this region is called "softening zone (SZ)".

The softening zone had already been reported by many other researchers[14,15] it is expected that the bainite structure of the matrix becomes softer as a result of tempering from the thermal cycle of welding for those microstructures experiencing temperatures above the eutectoid temperature, A_1. A slight overstepping of the A_1 temperature can cause meaningful structural changes; A_1 temperature was measured for the rotor steel used in this study using Differential Thermal Expansion and determined to be 780℃. Above the A_1 temperature, some bainite get tempered and the remaining of the bainite transforms into austenite. The new austenite is formed at the expense of carbide particles present in the tempered structure and on cooling it is expected to transform into hard phases such as lower bainite and martensite. The final hardness of this critical softening zone is a function of the amount of the newly formed hard phases and of the further tempering and carbide coarsening of the original microstructure.

In case of welding, the temperature caused softening could be higher than A_1 temperature. Because there was not enough time to soften just above the A_1 temperature, it must be much higher than A_1 temperature. It is clear that minimum hardness at the softening zone was obtained beyond boundary between HAZ and BM - corresponds to A_1 temperature - as shown in Figure 2. Since all the welding processes employed have a thermal experience in softening temperature range at the HAZ, the dwell time above A_1 temperature will affect on the softening zone size and hardness drop. The dwell time experience above A_1 temperature is related to both the welding processes and heat inputs selected, consequently the characteristics of the softening zone is also dependent on the welding parameters.

Characteristics of Softening Zone with Various Welding Processes and Heat Inputs

Selection of welding process influences the softening zone size and hardness. Since SAW possesses higher arc transfer coefficient, consequently larger softening zone size and lower hardness would be expected at the same heat input, compared with TIG and MIG processes. Table 3 shows the softening zone size and hardness with different welding processes. The largest softening zone width was obtained for SAW weld, which has 0.5-0.6 mm at 60.4 kJ/in heat input. In addition, the lowest microhardness readings in this region were obtained for the SAW weld. As expected, the TIG weldment has a softening zone of only 0. 1-0. 2 mm wide despite almost the same heat input with the SAW process. Not only was the size of softening zone small but also the hardness drop was negligible in the TIG weld made at 57. 6 kJ/in heat input. The thermal experience resulting from the MIG process (51. 0 kJ/in) is between SAW and TIG processes which translates into microhardness values in the softening zone between the SAW and TIG welds. Figure 3 compares three different welding processes in terms of their microhardness around the softening zone.

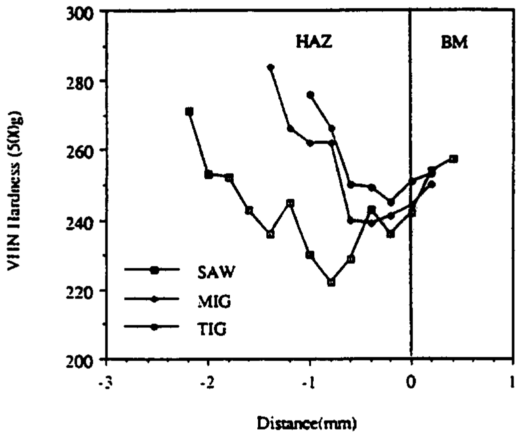


Fig. 3 Microhardness around the softening zone for SAW, MIG and TIG process

For the same welding process, the softening zone characteristics changed depending upon heat input. A higher heat input weld resulted in a larger softening zone and greater hardness drop than that of lower heat input weld. Figure 4 illustrates microhardness around the softening zone for TIG weldments of different heat inputs. No softening regions were found in the TIG welds that had heat input of 48 kJ/in, however the softening zone clearly redeveloped at the heat input of 78 kJ/in. The 78 kJ/in weldment had an average microhardness of 235 VHN at the softening zone and width of about 0. 3-0. 4 mm. TIG welds with high heat inputs, 90 kJ/in. 105 kJ/in and 120 kJ/in, were made with the aim of obtaining HAZ characteristics similar to SAW weld. As heat input increased, the microhardness at the softening zone in the TIG welds approached the value of SAW weld. The SAW process has an average hardness of 227 VHN at the softening zone. The average microhardness at each of the softening zones of the welds produced at 90 kJ/in, 105 kJ/in and 120 kJ/in was 231, 230 and 229 VHN respectively. The softening zone width was almost the same as 78 kJ/in heat input, that is about 0. 3-0. 4 mm. Since the microhardness indentations were only 0. 2 mm apart, it was technically difficult to differentiate the softening zone width. However the HAZ size increased proportionally with heat input as summarized in Table 3.

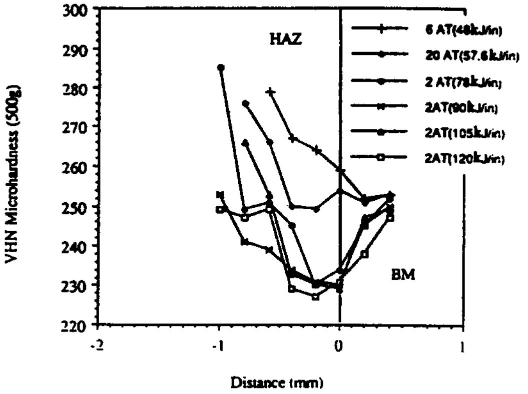


Fig. 4 Microhardness around the softening zone with different heat input TIG process

Correlation between Softening Zone and Creep Rupture Life

In the TIG process, as we mentioned, softening zone width was increased as heat input increased. The development of softening zone thought to be detrimental to the creep rupture life. This is because the rupture time was usually inverse relationship with hardness. A low hardness has a

Table 3. Summary of HAZ Properties with Different Welding Processes and Heat Inputs

Weld Type	Heat Input (kJ/in)	Softening Zone		HAZ Size (mm)
		Hardness (VHN)	Size (mm)	
SAW	60.4	227	0.5~0.6	5.9
MIG	51.0	240	0.3~0.4	2.7
TIG	48.0	259	None	2.1
TIG	57.6	247	0.1~0.2	2.3
TIG	78.0	235	0.3~0.4	2.8
TIG	90.0	231	0.3~0.4	3.2
TIG	105.0	230	0.3~0.4	3.4
TIG	120.0	229	0.3~0.4	3.8

trend shorter rupture time under the creep condition[1]. This was confirmed from simulation work in this study. Simulation work was conducted at temperature of 770℃, 790℃, 840℃ and 890℃ for 4hr to permit complete homogenization. After heat treatment, creep rupture tests were conducted for all the specimens at 30 Ksi (208 Mpa) and 593℃. A lowest hardness was obtained at 790℃ which is just above A1 temperature of 780℃. As we expect, a minimum rupture time was also achieved at 790℃ as summarized in Table 4. The rupture time again increased as temperature increased.

Table 4. Summary of Creep Rupture Test for Furnace Simulated Specimens Tested at 593℃ and 30 Ksi (208 Mpa).

Simulation Temp. (℃)	Hardness (VHN)	Rupture Time (hr)	Sec. Creep Rate (%h)
770	223	137.5	0.01740
790	216	102.0	0.02750
840	265	145.7	0.01230
890	273	407.2	0.00513

However, on the contrary to original thought, rupture time was improved as softening zone developed. Figure 5 attempts to correlate the weld heat input to the creep rupture time in the TIG process. The size of softening zone was increased between the heat inputs of 48 kJ/in and 90 kJ/in and the rupture time was also found to increase. The softening zone obviously contribute strain accumulation due to it s low hardness.

It was expected that the rupture times of the 105 kJ/in and 120 kJ/in welds would exceed those of the 90 kJ/in weldment. Nonetheless rupture time dropped when the welds were processed at heat inputs of 105 kJ/in and 120 kJ/in. Unless significant submicroscopic differences are found, the fluctuations in the welding parameters during fabrication or carelessness in the weld coupon production would have influenced the microstructure and led to lower creep rupture times than expected.

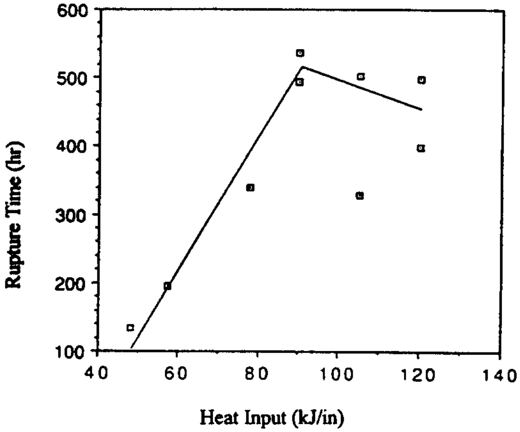


Fig. 5 Relationship between heat input and rupture time

Typical creep curves for the TIG with 48 kJ/in, 90 kJ/in, 105 kJ/in and 120 kJ/in heat inputs crossweldments tested at 593℃ and 19 Ksi (132 Mpa) are shown in Figure 6. It can be seen that the creep behavior of all the specimens were characterized by small instantaneous strains on loading, followed by primary, secondary and tertiary creep regions. As heat input decreased, primary and secondary stages of creep exhibited shorter. The steady state creep rate generally increased with decreased in heat input. The steady state creep rate (could be described by a power law relation $\varepsilon = A\sigma^n$ where n is the stress index and A is material constant. Stress exponent n was found to have higher values for lower heat input.

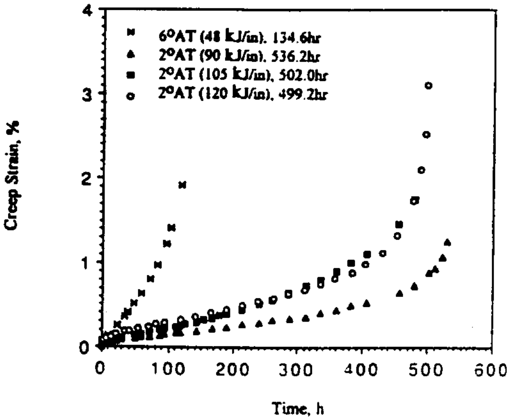
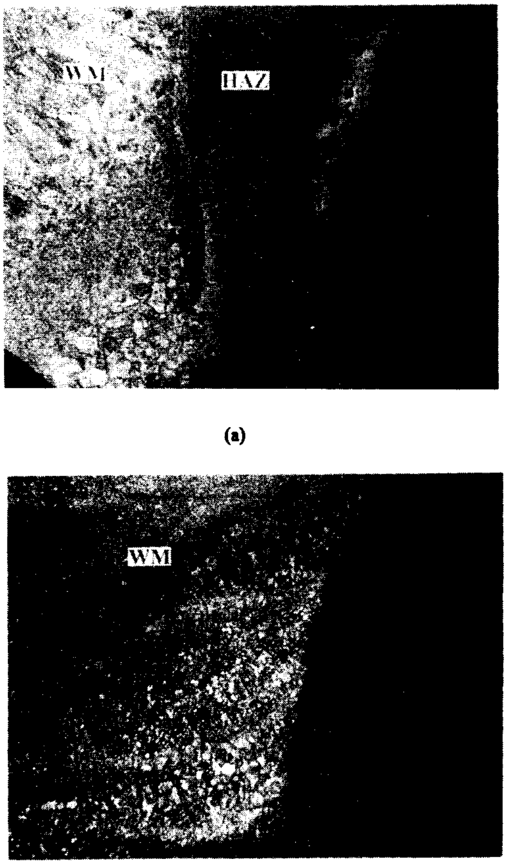


Fig. 6 Creep curve for 48kJ/in, 90kJ/in, 105kJ/in and 120kJ/in heat input at 1100°F and 19Ksi (132Mpa)

Creep Rupture Mode

During creep rupture test, all fractures occurred at the HAZ without any exception. Some fractured at the ICHAZ near the unaffected BM and others at the CGHAZ close to fusion line. Failure occurred at ICHAZ had already been designated as type IV cracking[12]. Precisely speaking, failure occurred at boundary between softening zone and hardness abruptly increase. R. H. Cook[17] found that the failure often occurred near structural or strength transition . Figure 7 (a) and (b) show cross sections of two creep rupture specimens ruptured at the ICHAZ and CGHAZ respectively. It was observed that welds which have clearly developed a softening zone would usually fail at the ICHAZ. The SAW and TIG with heat inputs of higher than 78 kJ/in welds were associated with this type of rupture. However, welds which did not have obvious softening zone would rupture at the CGHAZ that included TIG with heat inputs of lower than 57.6 kJ/in weld. It was also found that some welds had mixed type of rupture both ICHAZ and CGHAZ.

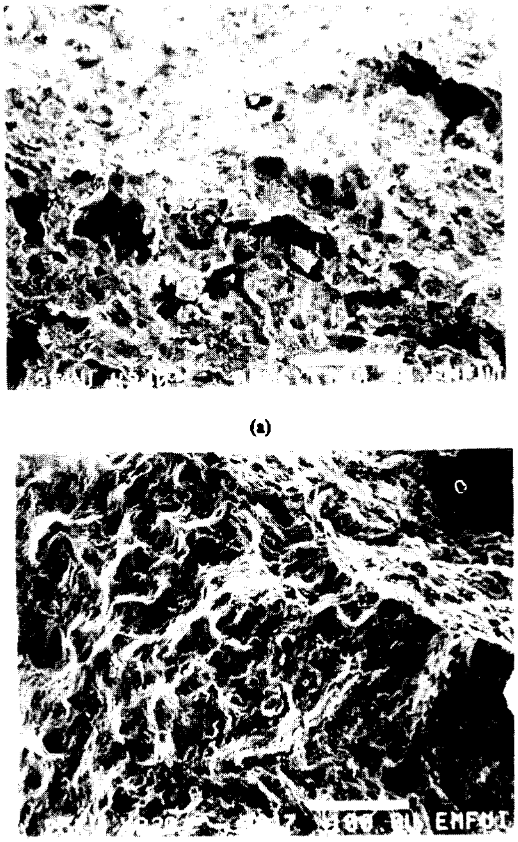


(a)

(b)

Fig. 7 Cross section of creep rupture specimens ruptured at (a) ICHAZ and (b) CGHAZ

Although the softening zone is critical for creep rupture test due to low stress, it becomes immune as increased the applied stress. It was confirmed in case of hot tensile test. Since tensile test has high applied stress and strain rate, softening zone does not much influence on the test results. This is clearly illustrated from the failure location. Failure occurred at BM instead of HAZ for hot



(a)

(b)

Fig. 8 Scanning electron micrographs obtained fracture surface of (a) SAW and (b) 78kJ/in heat input TIG weld

tensile test[18].

Figure 8 (a) and (b) show the fracture surface of the SAW and TIG with 78 kJ/in heat input crossweld creep rupture specimens observed by scanning electron microscope. All specimens failed by predominantly transgranular fracture showing a typical ductile mode with transgranular dimples. The SAW weldments showed also tearing as shown in Figure 8 (a).

4. Conclusions

Repair welding of bainitic HP rotor steels was performed and following conclusions were drawn.

1. Hardness drop was found at HAZ adjacent to the BM and this region is called "softening zone". The size of softening zone changed with the welding processes and heat inputs.
2. In creep rupture tests, most failure occurred at either ICHAZ or CGHAZ. The SAW and TIG with higher heat input than 78 kJ/in weld ruptured at ICHAZ. The failure location moved from ICHAZ to CGHAZ as heat input was decreased for the same TIG process. TIG weld with heat input lower than 57.6 kJ/in ruptured at CGHAZ near the fusion line.
3. SAW and/or high heat input TIG process provided the best creep rupture life.

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