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Investigation of the lubrication influence on single-phase and multi-phase ironing processes

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Abstract

The ironing process in the cold conditions is frequently accompanied by the high contact pressures and local loading of tools, especially in the multi-phase processes. In such conditions, lubrication has a decisive influence on the successful forming. Absence of lubricant would lead to direct contact of the thin sheet and the tool (die) what would consequently cause the disturbance of the forming process stability; frequently the process would be hindered. Lubrication, as a measure for decreasing the harmful influence of friction at the contact surfaces, enables increase of the deformation and drawing degree. In that sense, experimental investigations were conducted of influence of various types of lubricants on the single-phase and multi-phase ironing processes. The corresponding tribological model was adopted, which is based on sliding of the thin sheet strip between the two side contact elements, which are ironing it. The tribological model was realized according to original experimental device. The variation of the drawing (tensile) force, contact pressures and the friction coefficient were monitored for each type of lubricants, in the single-phase and the three-phase ironing conditions, at the constant sliding speed. In that way, the estimates of each individual lubricant was done. The objective of this research was to compare the tested lubricants from the aspect of their quality and applicability in the ironing processes.

*Keywords:*Ironing, tribological model; contact pressure; friction coefficient; tensile force;

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1. Introduction

The friction coefficient was selected as a main criterion for assessing the performance of lubricants in the ironing process. It was calculated according to research results given in [1, 2]. The objective of this paper was to compare behavior of three conventional lubricants during the process with contact pressure of medium-intensity, such as the single-phase and multi-phase strip-ironing test. An original experimental apparatus was designed using a methodology based on monitoring the friction coefficient during the process [3, 4]. It is based on sliding the samples made of thin sheets between the side elements (die). The contact surfaces of the sample and the sliding elements were separated by the lubricant's layer. The three types of lubricants were tested: (I) the lubricant in the form of the zinc-phosphate coating (denoted as lubricant L1); (II) lubricating grease based on the molybdenum – disulphide (denoted as lubricant L2); (III) mineral oil for deep drawing (denoted as lubricant L3). The friction coefficient values were calculated, for each type of lubricant and each ironing phase, in terms of the holding force and registered drawing force.

Numerous researchers were dealing with studying the lubricants performance during the ironing process, [5-11]. The specimen material in [9] was an AKDQ 1008 steel sheet. A cup-shaped thin sheets specimen was used in [12] and [13] to

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evaluate the lubricants, based on ironing load, surface quality and apparent shear friction factor. The friction coefficient was not considered while the influence of temperature was. In [13] lubricants were investigated in the dual-phase ironing of 590 galvanized steel sheet. A survey of several tests for investigating lubricants in the metal-sheet forming process is presented in [14] where simultaneously were conducted the production tests. The work included the strip reduction test with single-sided thinning where the phenomenon of galling was quantified by the surface roughness measurements. The influences of the coating and lubricant were investigated, in terms of the friction coefficient. The double-sided single-phase ironing test was used for classical lubricant evaluation in [15]. In [16, 17, 18, 21] were investigated the complex tribological influences in the strip sliding test, while in [19] was monitored the influence of oils on the scuffing of concentrated friction joints with the low-friction coated elements. Also, authors of paper [20] analyzed DC06 steel sheet which is very similar to DC04 analyzed in this paper.

Nomenclature

F	tensile force
F_S	side force
t_0	thickness before ironing
t_1	thickness after ironing
α	angle
R_a,	roughness
R_p,	yield strength
R_m,	tensile strength
A	elongation at fracture
n	strain hardening exponent
r	coefficient of normal anisotropy
r_1, r_2	radii of the sliding elements inclinations
L1	phosphate layer with mineral oil lubricant
L2	lithium grease based on molybdenum-disulphide
L3	mineral oil

2. Ironing test – device, tooling and procedure

An ironing test with double-sided thinning of the metal sheet, was applied in this experimental investigation, as depicted in the scheme presented in Fig. 1. The details of the device are given in Fig. 2, while its actual appearance is shown in Fig. 3. The sheet metal sample (13) is placed in the fastening jaws (12) vertically. In the initial phase, the thinning occurs such that the right-hand moving sliding element (10) acts upon the thin strip by the lateral force. Due to the fixed side element (11) and the action of the sliding element (10), the even double-sided ironing of the metal strip is realized. After the initial thinning deformation was realized, the tensile force F begins to act, and the ironing process continues until the sample length is executed. The main action of the ERICHSEN 142/12 laboratory hydraulic press is used as the tensile force across the measurement range of 0-20 kN at a speed of 100 mm/min. The lateral force is realized by the hydro-cylinder (7). The measurement range of the lateral force is also 0-20 kN. The piston (8) pushes the element (9), which is coupled to the sliding element (10). The hydro-cylinder (7) is powered by the independent hydraulic aggregate, which contains the filter (1), pump (2), electric motor (3), valve for pressure and lateral force adjustment (4), manometer (5) and the two-position directional control valve (6). The data acquisition system measures the tensile force dependence on the sliding length, or time, and the constant intensity lateral force.

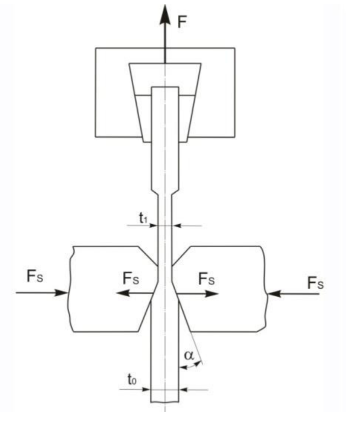

Fig. 1. The tribological model: Scheme of the contact between the sliding elements and sample

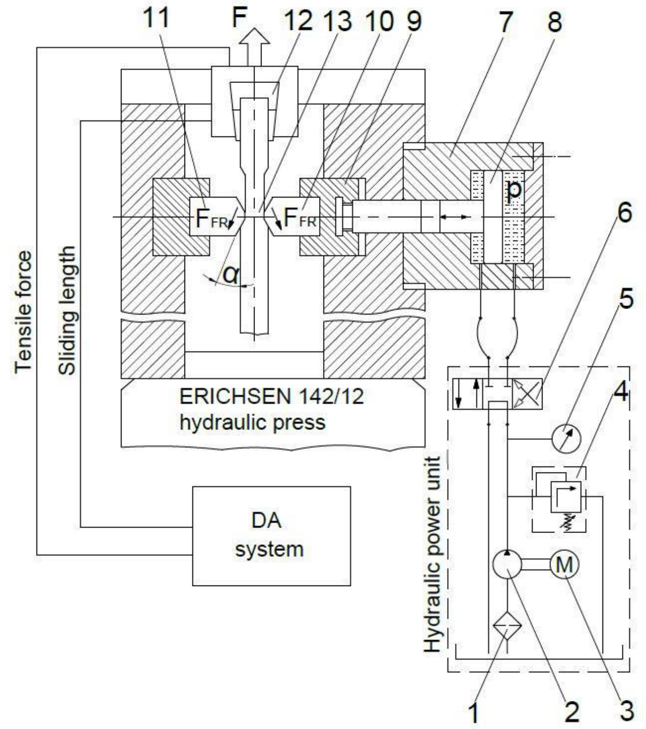

Fig. 2. Scheme of the experimental device

Fig. 3. Physical appearance of the experimental device

Sensors are placed within the ERICHSEN machine. The voltage signals, after amplification and filtering, are input into the A/D converter and converted into the files describing the tensile force dependence on the strip length using the corresponding software.

The geometry of the lateral sliding element is presented in Fig. 4(a, b), while its physical appearance is shown in Fig. 4c. Central rounding radius is 1 mm, one side radius 1 mm and the other 2 mm. These parts are made of the X210Cr12 tool steel (EN ISO 4957) without the surface coating and have hardness of 60-62 HRC. The surface is polished, and the roughness is expressed by the average absolute roughness height from the centre line R_a (0.08 µm), divided by the reference length of 5 mm.

The samples are strips of DC04 low-carbon steel thin sheets with a thickness of 2.5 mm, an average width of 20.2 mm and a length of 200 mm. Its main mechanical properties and properties of formability are given in Table 1 (R_p, MPa – yield strength, R_M, MPa – tensile strength, A, % – elongation at fracture, n – strain hardening exponent, r – coefficient of normal anisotropy). The surface roughness of the thin sheets, expressed by the average absolute roughness $R_{a,}$ is 1.03 µm over the referent length of 5 mm.

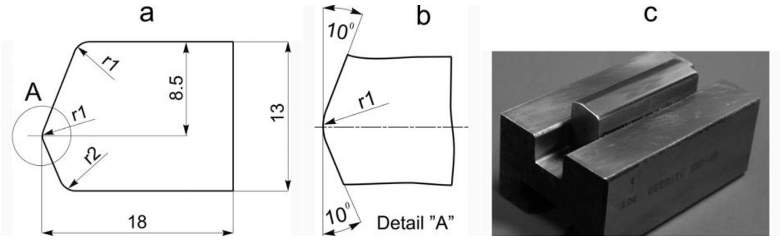

Fig. 4. Geometry (a, b) and physical appearance of the lateral sliding element (c)

Table 1. Material properties

Steel DC04				
R_p, MPa	R_m, MPa	A, %	r, -	n, -
185.2	284.5	35.3	1.68	0.215

3. Test conditions

Three lubricants, i.e. three contact conditions, were used in this analysis. The first (L1) was the classical phosphate layer of zinc phosphate, with a thickness of approximately 10 μm, over which the mineral oil was deposited (for characteristics see describing of third lubricant). The oil was applied considering the less strict requirements for the ironing process with respect to cold forming. The second lubricant (L2) was lithium grease, containing molybdenum disulphide MoS_2. Its NLGI consistency number and density are 2 and 0.9 g/cm^3, respectively, and the MoS_2 particle size is approximately 0.75 μm. The third lubricant (L3) was the classical mineral oil, containing the EP sulfur-based additives, which is used in thin sheets forming. Its density and kinematic viscosity are 0.93 g/cm^3 and 100 mm^2/s, respectively, at 40°C. The oil was deposited in large quantities onto the surface of the previously degreased sheet. It should be mentioned that the same oil was used as L3 and as the additional lubricant over the phosphate layer (in L1). As already mentioned, uncoated DC04 steel strips (2.5 mm thick), were used in this experiment. The strip sliding speed was 100 mm/min. Four values of side forces (F_s): 5 kN, 10 kN, 15 kN and 20 kN were applied in the single-phase ironing process. In the multi-phase ironing process the side force of 15 kN was applied for each lubricant.

Reason for applying somewhat lower value of the side force (F_s = 15 kN) was to avoid the risk of appearance of galling, which happens as a consequence of the high pressure forces and insufficient lubricating in the contact zone. During the multi-phase ironing lubricating was applied after each phase. The ironing sliding length was 60 mm, for both single-and multi-phase ironing processes. The multi-phase process was divided into three phases with the sliding length of 20 mm each.

4. Results and discussion

Evaluation of lubricants, from the aspect of applicability in the ironing process was done by comparing values of the friction coefficient for conditions explained in the previous section. The friction coefficient variation on the sliding length was calculated for each tensile force. The slope angle of the side element was $\alpha = 10°$ (Fig. 4). In this way, the curves of the friction coefficient variation for single-phase ironing process were obtained (Figs. 5 to 7). It is clear that the friction coefficient was much higher when the mineral oil (L3) was applied, with a range of approximately 0.16 to 0.2 (Fig. 7). This confirms that this lubricant's lubricating properties are worse than those of the other two. The friction coefficient variation for the lithium grease with MoS_2 (L2) is presented in Figure 6. The values are relatively low, ranging from 0.15 to approximately 0.165. The increase in the lateral force from 5 to 20 kN does not significantly influence the increase in the friction coefficient.

When the phosphate layer with mineral oil was applied (L1, Fig. 5), the values are similar to those for lubricant L2, ranging from approximately 0.14 to 0.17. The influence of the lateral force variation is somewhat greater than that for L2. The most probable cause is the worse lubricating properties of the mineral oil L3 (Fig. 7).

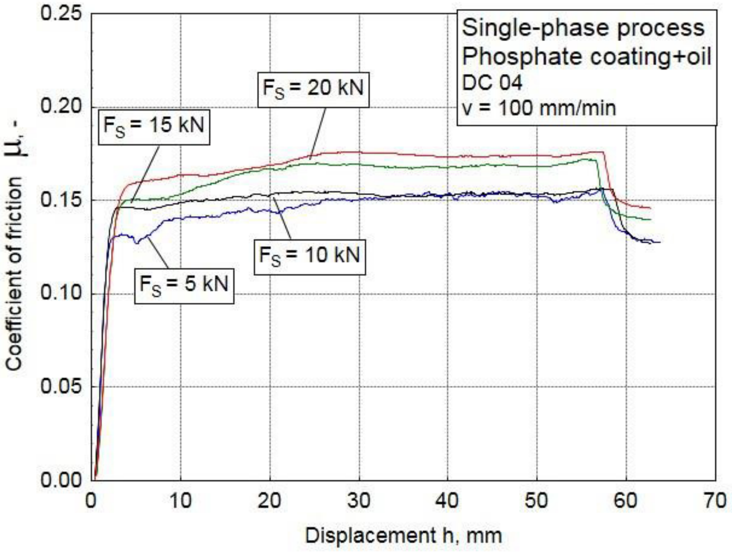

Fig. 5. Friction coefficient dependence on displacement for lubricant L1 (single-phase process)

The curves of the friction coefficient variation for three-phase ironing process are shown in Figs. 8-10. In the multi-phase test of the lubricant based on the MoS_2 (L2 – Fig. 9), it is noticeable that the friction is more prominent than for the phosphate coating with oil (L1 – Fig. 8), under the same conditions. The reasons for that are disturbance of the lubricant layer on the contact surfaces of the sample and the tool and affinity to appearance of galling [2]. The larger portion of lubricant, based on the MoS_2 is being retained on the thinning element (Fig. 4). On the contrary, for the lubricant in the form of the phosphate coating with oil (Fig. 8), one can notice the lowest values of the friction coefficient and good sustainability of the phosphate coating, and subsequently, the negligibly present appearance of galling. Application of the L3 lubricant (Fig. 10) resulted in relatively high values of the friction coefficient, especially in the second and the third phase. The worse lubricating properties of the L3 lubricant were noticed already during the experiment, when on certain parts of sliding length appeared difficulties in sliding (braking) during the ironing, while the appearance of galling was noticed on sliding elements.

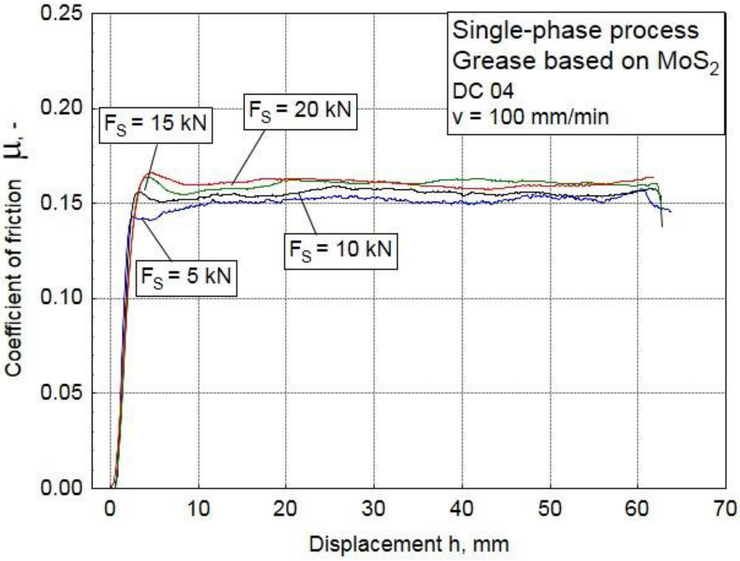

Fig. 6. Friction coefficient dependence on displacement for lubricant L2 (single-phase process)

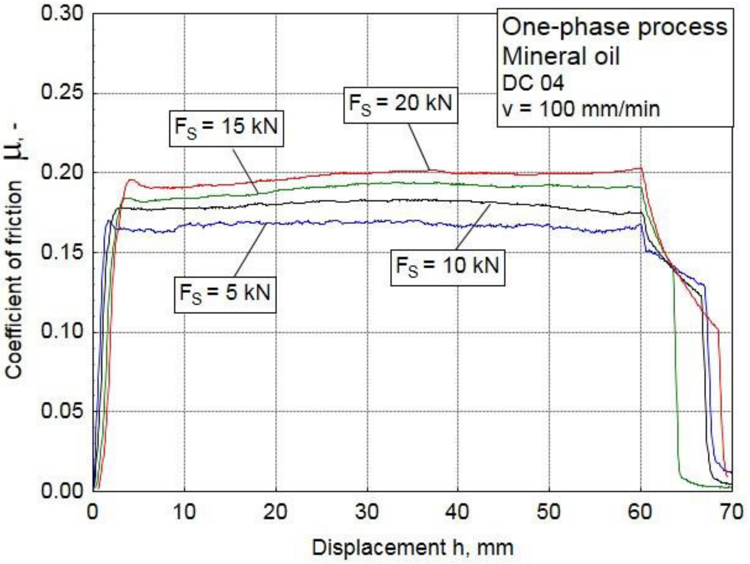

Fig. 7. Friction coefficient dependence on displacement for lubricant L3 (single-phase process)

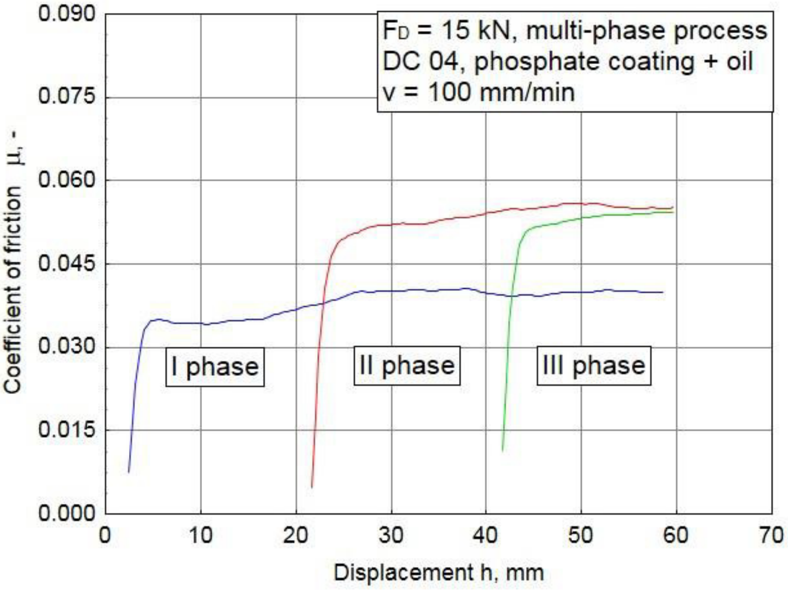

Fig. 8. Friction coefficient dependence on displacement for lubricant L1 (multi-phase process)

Retaining of lubricant is better for the multi-phase ironing, since lubricating is done after each phase, so the values of the friction coefficient for the second and the third phase of thinning are smaller than for the single-phase process. The fact contributing to this is that the sliding length is decreasing to 20 mm after each phase, so at the shorter sliding length the retaining of lubricant is better. It was shown that in both cases (single-phase and multi-phase ironing) application of the mineral oil resulted in high values of the friction coefficient and appearance of galling on the die surfaces, thus this lubricant should be avoided, especially for the multi-phase processes.

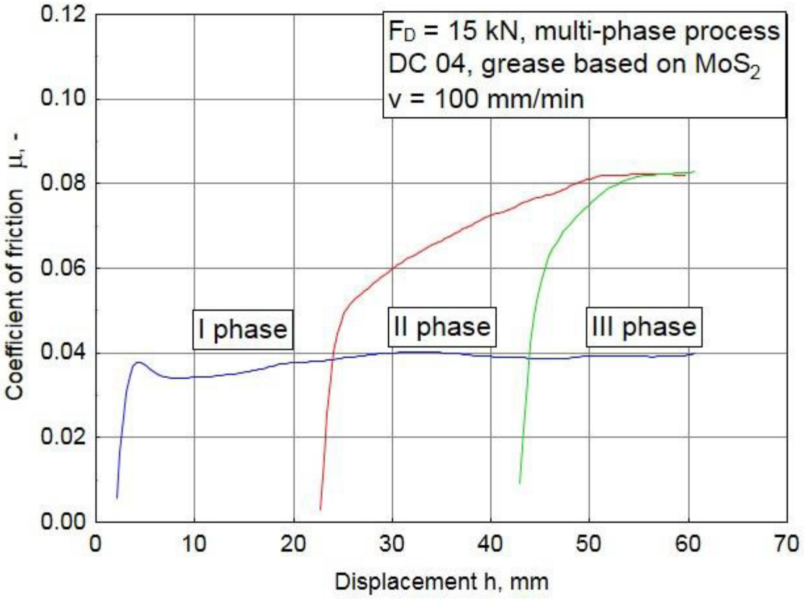

Fig. 9. Friction coefficient dependence on displacement for lubricant L2 (multi-phase process)

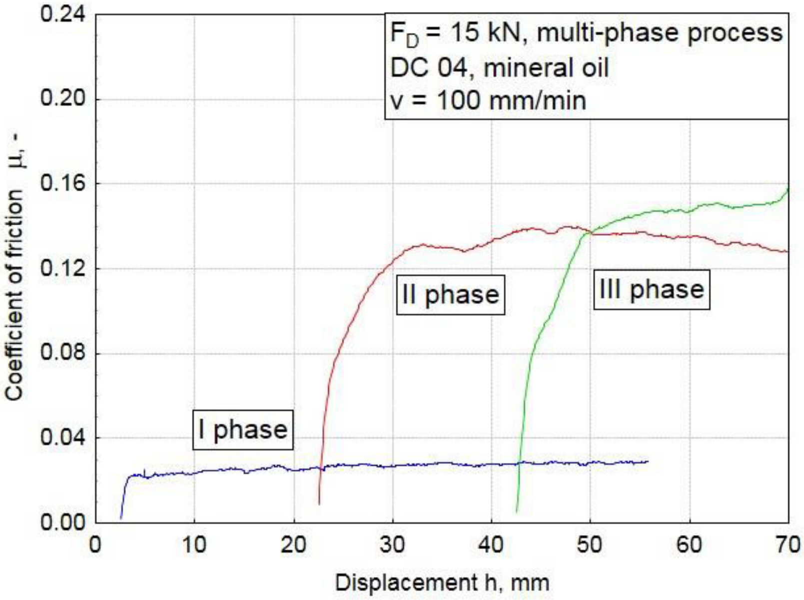

Fig. 10. Friction coefficient dependence on displacement for lubricant L3 (multi-phase process)

5. Conclusion

The following conclusions were drawn due to results of the conducted experimental investigation:

- The device for strip ironing testing with double-sided thinning created in this study is convenient for estimating the performance of lubricants in processes with moderate compressive forces and a thinning deformation of the low-carbon steel sheets of up to 25%. The tensile and side forces measurements based methodology is simple and provides clear results;
- The friction coefficient was set as the main criterion. The obtained values correspond to the process characteristics and can be used to test the lubricants performances;

- Three lubricants were tested in single-phase and multi-phase ironing process: zinc-phosphate layer with mineral oil, lithium grease based on molybdenum-disulfide and the mineral oil. The clear differences in the variation and intensity of the friction coefficient during the test enabled the reliable estimation of the lubricating properties of the tested lubricants.
- Based on presented results, evaluated by the friction coefficient, one can conclude that the mineral oil for deep drawing is not convenient for application for both multi-phases and single-phases ironing processes, in conditions of the high contact pressure, due to prominent appearance of galling and easy extrusion of lubricant from the contact zone;
- Lubricant based on the molybdenum-disulphide has good lubricating properties since it could be applied for somewhat higher values of the contact pressure forces, especially for the single-phase processes. For the multi-phase processes, the contact elements cleaning, as well as lubricating, are necessary after each phase of the process, which increases the time consumption what is an important factor in the real industrial conditions;
- The phosphate layer coating possesses the best lubricating properties, based on lower values of the friction coefficient and almost complete absence of appearance of galling. Those are the reasons for the wide industrial application of the phosphate coating in the ironing processes. Problems of the phosphate coating are in the process of phosphatizing, which is toxic for humans and environment. That caused development of the new, ecological lubricants, what opens new possibilities for investigations of application of this tribological model and apparatus presented in this paper.

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