Application of the FSW welding process and some of processes derived of it to the copper alloys processing

Radu COJOCARU[1,a], Lia-Nicoleta BOȚILĂ[1,b] and Horia-Florin DAȘCĂU[1,c]

[1] National Research & Development Institute for Welding and Material Testing - ISIM, Timișoara, 30, Mihai Viteazu Blvd., Timișoara 300222, România

E-mail: [a]rcojocaru@isim.ro, [b] lbotila@isim.ro, [c]hdascau@isim.ro

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Abstract

Due to its special qualities, copper and its alloys are commonly used materials in many important industrial fields.

Copper is one of the most difficult materials to join using conventional electric arc welding processes.

The paper presents results obtained by ISIM Timisoara for friction stir welding and processing (FSW and FSP) of some copper alloys frequently used in industrial production.

The results of the valuable experiments obtained as a result of FSW welding process application for the butt joint and by overlapping of the copper Cu 99 with 2-5 mm thicknesses are presented. Welds without defects/imperfections with values of mechanical characteristics close to those of the base material were obtained. Own contributions to the development of new methods of using the FSW process for copper joining are presented: FSW - TIG hybrid welding; friction stir welding in shielding gas environment (FSW-IG), being highlighted the positive influences due to them on the characteristics of the welded joints, respectively on the durability of the welding tools.

The paper also presents results obtained to the FSP processing of copper alloys in order to modify some surface properties of the base material (depending on the application), as well as data on an innovative method of friction riveting, developed based on the FSW process.

1. Introduction

Copper and its alloys are intensively used in important industrial fields as: electronics and electrical engineering, nuclear industry, electric motors, automotive industry, transportation, shipbuilding, aeronautics, precision instruments, power tools, etc.

Copper welding is difficult to be achieved by classical melting welding processes due to the very high thermal conductivity, which is 10-100 times higher than that of steel and nickel alloys. That is why the amount of heat required to be introduced into the process is very high, which determines a very low welding speed. As an alternative to these processes, the FSW process is also used for welding copper and its alloys [1].

Due of the fact that the melting point of copper is 1084° C, it is very important to choose the correct welding parameters, the material of welding tools and their geometry, as well as the theoretical understanding of the factors influencing the weldability of FSW of Cu and its alloys [2].

The paper presents the results obtained from the frictional processing of copper alloys, based on the principle of the FSW process.

ISIM Timișoara obtained good results when joining copper, especially by using ultrasonic welding processes [3], respectively soldering and brazing [4].

Researches, realized at international level, evidenced that Cu 99 copper, in particular, behaves very well when applying the FSW welding process [4-8]. FSW copper welding has been used successfully in important fields, such as the nuclear field [9].

Using the FSW process can bring important benefits. For example, compared to TIG welding, FSW welding produces residual contraction and net lower angular deformations, which recommends this process for the manufacture of parts and subassemblies who need a good dimensional accuracy.

At ISIM Timișoara, due to the problems that are / appear when welding copper by classical electric arc processes, the joining of copper by means of an alternative processes to electric arc, has become a necessity. Figure 1 shows a Cu 99 copper piece, welded by the TIG process. The sequence shows images from the leak test.

Fig. 1. Copper welded by arc welding

We can observe that the weld contains pores and is not tight. It is an example that supports the fact that FSW copper welding has been part of the ISIM Timisoara research program in recent years. Significant results were obtained in the welding of Cu 99 copper, in the variant of couples of similar materials, as well as in couples of dissimilar materials to be joined [10-12].

The FSW welding method in a shielding gas environment, FSW-IG, has been developed with positive results worldwide, the research focusing on the identification of possible application benefits. ISIM Timisoara developed the technique for FSW - IG application in its own conception and developed a program of experimental research for copper Cu 99 welding [13].

Hybrid FSW - TIG welding was proposed, by ISIM Timișoara, for development and application (patent no. RO 123349 B1). The results of the experimental programs for FSW-TIG welding of Cu 99, highlighted some important advantages compared to the application of the classical FSW process [10], [14]:

- increase of productivity, by increasing the welding speed of metallic materials by up to 200%;
- obtaining a more stable welding regime (without vibrations) which ensures a better protection of the welding machine and of the welding tools;

- increase the service life of welding tools made of sintered tungsten carbide P20S, (especially when welding steels);
- improving the characteristics of welded joints (breaking strength Rm can increase approx. 30%);
- better control on the development and distribution of heat in the materials to be welded (FSW-TIG allows the extension of the mixing area of the materials to be joined, thus creating the premises for obtaining quality joints).

Some of these advantages can be found in welding through the FSW-IG and FSW-US methods.

At international level, friction stir processing (FSP) is highly relevant in major research centers, which have studied and developed this technique of solid state refining of microstructures and increasing the plasticity of processed materials, in limited areas. Friction stir processing has been used to obtain new surface layers, with characteristics closely correlated with specific requirements of specific industrial applications [15], [16].

Hybrid riveting is a new riveting joining process proposed by ISIM Timisoara. The new process generated very good results when joining aluminum alloys, but also at joining by riveting some couples of Al - Cu alloys [17].

2. FSW welding of copper Cu99

At ISIM Timişoara, the development of FSW welding of copper were based on the experience gained in FSW welding of light metals. It was also necessary to modernize the usage of the technique (FSW welding machine, process-related devices) and a new approach to FSW welding tools in terms of constructive solutions, but also related to the tool materials.

The research carried out for FSW welding of copper was based on the specific characteristics of the material, in close correlation with the main defining characteristics of the FSW welding process.

2.1 FSW butt welding

The FSW welding equipment, type FSW-4-10, existing in ISIM (fig. 2) and the FSW welding tools, designed and made as own design, were used.

The FSW 4-10 welding machine (4kW tool rotation motor power) allows the use of a welding speed of 10-480 mm / min, a welding tool speed ranging between 300-1450 rpm, as well as welding on a maximum length of ~ 800 mm. The welding machine has been continuously modernized / completed, in correlation with the requirements of specific research programs.

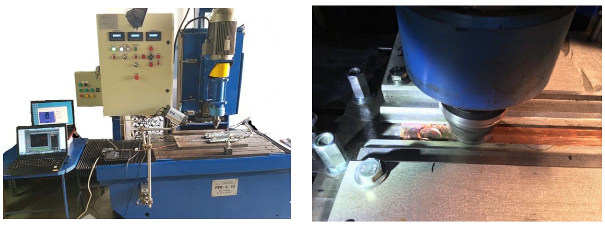

Fig.2. FSW 4-10 welding equipment, detail welding Cu 99

The best results regarding the FSW welding of copper were obtained using welding tools made of sintered tungsten carbide P20S, with a smooth shoulder and a smooth conical pin, respectively smooth cylindrical pin and conical pin with 4 flat chamfers, as shown in fig. 3.

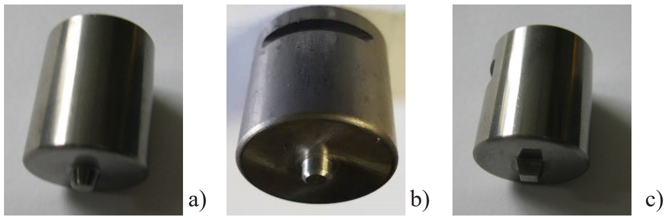

Fig. 3. FSW tools: a) - smooth conical pin, b) - smooth cylindrical pin; c) - conical pin with 4 flat chamfers

For each welding tool solution, the formation mechanism of the FSW joint was analyzed, based on the flow and "mixing" of the welding materials, as well as the process parameters that ensure a temperature necessary for optimal plasticization in the area of action of the welding tool.

Experimental programs have been developed and technological process parameters have been optimized for butt welding of Cu99-plates, with 2-5 mm thickness.

In the frame of the experimental welding programs, a new method of monitoring the FSW process was used, using the infrared thermographic technique.

For example, fig. 4 shows the real-time evolution of the temperature during the welding process in an experiment in which were used: Cu 99 copper sheet (5 mm thick); a welding tool with smooth conical pin, with pin having the length of 4.8 mm and the shoulder diameter of 20 mm; the welding speed of 80-118 mm/min; the welding tool speed n = 950-1000 rpm; the direction of rotation of the welding tool being counterclockwise [18].

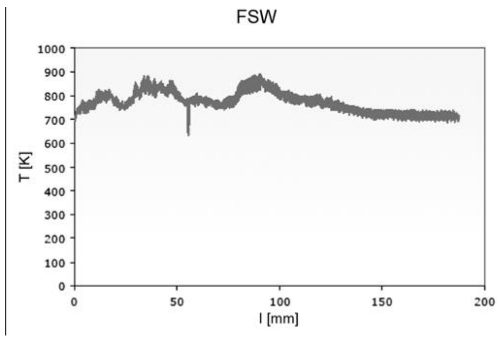

Fig. 4. Temperature variation - welding Cu 99 (s=5 mm) [18]

It can be observed that the average temperature at which the welding process takes place is approx. 525˚C, temperature peaks reaching about 6100˚C. A constant evolution of the temperature diagram can highlight the fact that the welded joint is compliant (no defects or imperfections).

In fig. 5, the macroscopic aspect of the welded joint, obtained under the mentioned process conditions, is presented [18].

Fig. 5. Macroscopic aspect - FSW welding Cu 99 [18]

The evaluation of the welded joints for static tensile tests and at plastic deformation tests, have demonstrated the good behavior of Cu 99 at FSW welding [18]: tensile strength Rm ~ 97% of the mechanical strength of the base material;

maximum degree of deformability; the value of elongation at break represents 53.82% of the base material elongation.

It can be stated that the FSW process can be applied, with remarkable influences on the quality of the joint, compared to conventional welding processes.

There were no significant differences in tensile strength and maximum elongation, when using welding speeds of different values, in the range of 20–60 mm / min.

In the classical FSW welding of Cu 99 copper, several shortcomings were found, which referred in particular to a rather low durability of the welding tool, but also to limitations of the welding speed. For these reasons, ISIM Timişoara proposed the development of the FSW welding method in inert gas environment (FSW-IG) or of the alternative hybrid processes, such as FSW-TIG welding.

2.2 FSW-TIG butt welding

The FSW - TIG hybrid process is a process proposed for research, development and application by ISIM Timişoara (patent no. RO 123349 B1).

In order to demonstrate the utility of the new hybrid process, the application and experimentation technique was conceived, designed and realized as an "Complex welding system", a system that included, in a functional whole, the specific modules of the FSW process and the characteristic modules of the TIG process (fig. 6): FSW welding machine (pos.1), TIG welding source (pos.2), device for adjusting and positioning the TIG welding head (pos.3); shielding gas supply installation (pos. 4); TIG welding source control module (pos. 5), integrated in the electric drive and control installation of the FSW welding machine; welding process monitoring and control system, using infrared thermography (pos.6), welding device and tool (pos.7), respectively TIG welding head (pos.8).

The TIG system, located in front of the FSW welding device in terms of location on the welding machine, is mainly intended to provide an additional heat input (to preheat the materials to be welded).

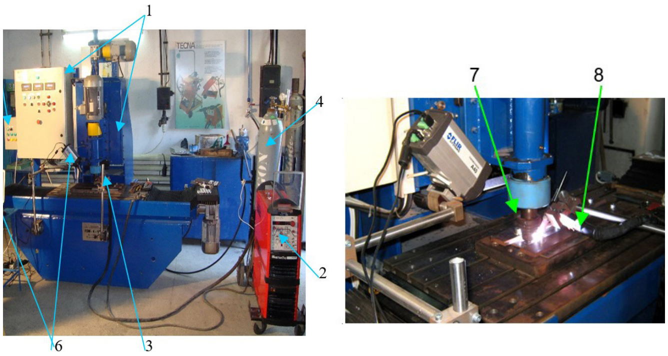

Fig. 6. Complex system for FSW-TIG welding

Beneficial effects of applying the FSW - TIG process:

- preheating of the materials allows a faster plasticization of the materials to be welded in the area of action of the FSW welding tool, also facilitating a better "mixing" and homogenization with direct effects on the quality of the welded joint (minimizing the possibility of defects in the joint welded);
- the process allows to increase the welding speed by 50–100%;
- the decrease of the friction forces between the FSW welding tool and the welding materials increases the welding tools life by 100%, up to 200%).

2.3 FSW - IG butt welding

The FSW-IG welding method in inert gas environment (e.g. argon) is useful for improving the quality of welded joints realized from materials with high mechanical strength and a high melting temperature (e.g. steel, titanium, etc.) by protecting the tool and the welding area against oxidation. For example, when welding reactive materials with high affinity for oxygen (e.g. titanium alloys), welding in an inert gas environment is required.

ISIM Timisoara proposed a research program to analyze whether the FSW-IG method can bring additional benefits compared to the application of the classical FSW process to Cu 99 copper welding [13].

A complex system was conceived, designed and realized, system that allowed the application and experimenting in optimal conditions of the new method (fig.7). The ISIM friction stir welding machine (pos.1) was completed with specific components as: shielding gas supply installation (pos.2) and the enclosure for applying shielding gas (pos.3), being also presented a detail regarding the FSW-IG welding of copper.

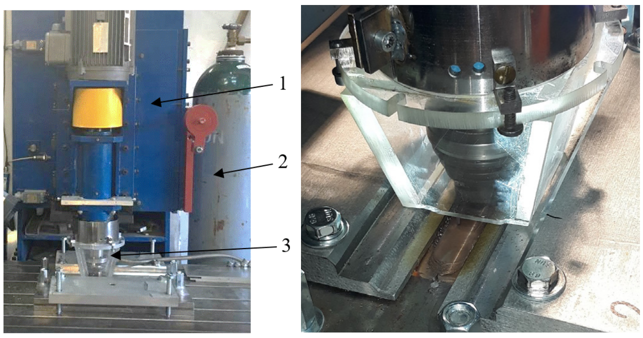

Fig. 7. FSW-IG system, detail FSW-IG welding of Cu 99 [13]

Higher welding speeds compared to the conventional FSW welding process were also used to highlight the application limits of the FSW-IG method.

Analyzing the macroscopic aspect of the FSW-IG of copper Cu99 joints (fig. 8 a, b, c) it can be observed that a "clean" welded joint was obtained, without defects or imperfections, for speeds of 40-80 mm/min. With the considerable increase of the welding speed to 120 mm/min (fig. 8 d), the formation of a "non-adhesion" type of defect can be observed, at the interface between the nugget (N) and the thermomechanically affected zone (TMAZ), zone corresponding to the advancing side of the welding tool.

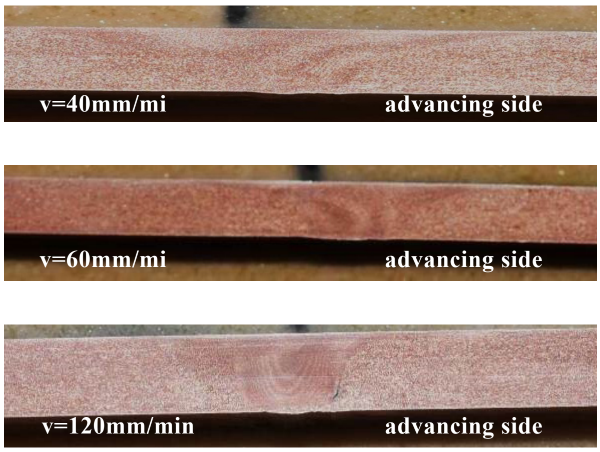

Fig. 8. Macroscopic aspect FSW-IG welding of Cu 99 [13]

It is certain that using optimized welding parameters, "clean" welded joints were obtained, without defects or imperfections (fig. 8 a-c).

However, applying the classic FSW welding to Cu99 copper, in the same process conditions (welding equipment and tools, respectively the same technological parameters) and performing a comparative analysis of the obtained results (FSW-IG and classic FSW) very important aspects were highlighted. Thus, using classic FSW welding (with welding speeds of 60 mm/min and 80 mm/min), defects of the "non-adhesion" or "tunnel" type were observed in the welded joint, as opposed to the positive results presented above at FSW-IG welding (fig. 8 a-c). In both cases (FSW-IG welding and FSW welding), but at different maximum values, increasing the welding speed beyond certain limits led to defects as pores or lack of adhesion, in the welded joint at the boundary between the nugget (N) and thermomechanically affected zone (TMAZ). With the formation of welding defects, the tensile strength of the welded joint was lower compared to FSW-IG welding.

2.4 FSW butt welding of copper Cu99

Given the different way of placing the materials to be welded (compared to FSW butt welding), the different way of mixing and flowing of the material, in this case, under the action of the welding tool and thereby the different mechanism of forming the welded joint, a new approach to the research program was needed to respond to the new situations.

In correlation with the thickness of the package of materials, we used welding tools with constructive and dimensional characteristics verified by experiments (e.g. conical pin tool with four flat chamfers, made of sintered tungsten carbides P20S). A number of 2-3 overlapping sheets were welded, with the total thickness of the package having values in the range of 4-8 mm. The technological process parameters that were used: welding speed with values in the range of 60-80 mm/min and welding tool rotation speed 1400-1450 rpm.

Fig. 9. FSW overlap welding - Cu 99 [19]

Similar to the case of FSW butt welding, very good results were obtained to the FSW overlap welding of copper Cu 99 (fig. 9), resulting in a welded joint without defects or imperfections [19].

2.5 FSW welding of dissimilar material couples

In general, joining of copper and its alloys is difficult or, in some cases, impossible to achieve, by using conventional electric arc welding processes. Moreover, the problems increase in the case of welding of dissimilar materials couples in which one of the materials is copper or an alloy of it.

FSW welding of a Cu-Al couple of materials has been requested by an important manufacturer in the automotive industry. These types of joints are needed in the industry to manufacture and safely operate of the automotive electrical installations. Figure 10 shows a butt joint of dissimilar materials: EN AW 5754 aluminum alloy having 2 mm thickness with Cu 99 copper having 5 mm thickness [10].

Fig. 10. FSW butt welding EN AW 5754 - Cu 99 [10]

FSW overlap welding of Cu 99 with aluminum alloys, as couples of dissimilar materials, using welding tools with geometries and dimensions in correlation with the package thickness of the overlapping sheets, respectively using optimized welding parameters, led to positive results, provided that the aluminum alloy is positioned above the copper (Fig. 11) [19].

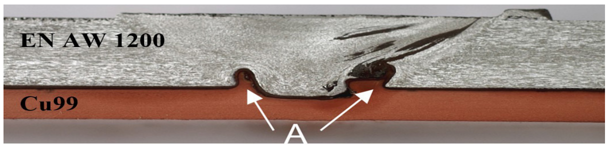

Fig. 11. FSW overlap welding EN AW 1200-Cu 99 [19]

Macroscopic analysis (fig. 11) shows that there was a good mixing of materials, the two materials migrating to each other, forming the "mechanical grip", characteristic in this type of application, when applying the FSW process (areas marked A).

3. FSP processing of copper and its alloys

The main role of FSP processing is to modify some local (zonal) properties, according to specific requirements of punctual applications:

- increasing the degree of deformability in well-defined areas;
- increasing the hardness in the surface layers;
- elimination of surface defects and surface finishing (especially for cast ferrous metallic materials);
- repair of welds made by electric arc processes.

For example, applying the FSP processing to the CuSn10 casted copper alloy (fig. 12), leaded to significantly improved roughness values (fig. 13), comparable to those obtained by mechanical machining (Ra ~ 2μm) [19].

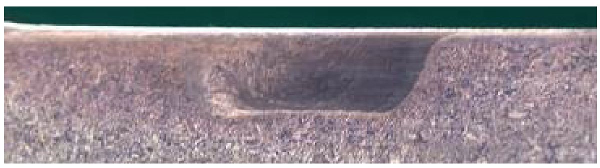

Fig. 12. FSP processing - bronze CuSn10 [19]

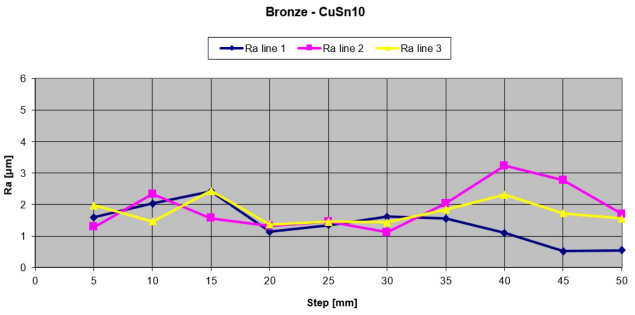

Fig. 13. Roughness variation - CuSn10 (FSP processed) [19]

From the point of view of the hardness evolution, it is observed that in the nugget of the processed material, the highest hardness value is obtained (in this case 135HV1), with about 30-35% higher (on average) than the values from base material BM (fig. 14) [19].

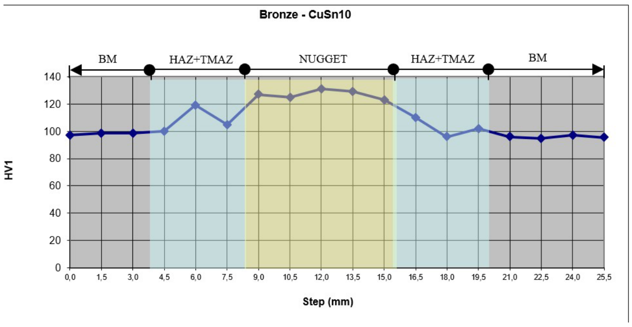

Fig. 14. Hardness evolution in processed CuSn10 and in BM [19]

For the cast CuSn10 bronze, FSP processing produced local changes that have the effect of improving the properties by closing the pores that appeared during casting and also refining the microstructure (fig.15) [19].

Fig. 15. Comparison - casted and FSP processed bronze FSP [19]

The roughness obtained at the surface of the processed material (Ramed ~ 1.5µm) denote an excellent quality resulting from the FSP process.

The hardness values obtained in the processed areas were 65-80% higher than those of the base material. Also, the tensile strength of the samples, taken from the processed material area, was up to 30% higher than that of the base material.

The obtained results demonstrate that in combination with FSP processing, the transformations that take place into CuSn10 cast bronze parts can lead to a considerable improvement of wear resistance.

4. Friction riveting with hybrid effect

Hybrid friction riveting is a new riveting joining process, proposed and developed by ISIM Timişoara in a project within the national research program [17]. The joining of the couples of dissimilar materials Cu 99 - EN AW 6082, respectively Cu 99-EN AW 7075, using C45 steel rivets, have been approached [17].

Figure 16 presents the macroscopic aspect of the joint, highlighting the characteristic areas of this new process.

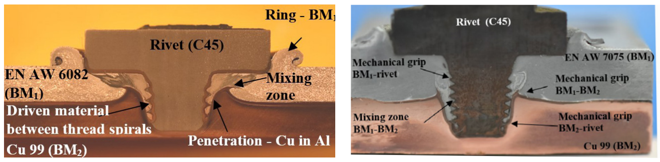

Fig. 16. Riveted joint with hybrid effect Cu99- Al alloys [17]

The hybrid riveting process actually combines three types of joints:

- two mechanical grips resulting from the "anchoring" of BM1 with BM2 (obtained by the fact that there is a "migration" of one part from one base material into the volume of the other base material), respectively by a mechanical grip between the threaded part of rivet and mixing zone (between BM1-BM2);
- friction welding between materials BM1 and BM2.

For some couples of base materials, an additional friction welding can also occur between rivet and base material.

The mechanical strength of the joint decreases as the thickness of the base material BM2 decreases. In the case of the couples of materials mentioned above, the hybrid riveting process may be applied provided that the minimum thickness of the BM2 materials (positioned at the bottom of the joint) is s_{min}=2 mm.

The positive preliminary results obtained by ISIM show that hybrid riveting is a technically viable process, that can be used in industrial applications.

5. Conclusions

The research conducted at ISIM Timişoara has shown that certain friction processing can be applied with very good results to copper and its alloys:

- excellent results have been obtained for butt welding and overlap welding of copper Cu 99 by the classical FSW process, but also by using the processes and methods of joining derived / developed from it (FSW-TIG, FSW-IG, friction riveting with hybrid effect). These methods have contributed, as appropriate, to: considerably improving of important characteristics of the welds, increasing the welding tools life, increasing of the welding speeds with a positive effect on the productivity, proposing and developing of the 100% ecological and environmentally friendly joining technologies.
- by applying the FSP processing to the CuSn10 casted copper alloy, local changes occur which have as a positive effect: closing the pores (which appear as a result of the casting process); refining the microstructure; a very good quality of the surface of the processed material, highlighted by the value of its roughness (Ramed~1.5µm); increased hardness, by 65-80% in areas of processed material compared to the base material; good ratio between mechanical resistance of processed material and of the base material ($Rm_{proc.mat.}/Rm_{BM}$ = 1.3), contributing to the improvement of the properties of the processed material.

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