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Optimization of pre-forging heating procedures: an approach based on finite element modeling

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The productivity of batch furnaces for heating steel input stocks devoted to forging is analysed and optimized by means of a coupled numerical-experimental approach. The heating procedures heavily affect process efficiency and product quality: it is experienced by operators that high starting temperatures and heating rate enhance productivity but may promote large skin-to-core thermal gradients in the input stock, this increasing the risk of cracking at the core. Susceptibility to failure depends on the steel composition, grain size, as well as on input stock size and geometry. A Finite Element Analysis, FEA, model is developed and validated, which couples the furnace-to-ingot heat transfer and the thermal-structural phenomenon inside the volume. The model estimates the temperature and stress field across the material during the whole reheating, basing on its composition, local temperature, and microstructural phases. In the present work, the reheating of two 42CrMo4 input stocks of different size is investigated by simulating the thermal and stress field across the material in accordance with the temperature setpoint of the furnace. Standard heating procedures are simulated along with two revisions, in the aim of evaluating any potential improvement in productivity and energy saving. Results show that a beneficial shortening up to 2.7hrs and energy saving up to 6% are achievable when FEA-based procedures are applied.

KEYWORDS: PRE-HEATING PROCESS, BATCH FURNACE, STEEL INPUT STOCKS, THERMAL-STRUCTURAL ANALYSIS, CRACK SUSCEPTIBILITY, NUMERICAL MODELING, FINITE ELEMENT ANALYSIS

INTRODUCTION

Aim of the heating is to provide an adequately high and uniform temperature distribution within the input stock (typically around 1200°C), while optimizing the energy consumption and the furnace productivity. Heating procedures are designed under three main priorities: 1) assuring target temperature uniformity down to the core to prevent drawbacks due to "cold heart" forging. For those reasons reheating is generally prolonged to assure a uniform temperature distribution across the whole input stock, 2) controlling the microstructure: the heating rate, the holding time and soaking time are designed to mitigate the risk of forming very coarse grains during austenitizing/solutioning treatment, 3) avoid excessive thermal stresses due to high skin-to-core temperature gradient, as this promotes the formation of cracks or the enlargement of pre-existing ones. Such phenomenon

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is described in literature since long time [1] and further investigated recently, with Finite Element Analysis, [2, 3, 4].

FINITE ELEMENT MODELING

Model setup

The thermal-structural analysis makes use of Dassault Systèmes Abaqus software. An uncoupled non-stationary thermal/structural analysis is performed, the furnace/ ingot model is built with solid elements with 8 nodes (C3D8 type brick elements) and replicates the actual materials' layers and according to the procedures in [5]. The widely adopted Hottel's Well Stirred Furnace Model [6]. is employed and temperature time history is assigned to the vertical walls and the roof.

The following mechanisms are simulated: wall-to-stocks thermal radiation, furnace walls' self-radiation, convection from hot gases on all surfaces (both input stock and furnace), sole-to-stocks heat conduction, heat dissipation due to external radiation, and convection. The heat radiation mechanism is governed by variable emissivity based on temperature and according to the recommendations of the Bureau of Energy Efficiency (BEE, India) [7]. The emissivity of the material is set to 0.8, as typical for a heavily oxidized steel surface, across the entire temperature range. The numerical model enables the calculation of radiation view factors for a general geometrical configuration, which is crucial when complex charge configurations result in shadow effects. This allows the model to handle various charge configurations inside the furnace. Concerning forced convection within the furnace for heat transfer, a coefficient of 25 W/m^2K, in line with Eurocode1 [8], is applied. For heat losses to the ambient due to natural convection, a coefficient of 5 W/m^2K is used. The 42CrMo4 steel thermo-physical properties and their variation with temperature are calculated by basing on JMatPro software. In general, higher temperatures heavily reduce the yield, tensile strength, and elastic modulus.

Model validation

The capability of the FEA model to simulate the whole thermal phenomena inside the furnace and in the input stock is assessed and described in detail in previous works, [9]. Briefly, a twofold validation is accomplished. First, the temperature trend inside the empty furnace is sampled by the control thermocouple during a cooling starting at high temperature. An identical process was simulated and the good agreement between numerical and experimental temperature decay proves that the furnace thermal performance is well accounted by the FEA model, Fig. 1-left. Secondly, the heating process of a full charge of input stocks was performed and monitored through thermocouples located in the furnace, on the ingot surfaces and inside its body through a deep drilled hole. As in Fig. 1-right, the simulated trend of the average temperature of the ingot well fits with the experimental plot. This confirms the soundness of the FEA model and its capability in predicting the thermal phenomena in the furnace and in the material. More details are given in [9].

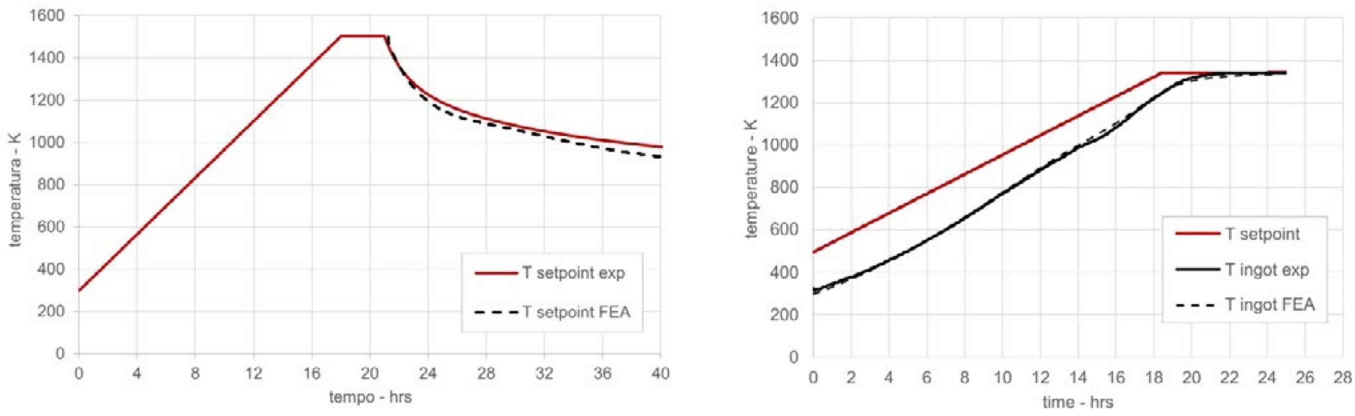

Fig.1 - Experimental to FEA prediction: furnace cooling (left) and input stock heating (right).

SIMULATION OF REFERENCE CASE

The standard procedure

Two cylindrical 42CrMo4 work stocks are considered in the frame of the present activity. Diameters are respectively D=600mm and D=900mm while both have identical height/diameter ratio, Fig. 2. Each of the two is subjected to the standard heating schedules. The simulated temperature trends are plotted in Fig. 3, reporting the furnace setpoint (Tset), the temperature at the ingot core (Tcore), at the external surface (Tsurf) and the difference between the two. After a preliminary holding time at 600°C, temperature ramps up to 1200°C. The final holding is proven by the operator to be sufficient to provide temperature equalization and soaking.

		D600	D900
Input stock data	Diameter, D (mm)	600	900
	Height, H (mm)	1320	1980
	H/D	2.2	
	Surface (m2)	3.05	6.87
	Volume (m3)	0.37	1.26
	Mass (kg)	2930	9888
	Initial Temp. (°C)	25	
	Material	42CrMo4	
Furnace	Internal Surface (m^2)	~56	
	Initial Temp (°C)	600	
Heat Schedule	Initial hold.	3h @ 600°C	7h @ 600°C
	Temp. increase	4 h @ 150°C/h	
	Final hold	5h @ 1200°C	7.5h @ 1200°C
Outcome		No cracks are commonly observed	

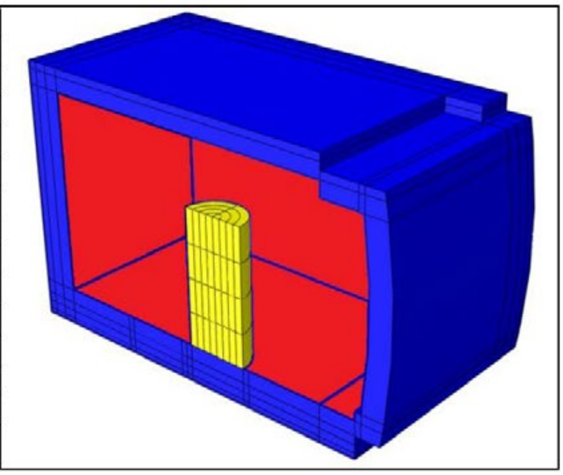

Fig.2 - Standard heating process: main parameters used for simulation.

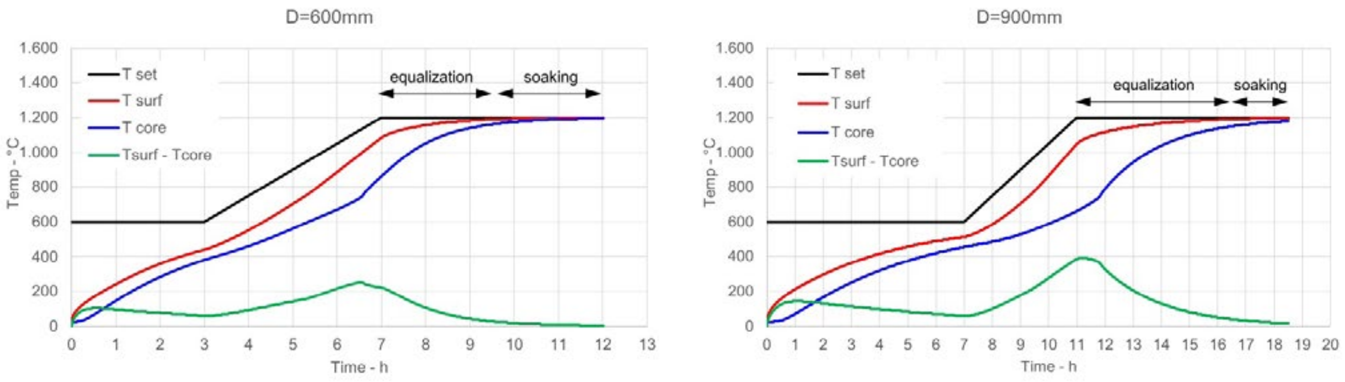

Fig.3 - Simulated heating process and temperature evolution in the input stocks.

The failure criterion

To assess the severity of the stress towards the failure, a criterion is needed. Typically, Rankine-Coulomb finds common application in brittle materials refers to maximum principal stresses σ1, σ2, σ3.

$$-\sigma c < \max(\sigma 1, \sigma 2, \sigma 3) < \sigma t \qquad [1]$$

where σt and σc are the failure stresses in tension and compression respectively. The adoption of this criterion is supported by the theoretical analysis and observation by [10, 11], which reported the formation of cracks at ingot center due to axial stresses and its propagation towards the external surface. The ultimate strength (UTS) evolution at high temperatures is therefore estimated by basing on data provided by the software JmatPro, see continuous line in Fig. 4. A certain dispersion of the mechanical properties is observed inside the stock, and the plot is assumed to be representative of the average values.

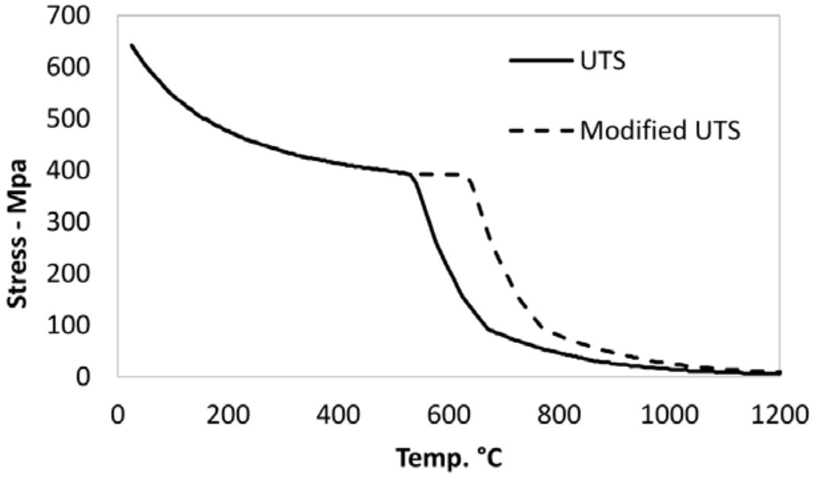

Fig.4 - Tensile strength of 42CrMo4 with temperature. Elaboration from JMatPro data.

Fig. 5 shows the evolution of stresses calculated at the core in both geometries. Two stress peaks take place:

- A first peak, red solid symbol, arises from the stress state during the first heating phase as consequence of the thermal shock. For the cases of interest, the core undergoes an intense state of stress (210-285MPa in axial direction), while along the vertical axis, circumferential and radial stresses are respectively equal to and half of the axial stress. The positive triaxiality, i.e. tension state in the three directions, makes it particularly critical for the crack promotion.
- A second peak, red outline symbol, takes place as the furnace temperature rumps up. It originates from the thermal core/skin gradients during the temperature increase. Shortly after, the stress at core is also sustained by the local microstructural transformation, green line in Fig. 5. The abrupt change of the expansion coefficient during austenitization leads to a differential straining and therefore to a local stress abrupt in-crease.

In Fig. 5 the failure stresses criterion is reported in the timeline and compared against the stress at the core. Both for D600 and D900 cases, stress lays far below the limiting tensile stress for most duration of the process. As the temperature rises, a steep strength decrease (UTS) occurs and the core stress in axial direction exceeds the criterion. Nevertheless, the consolidated experience of the operators reveals that no failure takes place in reality for the cases considered, this suggesting that the applied criterion is too conservative and might be relaxed to match with the empirical evidence. Therefore, in the frame of the present study, the stress-temperature correlation for the material shown is modified as in the dashed line in Fig. 4 and converted as stress/time plot in Fig. 5.

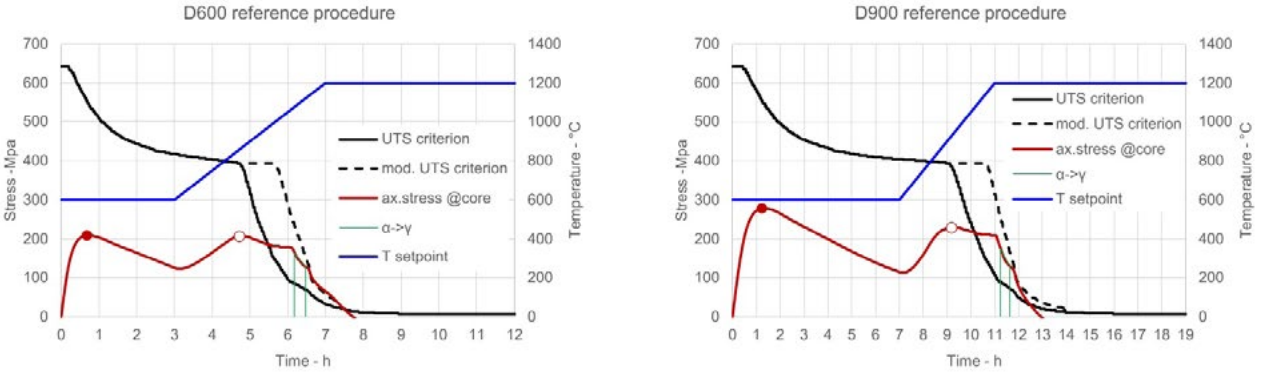

Fig.5 - Stress evolution at the core and criteria for failure.

REVISION OF HEATING PROCEDURES

Based on the above considerations, a revision of the heating processes is proposed in the aim of achieving time and energy savings, though not significantly increase the risk of cracking. The following options are considered:

- Rev.#1: elimination/reduction of the steady stage at 600°C.
- Rev.#2: adoption of stepwise procedure: the input stock is kept at 600°C and transferred to another furnace at 1200°C. This is a common practice of forgemasters to optimize production rate.

The results of the simulations are reported in the following Fig. 6 and Fig. 7.

Influence of reducing the steady stage at 600°C – rev.#1

Application of rev.#1 to D600 reflects into the elimination of the initial stationary phase at 600°C. The comparison between Fig. 5 and Fig. 6-left reveals that rev.#1 leads to an increase of about 100MPa in the first peak (time~2h) while the second peak is smoothed out and not undetectable anymore. As in the reference case, the core stress is not exceeding the modified UTS-criterion, therefore suggesting the feasibility of applying the revised process.

For D900, the larger size suggests not to suppress the plateau at 600°C to avoid critical thermal gradients. In this case rev.#1 leads to a reduction of 2hrs, that is from 7hrs to 5hrs. The comparison between Fig. 5 and Fig. 7-left shows that similar pattern with two stress peaks is produced in both standard and revised process. The first peak is almost unaltered, while the second peak is slightly anticipated and increased in value in the revised procedure. However, it is confirmed that the failure criterion is not exceeded as stress are below the maximum allowable value.

Influence of applying a stepwise procedure – rev.#2

The rev.#2 strategy is often considered as a practical alternative for improving productivity. The stock is moved from a furnace at 600°C into a furnace at 1200°C, so that no significant ramp is applied. This option is expected to be severe in terms of thermal-stress and simulation results in Fig. 6-right and Fig. 7-right fully capture this aspect: the onsetting of a secondary peak of large magnitude is predicted both for D600 and D900 cases. However, the stress still remains below the critical value for the whole process thus suggesting the applicability of the procedure, for the dimensions here considered. Input stocks of larger size require specific analysis.

Time and energy saving

Tab. 1 summarizes the results of standard and revised simulation for both D600 and D900. The standard and revised processes are compared in terms of time to target temperature, that is the time necessary to assure that the surface temperature at half height falls within 10°C to the furnace setpoint. For the cases of interest, this means Tsurf=1190°C. Any stay of the input stock at high temperature beyond this condition is referred as soaking and it is disregarded to the sake of comparison, as it is assumed to be applied identically to all procedures, both standard and revised.

The results highlight that the process revision does not affect the temperature distribution inside the material, though strongly affecting the time to target temperature. With reference to D600, the revision of heating procedures as per rev.#1 and rev.#2 does not affect the skin-to-core temperature gap, i.e. 24°C for all cases at the time to target temperature, but it allows saving respectively 2.7hrs and 2.1hrs.

With reference to D900, the skin-to-core temperature gap is of 40°C for both standard and revised processes while the time savings is of 1.9hrs and 2.1hrs respectively for rev.#1 and rev.#2.

The energy balance of the whole furnace requires devoted analysis to account for the burners' combustion efficiency, the heat loss through the exhaust fumes and the heat recovery. This is out of the scope of the paper. Anyway, some energy comparison among procedures have been carried out by basing on the available data, that are: the energy inside the furnace, the heat loss to the outside and the and the thermal energy inside the ingot stock. Although simplified, this allows getting indication that potential energy savings are expected when revising the heating processes, that are preliminary estimated in 5-6% for D600 and 2-3% for D900.

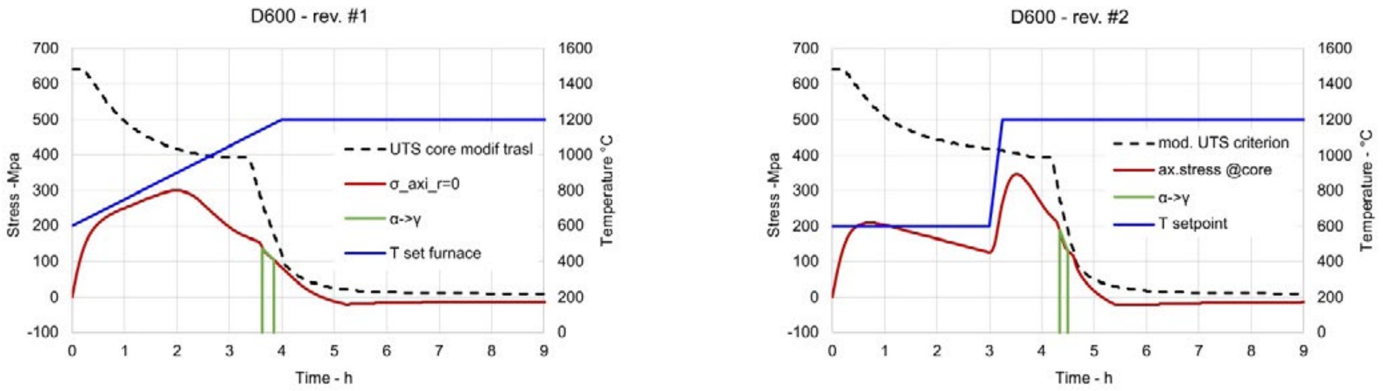

Fig.6 - Evolution of stress for the modified heating procedures for the D=600mm stock geometry.

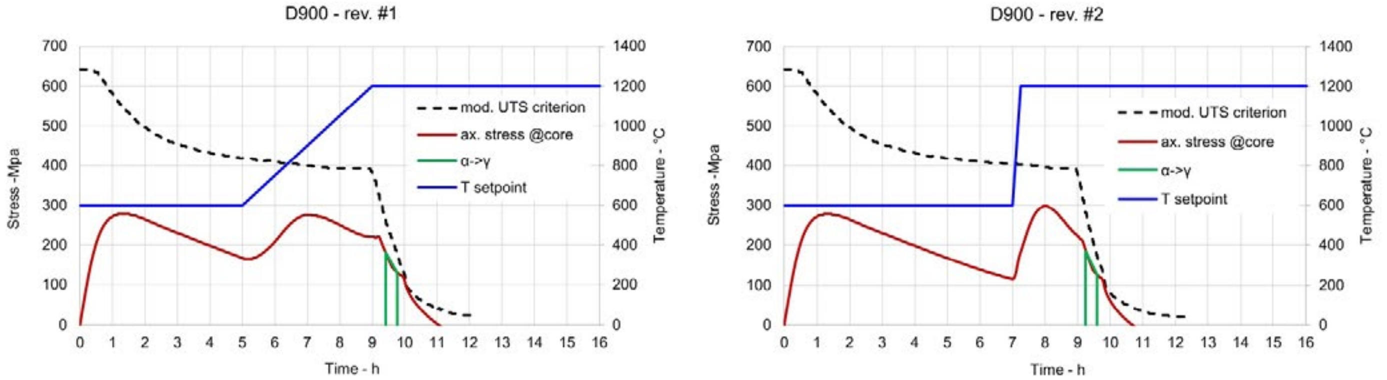

Fig.7 - Evolution of stress for the modified heating procedures for the D=900mm stock geometry.

Tab.1 - Standard vs revised procedures: results summary.

Diameter	Procedure	Planned schedule time	Actual time to target temp.	Time diff. respect ref case	Skin/core temp. diff	Equaliz. time	Energy input in the furnace	Energy diff. from ref case
mm	ID	hrs	hrs	hrs	°C	hrs	MJ	-
D=600	reference	12.0	9.6	-	24.3	2.6	30356	-
	rev.#1	9.0	6.9	-2.7	24.3	2.9	28976	-5%
	rev.#2	8.3	7.5	-2.1	23.9	4.2	28396	-6%
D=900	reference	18.5	16.5	-	40.1	5.5	43933	-
	rev.#1	16.5	14.6	-1.9	40.3	5.6	43259	-2%
	rev.#2	14.8	14.4	-2.1	40.0	7.1	42684	-3%

CONCLUSIONS

A finite element model is developed and validated for the simulation of thermo-structural phenomena occurring during input stocks reheating. It is able to accurately map the temperature and stress evolution across the input stock during the whole process. By comparing the local stress values against a failure criterion based on maximum normal stress limit, it is possible to predict whether a heating process may promote crack formation and compare various options. In the frame of the present activity, the model was applied to simulate heating procedures on two 42CrMo4 input stocks of different diameter: D600 and D900. For those cases, the failure criterion is tuned basing on the operator experience on its consolidated heating procedures. For each ingot, standard procedures are simulated and compared against two revised processes, aimed at exploring any potential productivity increase and energy saving. The revisions focus respectively on the influence of reducing the initial temperature plateau at 600°C, and on the adoption of a stepwise approach to 1200°C in lieu of the traditional ramp up. In both cases, no increase in the susceptibility to crack formation is predicted, as the stresses at the core do not exceed the failure criterion in any circumstances. On the other hand, a beneficial shortening of the entire process is estimated in 2.1-2.7hrs for the D600 and in 1.9-2.1hrs. for the D900. Energy saving is expected if revised procedures are applied and quantified in about 5-6% for D600 and 2-3% for D900.

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