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Multi-sensor in process monitoring for WAAM: Detection of process instability in electrical signals

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Abstract. Wire Arc Additive Manufacturing (WAAM) is a promising process for producing medium to large scale metallic parts at a low cost and with a high deposition rate. However, the multitude of process parameters and physical phenomena involved makes it complex and hard to master. Therefore, monitoring the process becomes crucial for unraveling complexities and attaining a more profound comprehension of the intricacies inherent in WAAM, hence ensuring process stability. In order to produce a defect-free part, while keeping a stable process, the operating parameters must be carefully selected. Nonetheless, one of the significant hurdles in WAAM is the variability of the deposited layers height. The accumulation of these geometrical inaccuracies induces instabilities in the process which results into the appearing of defects on the deposited part. The aim of this study is to investigate the correlations between process instabilities and electrical signals obtained by a deposition monitoring system. A monitoring criterion is then extracted from experimental data. Correlation with instabilities will be confirmed using a thermal camera.

Introduction

Additive Manufacturing (AM) is the process of joining materials layer upon layer to make a 3D part. AM presents a long list of advantages among which the reduction of material waste and manufacturing cost. Compared with conventional subtractive manufacturing, namely machining, additive manufacturing offers a higher level of design complexity and an increased automation level from part design to fabrication [1]. Directed Energy Deposition (DED) is a category of AM established to manufacture metallic parts. It involves using a focused thermal energy (e.g. electron beam or electrical arc) to melt materials as they are being deposited [2].

Wire Arc Additive Manufacturing (WAAM) is a DED technology that offers a remarkable energy efficacy. WAAM employs the concept of arc welding combined with a wire feeding mechanism and a motion platform to produce parts. The feedstock wire undergoes melting through the heat energy of an electric arc created between the wire and a metallic substrate. Subsequently, the melted drops are deposited on the substrate and the formation of the deposition bead occurs through the cooling of the molten pool. Additionally, the process involves gas-shielding techniques to protect the molten metal from atmospheric contaminants [3].Various energy sources are employed for generating input energy, including Cold Metal Transfer (CMT), a variant of Gas Metal Arc Welding (GMAW) developed by Fronius. It provides a precise method of material deposition through a mechanical retraction wire system, facilitating controlled droplet release in a short circuit. This results in low heat input, heightened stability, and minimal spatter [4].

In WAAM, the occurrence of defects on manufactured parts represents a significant challenge. Commonly observed defects include porosity, deformations due to residual stresses, surface cracks and spatter. These imperfections often stem from inappropriate process parameter configurations, excessive heat accumulation, or external environmental factors such as gas contamination or machine malfunctions [5]. Therefore, monitoring the process represents a first step toward a stable and defect free fabrication [6].

Monitoring WAAM processes can improve stability and part quality. Methods include temperature sensing, arc electrical signal sensing, visual sensing with cameras, and acoustic emission sensing [7]. Optical and InfraRed cameras are proven to be efficient in detecting geometrical inaccuracies [8] and surface defects [9] but collecting data can be challenging in harsh welding conditions due to sensitivity to lighting conditions. On another hand, welding sound signals were confirmed to be a good indicator of weld defects [10]. Yet it is very challenging to precisely discern these signals amid a noisy welding environment.

To produce part by WAAM, the designed CAD model undergoes layer slicing with constant estimated layer height, defining the torch toolpath. Setting key process parameters, including wire feed speed, torch travel speed, and gas flow rate, is also crucial. Unfortunately, despite optimized parameters, geometric inaccuracies remain inevitable. In some cases, the accumulation of these geometrical inaccuracies leads to the increase of the Contact Tube to Workpiece Distance (CTWD) causing the appearance of porosity. Conversely, an excessively short CTWD might cause collision with the work piece [11]. In both cases process instability is noticeable through the appearance of spatter. Researchers explored the stability of the process through optical measurement of the distance between the tip of the electrode and the top layer in Gas Tungsten based WAAM. They confirmed that the stability of the process is reflected by the measured distance and developed a closed loop control to maintain it constant, resulting in a spatter free part [12]. On another hand, monitoring arc stability in Gas Metal based WAAM was also explored and characterized for different metal transfer modes [13]. It was proven that arc electrical signals are very sensitive to CTWD variations, hence to process stability. Finally, many researchers underscore the need for increased focus on identifying criteria parameters that give insights into the welding process, including spatter [14]. This paper introduces a method for detecting process instability. Section 2 outlines the experimental procedure. The experimental results are presented in section 3. In section 4, the identification of instability in the signals leads to the proposal of a monitoring criterion, validated by thermal camera data.

Experimental procedure and methodology

To conduct experiments, a Fronius TPS 500i© welding machine was used. The welding torch is mounted on a Staübli TX90© six-axis robot which serves as motion platform and allows the production of large-scale parts (Fig. 1).

Table 1 : Process parameters

Wire material	Wire diameter	Gas composition	Gas flowrate	Substrate thickness
ER70S-6	1 [mm]	(M20 Ar+5-10%CO2)	20 [L/min]	6 [mm]

For all the experiments, the gas flow rate was fixed at 20L/min. A steel wire with a diameter of 1.0 mm and a 6 mm thick steel substrate were used. The substrate was clamped at four diagonal points to avoid the effect of residual stress and maintain consistent substrate flatness for all tests (Fig 1.). Table 1 lists the process parameters for all the experiments.

Figure 1 : Experimental setup

Arc current was measured at the welding machine ground using a Pico TA167© current probe. As for arc voltage, it was recorded at the nearest possible points to minimize external interference and signal noise using GE8100 differential probe. Data acquisition was done using a National Instrument© card at a sampling rate of 10 kHz in order to capture all phenomena. Finally, an Optris© IR camera was mounted on the welding torch and used to acquire images to validate the detection of instabilities.

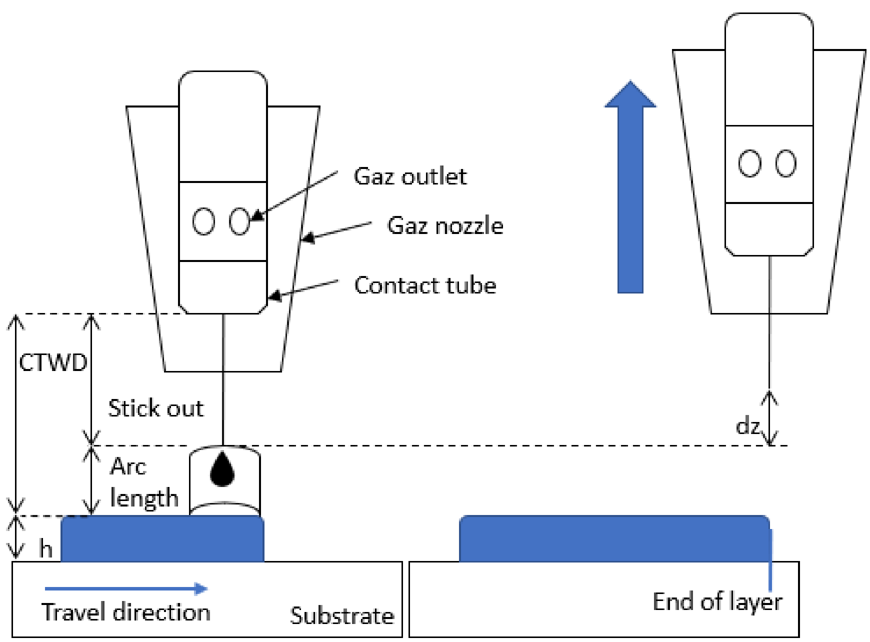

Figure 2 : Schematic representation of WAAM

Table 2 : Experimental test conditions

Wall nb	WFS [m/min]	Set_U [V]	Set_I [A]	TS [mm/s]	CTWD [mm]
1	11	239	25,4	10	14
2	11	239	25,4	10	17
3	11	239	25,4	10	20

Three thin walls of 24 layers were deposited, as outlined in Table 2. Both Wire Feed Speed (WFS) and the Torch Travel Speed (TS) were the same for the three walls to maintain a constant material deposition rate throughout all experiments. The height increment dz (Fig. 2) was set based on previous experiments and kept constant throughout all the experiments. Manual adjustments of the Contact Tube to Workpiece Distance to the nominal designed values are made at layer 12 and layer 24 for all walls.

Experimental results

Figure 3 exhibits the measured current and voltage signals during deposition. The waveforms of the chosen CMT-MIX synergy show a periodicity, of around 115 ms. It alternates cold CMT cycles (red rectangles) and pulsed hot arc sequences of 4 ms. This method combines the advantages of both CMT and Pulsed modes and ensures a stable, regular and rapid process with controlled heat input [15].

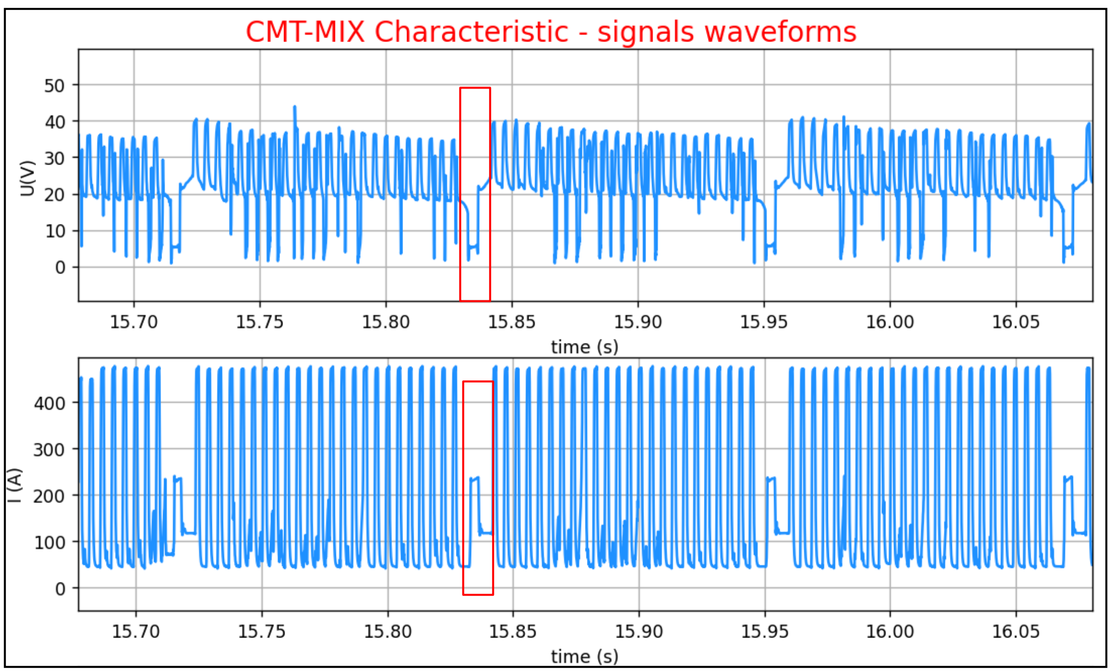

Figure 3 : Waveforms of the typical voltage and current in CMT-MIX characteristic

During deposition, the more layers are deposited, the more geometric errors accumulate. This is primarily attributed to the increasing flatness of each layer. The difference between the actual observed value of CTWD and the set value of CTWD increases progressively. For all walls, from the 7th layer onwards, process instabilities appear in the form of projections. Fig.4 illustrates how these instabilities are also reflected in both current and voltage signals for layer 11 of artifact 3.

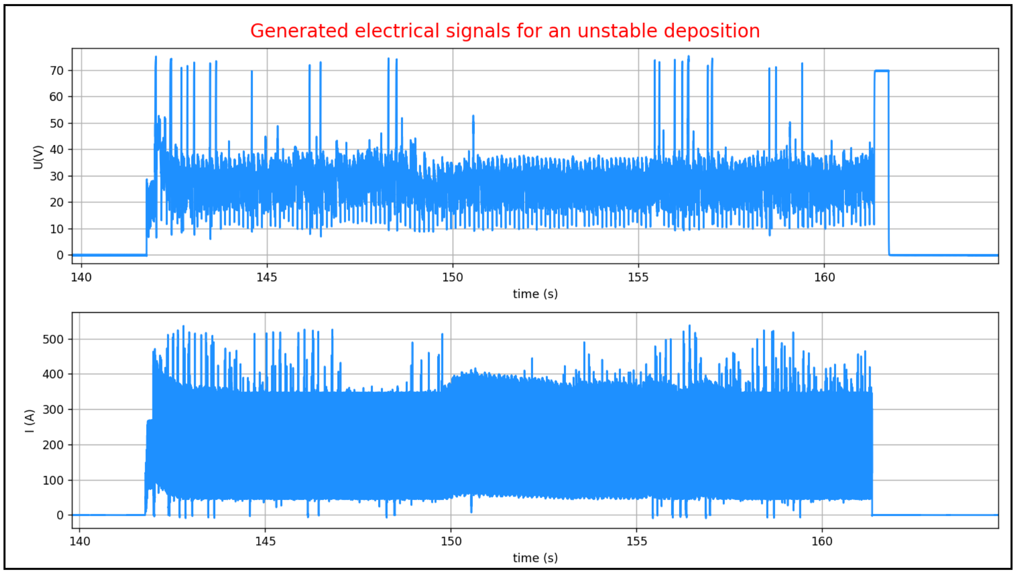

Figure 4 : Electrical signal before CTWD correction

As soon as the CTWD is manually adjusted to its nominal value at layer 12, the deposition resumes a stable appearance, reflected by a significant reduction in spatter. Figure 5 shows the electrical signals of layer 12 of the same wall, just after manual adjustment to its nominal value of 20 mm. It can be seen that the electrical signals are more stable (stationarity and absence of erratic peaks). The same behavior is observed between the 13th and 24th layers for all three walls.

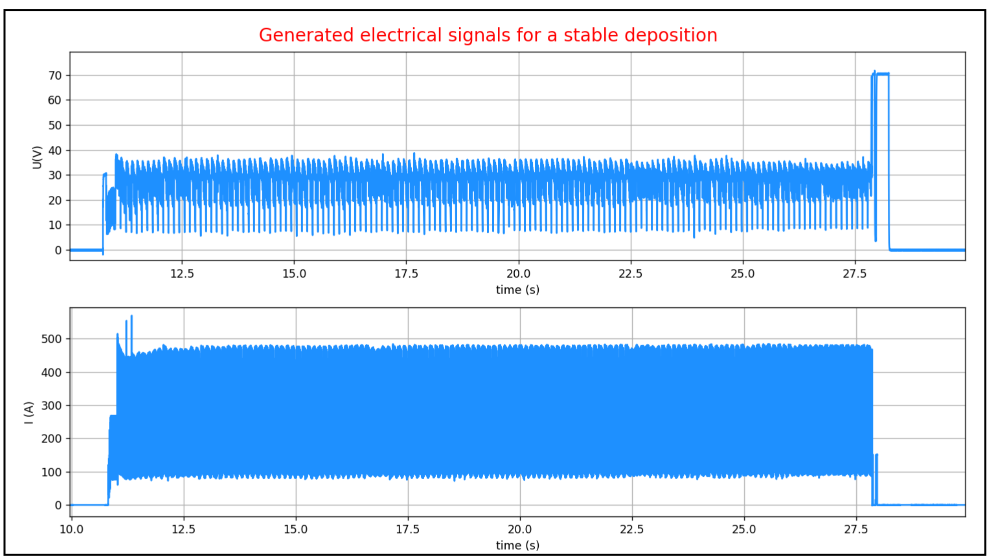

Figure 5 : Electrical signal after CTWD correction

Results and discussion

The experimental results show a clear correlation between the CTWD (Contact Tip to Workpiece Distance) and the stability of electrical signals: as the deviation between the nominal CTWD and the actual CTWD value increases due to the accumulation of geometric inaccuracies, the deposition becomes unstable. During the deposition, three different and interconnected variables are involved: The height increment (dz), the layer height (h) and the contact tube to workpiece distance (CTWD) as shown in figure 2. It is important to note that the layer height h is not constant [16].

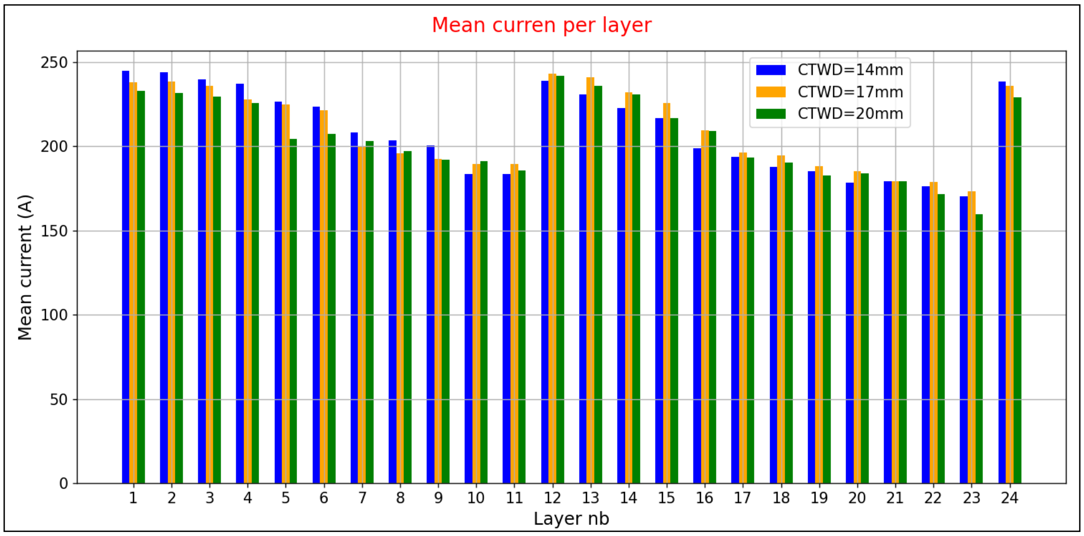

Figure 6: Mean current per layer for artefacts 1,2 and 3

As CTWD increases due to accumulation of geometrical inaccuracies, the Fronius generator autonomously adjusts the stick out (SO) value to maintain a constant arc length, consequently leading to a proportional increase in SO (Fig2.). The extended length of wire extruding from the contact tube results in an elevated wire resistance. On another hand, the welding machine performs corrective measures by manipulating currents. Figure 6 illustrates a decrease in average currents as the CTWD increases. Once the CTWD is corrected, the average currents rise again, as observed in layers 12 and 24, approaching values nearly equal to the set current (set_I = 239 A).

On another hand, figure 7 illustrates an almost constant average voltage aligned with the set value (Set_U= 25.4 V) for all three walls. Recorded data for layers 5 and 7 show lower values due to issues encountered with the voltage probe during the deposition of these layers. This observation confirms that as the CTWD increases, leading to an increase in resistance, the Fronius welding machine responds maintaining a constant arc voltage, resulting in a decrease in currents. This correlation between CTWD adjustments and current changes underscores the real-time correction capability of the Fronius generator, ensuring stability in material deposition despite varying geometric conditions.

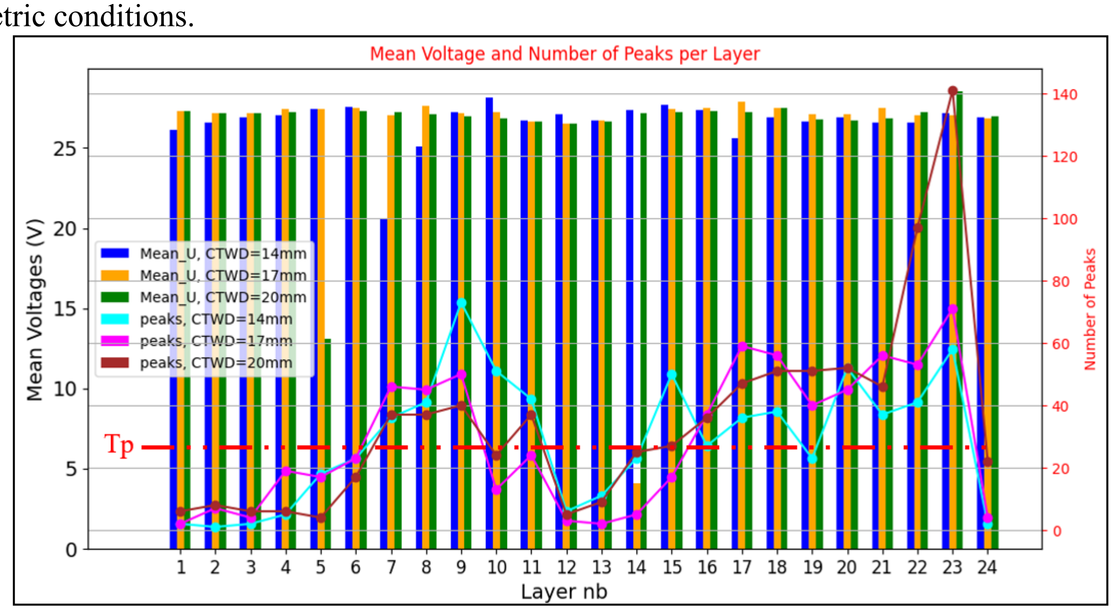

Figure 7: Mean voltage and peak count for artefact 1,2 and 3

Figure 4 shows that, for a large CTWD of 33 mm, the voltage signals exhibit instability with significant and random peaks. This behavior has also been observed for other unstable layers. To characterize these instabilities, a monitoring criterion is proposed based on the detection of peaks in the voltage signals. The detection and counting of peaks with amplitudes exceeding a fixed threshold T_u, as shown in Equation (1), allow quantifying the number of peaks surpassing a defined threshold Tpic, providing information about the process stability.

$$T_u = 1{,}5\,.\,\text{Set\_U} \quad (1)$$

Figure 7 illustrates the increase in the number of peaks with the accumulation of layers, corresponding to the accumulation of geometric errors and the widening gap between the actual CTWD and nominal CTWD. When manually adjusting the CTWD at layer 12, a decrease in the number of peaks is observed. This trend repeats until the final adjustment of the CTWD at layer 24.

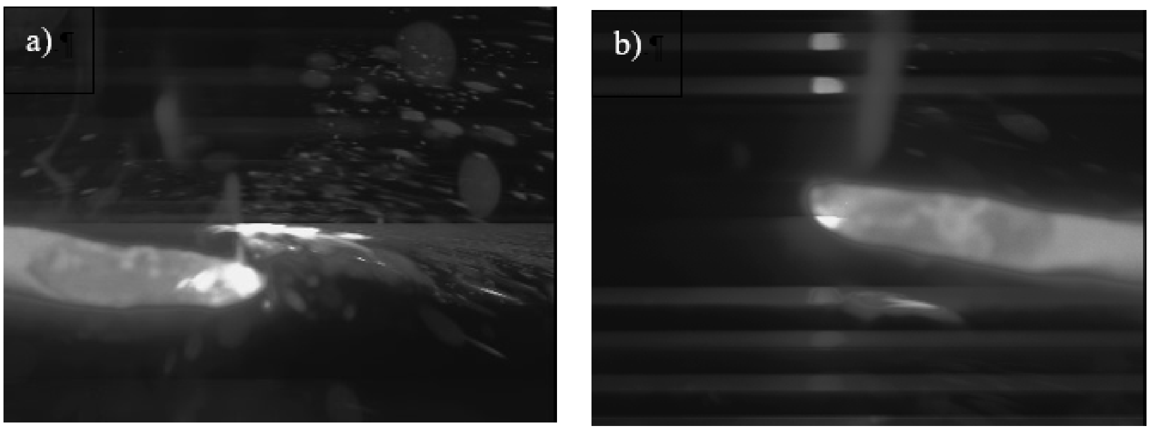

Figure 8: IR-images of a) unstable process, b) stable process

To validate this result, infrared camera images showcase abundance of spatter in the deposition area prior to the correction of CTWD (see Figure 8.a). Conversely, a notable decrease in spatter is evident in the layer immediately following the CTWD correction (see Figure 8.b). These findings suggest the possibility to establish a threshold T_p for the number of peaks, providing valuable insights into the stability of the process (Figure 7).

Conclusion and perspectives

In summary, our study establishes a link between CTWD and electrical signals during WAAM. Peak detection analysis reveals a correlation between layer accumulation, geometrical errors, and CTWD increase. Manual CTWD correction reduces peaks, suggesting the potential for establishing a stability threshold. Infrared camera images validate our findings, demonstrating decreased spatter post-CTWD correction. This collective evidence supports the feasibility of defining a peak threshold, offering valuable insights into welding process stability.

The findings presented in this paper mark the initiation of data analysis for an extensive experimental campaign. Geometric and thermal data have been collected and pending analysis, and criteria for monitoring are yet to be formulated.

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