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Anisotropic Plasticity Model Considering the Dynamic Strain Ageing Effects

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Abstract. For the precise description of plastic deformation behaviour of metallic materials in various forming processes, the accuracy of the applied constitutive model is of essential importance. It is well known that the mechanical properties of commonly used constructional materials, such as steels, aluminium alloys, are affected by several factors, temperature, strain rate, and loading orientation. However, a constitutive model considering all these involved phenomena with high accuracy is still missing. In this study, a comprehensive experimental program is designed to investigate the effects of anisotropy and temperature on the mechanical properties of a high-strength steel. The anisotropic flow behaviour of the investigated material is characterised by performing uniaxial tensile tests along three different directions with respect to the rolling direction. The thermal dependence of the mechanical properties, especially the flow stresses, is revealed by repeating uniaxial tensile tests along three directions over a wide range of temperatures, within which a special phenomenon called the dynamic strain ageing takes place. The mutual effects of the temperature and anisotropy on the plasticity are discussed. A phenomenological constitutive plasticity model is proposed to describe the anisotropic flow behaviour of the investigated material considering the complicated thermal effects over a wide range of temperatures.

INTRODUCTION

The accurate description of the flow behaviour of metallic materials is of significant importance in various industries. One major aspect that affects the plastic deformation of sheet materials is the anisotropy. There are various constitutive models developed to capture the anisotropic flow behaviour of different metallic materials, starting from the most widely applied quadratic Hill48[1] model to the advanced non-quadratic plasticity models[2-4] and the ones based on non-associated flow rule[5, 6]. However, most of these models are only focusing on the initial yield behaviour and the evolving characteristics during plastic deformation are not being considered. Recently, the evolving features of anisotropy have attracted more attention[7-9], such as the evolving non-associated Hill48 (enHill48) model proposed by Lian et al.[9], which provided improved accuracy in the prediction of the forming limit curve incorporating with either the modified maximum force criterion[9] or the Marciniak-Kuczynski (MK) model[10].

The plastic deformation behaviour of metallic materials under the influence of temperature and strain rate is of high interest for both the scientific community and industry. It has been reported that under a certain combination of temperature and strain rate, more complicated deformation mechanisms might occur, such as the dynamic strain ageing (DSA) and dynamic recovery. The occurrence of DSA has been reported to have undesired impacts on the final products[11]. There have been many constitutive models developed and applied to describe the thermal softening

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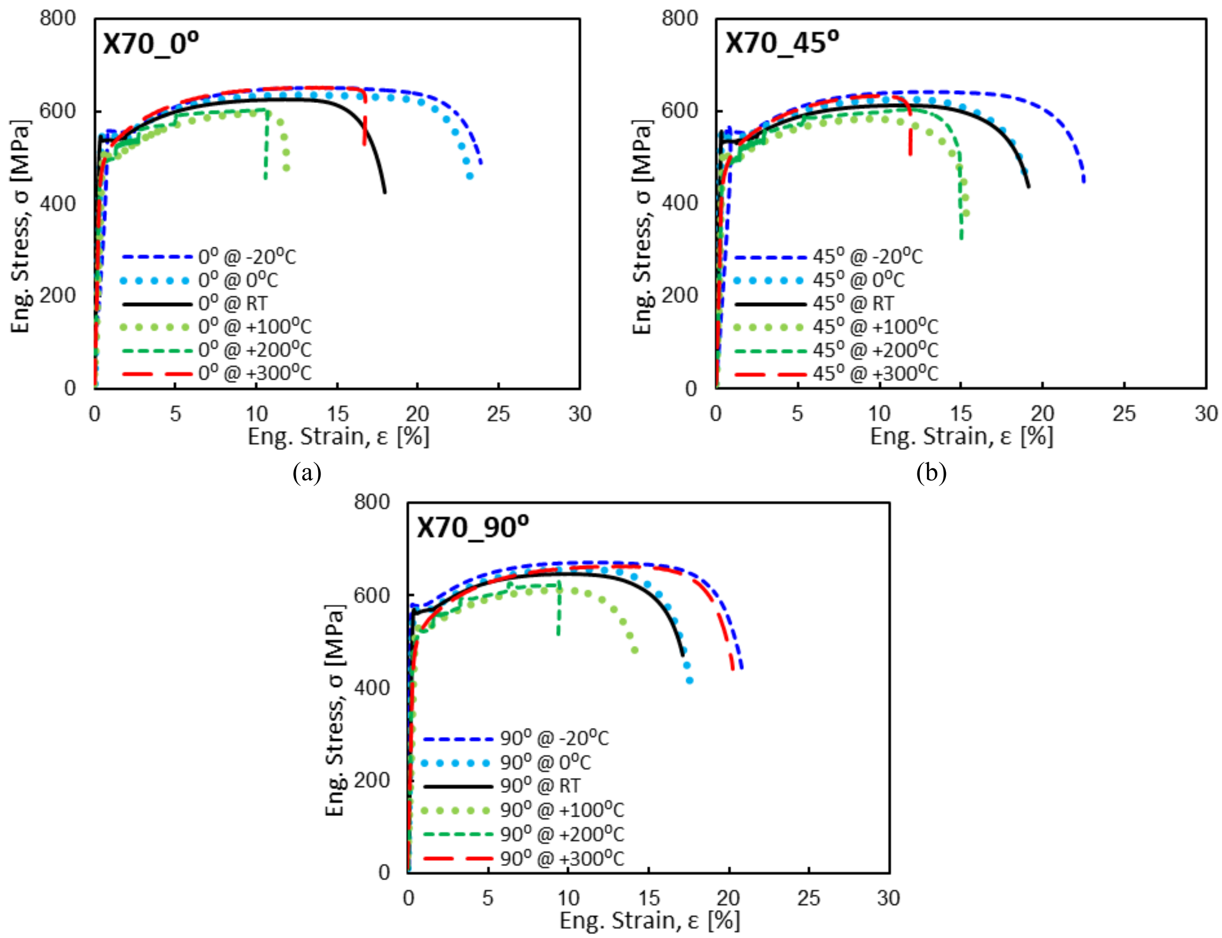
behaviour[12-16] for various metallic materials. In addition, constitutive equations have been also developed and validated for certain materials with more complicated deformation mechanisms, such as DSA[17, 18]. However, the effects of temperature on the anisotropy of high-strength steels have not been systematically investigated especially when the DSA effects are also present. Therefore, it is the aim of this study to perform an experimental investigation on the thermal effects on anisotropy and further develop a constitutive model, based on the enHill48 model[9], with high accuracy and efficiency in the description of the temperature affected anisotropic flow behaviour.

MATERIAL AND EXPERIMENTS

The high-strength pipeline steel X70 with an initial thickness of 14 mm has been used in this study and the thickness has been reduced to 2 mm for the ease of sample manufacturing and experiments. After the thermal-controlled rolling process, a certain intensity of texture has been generated in the material. Uniaxial tensile tests have been performed using smooth dog-bone along three directions (0°, 45°, and 90°) with respect to the rolling direction to characterise the plastic anisotropy of the material. In order to understand the effects of temperature on the flow behaviour of the investigated material as well as on the anisotropy, quasi-static uniaxial tensile tests ($\dot{\varepsilon} = 1 \times 10^{-4}\, s^{-1}$) have been performed at six different temperatures (from -20 °C to 300 °C) along the three loading directions. For each loading condition, three parallel tests have been conducted and based on the high repeatability of the experimental results one representative result is selected. More detailed information of experimental procedures and results can be found in Ref.[19]. The engineering stress–strain curves of three loading directions obtained at six temperatures are depicted in Fig. 1.



(a) (b) (c)

Fig. 1: The engineering stress–strain curves obtained from uniaxial tensile tests at different temperatures from the loading angles of (a) 0°, (b) 45° and (c) 90° with respect to the rolling direction.

From the tensile test results, the anisotropic flow behaviour is observed in the investigated material as the strength is the highest along the transverse direction (90°) while the lowest strength occurs along the diagonal direction (45°). The effects of temperature on flow stress of the investigated material are also obvious. Along all three loading directions, the highest strength is observed at -20 °C, while the lowest strength is found at 100 °C and obvious serrated flow behaviour is observed at 200 °C. At elevated temperatures, these unusual phenomena such as serrated flow stresses and higher stress with increasing temperature are indicating the occurrence of DSA, which has been reported in several alloys within a certain range of temperatures and strain rates[11]. Further analysis has been performed to evaluate the influence of DSA on the anisotropy in the following sections.

MATERIAL MODEL FORMULATION

For the accurate description of anisotropic plasticity behaviour of metallic materials, the most widely applied Hill48 yield criterion has been combined with non-associated flow rule to formulate the non-associated Hill48 (nHill48) plasticity model[6], where the yield function *f* and the flow potential *g* are independent. The anisotropic hardening behaviour has been further included in the recently developed enHill48 plasticity model[9], which has shown improved accuracy in the prediction of forming limits. In this study, the effects of temperature on plasticity are further considered and described by the following equations.

$$f = \bar{\sigma}_{\sigma}(\boldsymbol{\sigma}, F, G, H, L, M, N) - \sigma_{Y}(\bar{\varepsilon}^{p}) \cdot f(T) \leq 0 \tag{1}$$

$$g = \bar{\sigma}_{r}(\boldsymbol{\sigma}, F, G, H, L, M, N) - \sigma_{Y}(\bar{\varepsilon}^{p}) \cdot f(T) \leq 0 \tag{2}$$

In the anisotropic plasticity model based on the quadratic Hill48 formulation, the loading orientation dependence of plastic behaviour is described by six anisotropic parameters *F, G, H, L, M* and *N.* The yield stresses and r-values obtained from uniaxial and/or biaxial tensile tests are used to calibrate these anisotropic parameters in the yield function and flow potential, respectively. Due to the observed evolving features of anisotropy in the experimental results, these anisotropic parameters depend on the equivalent plastic strain. $\sigma_{Y}(\bar{\varepsilon}^{p})$ is the flow curve obtained at the reference temperature and quasi-static condition. The temperature function $f(T)$ is used to describe the thermal effects on the flow behaviour characterised by the normalized strength, which is defined as the ratio between the flow stress at a certain temperature σ_{T} over the one at the reference temperature σ_{ref}.

$$f(T) = \frac{\sigma_{T}}{\sigma_{ref}} \tag{3}$$

$$f(T) = C_1 \cdot exp(-C_2 \cdot T) + C_3 + C_4 \cdot exp\left[-\left(\frac{T - C_6}{C_5}\right)^2\right] \tag{4}$$

where $C_1 \sim C_6$ are six thermal parameters which are calibrated from tensile tests results at different temperatures. Typically, room temperature (RT) is chosen as the reference temperature. $C_1 \sim C_3$ are three materials parameters describing the thermal softening effects, which can be calibrated based on experimental results in the low temperature range where the DSA is unlikely to take place. By subtracting the thermal softening components from the experimental results, the contribution of DSA on the flow stress can be determined. As the DSA usually occurs within a specific temperature range, the intensity of DSA is described by a peak function with three parameters $C_4 \sim C_6$, which are calibrated using experimental results within the temperature range of high DSA intensity. When the influence of DSA is not evident at all, the contribution of DSA on flow behaviour can be omitted by setting C_4 as zero. These thermal parameters are calibrated for each individual loading direction to describe the thermal dependence of anisotropy. It is further noted that the evolving features of the thermal effects are also taken into account for a high predictive accuracy.

RESULTS AND DISCUSSION

In this study, RT is taken as the reference temperature. For the direct visualisation of the thermal effects on plasticity, the normalized strength at the strain level of 0.02 at different temperatures for three loading angles are shown in Fig. 2. Besides the average value, the error bar based on three parallel experimental results is also shown. In the relatively low-temperature range up to 100 °C, the normalized strength is decreasing with the increase of temperature, indicating the typical thermal softening behaviour. At the elevated temperatures, the normalized strength is increased with the increase of temperature, which is attributed to the DSA effects. The same trend is observed in all three directions. The dashed lines in Fig. 2 correspond to the prediction results of the normalized strength based on the calibrated thermal parameters for all three angles. As shown in Fig. 2, both the thermal softening and DSA effects are well captured by the temperature function. Due to the limitation of the experimental facilities, r-values are available only at RT, therefore, the thermal effects on the r-value are not considered in this study.

The thermal effects on anisotropy are depicted in Fig. 2 (d). The normalized stress σ_{N} in this case, is defined as the ratio between flow stress along different loading directions σ_θ over the one along the rolling direction σ_0 at a certain temperature ($\sigma_{\mathrm{N}} = \sigma_\theta/\sigma_0$). The experimental results are represented by different symbols at various temperatures and the prediction results are shown as different curves. In the calibration of anisotropic parameters, the tensile stress of the equibiaxial tests is taken as the average value of tensile stresses from three different loading directions ($\sigma_{\mathrm{b}} = (\sigma_0 + 2 \cdot \sigma_{45} + \sigma_{90})/4$). As shown in Fig. 2 (d), the thermal effects on anisotropy are not significant but evident within the experimental temperature range. It is also clearly shown that the proposed thermal-dependent enHill48 model is capable of describing the temperature dependence of the investigated material.

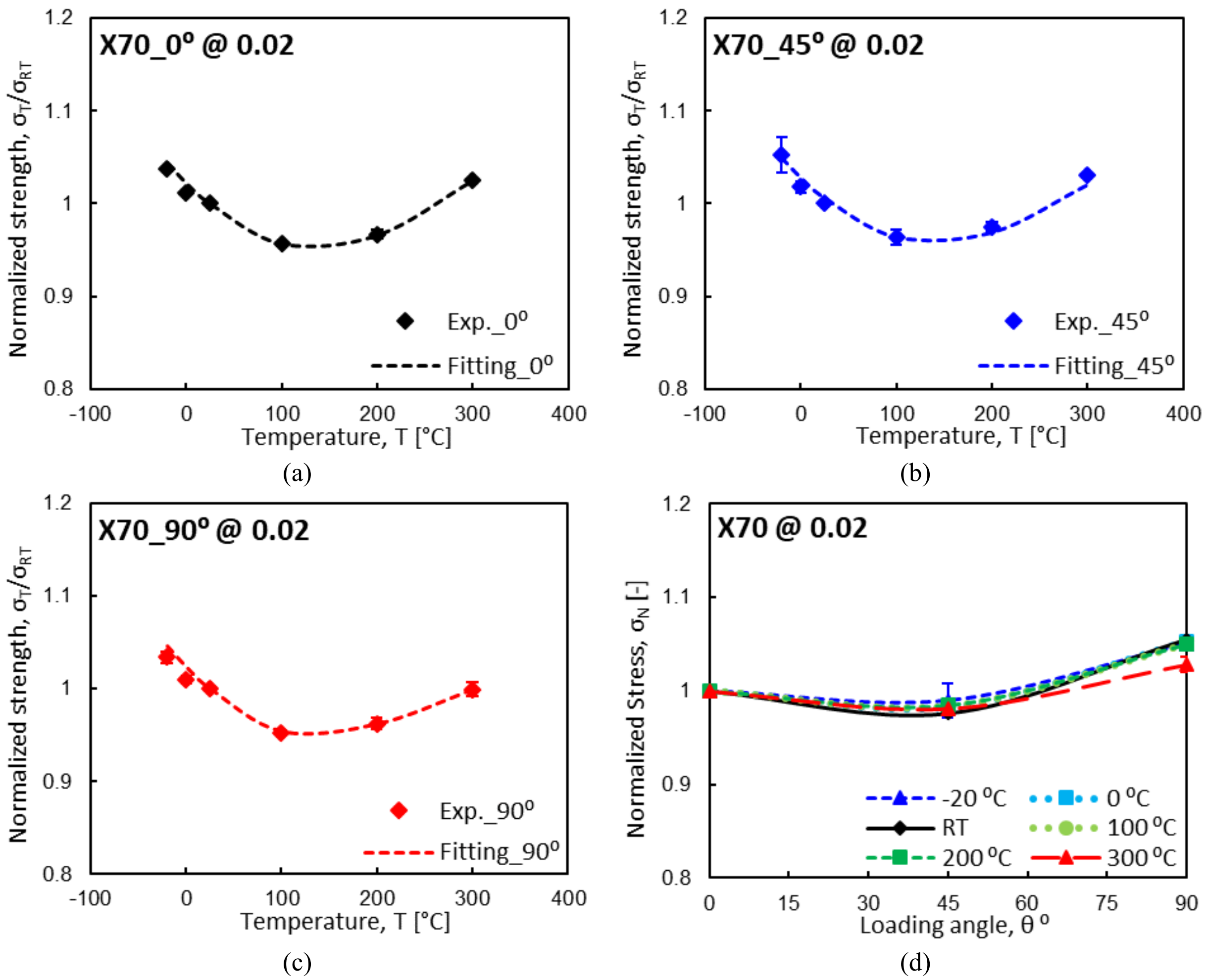


Fig. 2: The comparison between experimental and numerical results of normalized strength obtained from uniaxial tensile tests at different temperatures from the loading angles of (a) 0°, (b) 45° and (c) 90° with respect to the rolling direction. (d) The effects of temperature on the anisotropy of the investigated material.

The plastic deformation of metallic materials with the body centred cubic (BCC) crystalline structure is typically accomplished by dislocation slipping. Any mechanisms that affect the dislocation movement have impacts on the flow stress. As dislocation slipping is a thermal activation process, the flow stress is decreased with increasing temperature due to enhanced thermal activation effects in the typical thermal softening phenomena. The occurrence of DSA is attributed to the interaction between the solute atoms and dislocations. During plastic deformation, solute atoms tend to diffuse to the dislocation cores to generate some additional resistance to the dislocation movement. The dragging force caused by solute atoms depends on the loading conditions as diffusion is also a thermal activation process. Under a selective combination of loading strain rate and temperature, the competition between solute atom diffusion and dislocation slipping reaches such a balance that the additional dragging force is maximized. With further increase of plastic deformation, the dislocation density is also increased, which also affects the interaction between solute atoms and the dislocation movement. Therefore, the intensity of DSA is also dependent on the level of plastic deformation. Based on the deformation mechanisms, the thermal parameters $C_1{\sim}C_6$ should not be considered as constants but dependent on the plastic strain values. Therefore, experimental flow curves up to the strain value of 0.08 have been used to calibrate these thermal parameters. By calibrating the thermal parameters with plastic strain dependence for all three loading directions, the flow curves at different temperatures can be predicted as shown in Fig. 3.

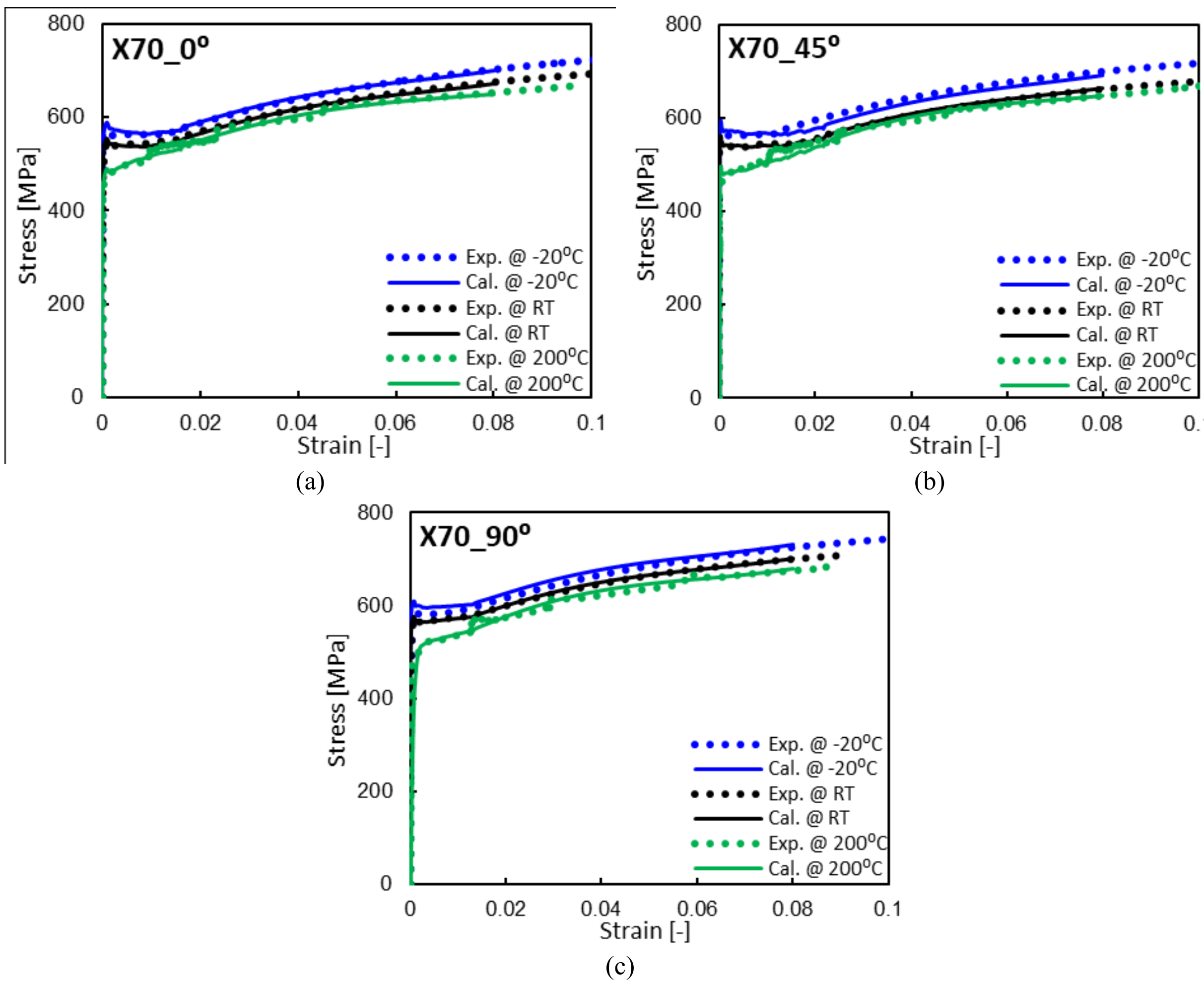


Fig. 3: Comparison between the experimental and numerical results of true stress versus true plastic strain curves at different temperatures from the loading angles of (a) 0°, (b) 45° and (c) 90° with respect to the rolling direction.

From the comparison between experimental and numerical results of the true stress versus true plastic strain curves at three temperatures along three loading directions, high accuracy in the flow stress prediction is obtained using the thermal-dependent enHill48 model. For each individual loading direction, the flow curves up to the true strain value of 0.08 at different temperatures can be accurately predicted given the corresponding flow curve at RT as reference, indicating the high accuracy of the temperature function in describing the flow behaviour considering the influence of DSA as well as the evolving characteristics. With calibrated thermal parameters $C_1{\sim}C_6$ as functions of plastic strain for three angles, flow stresses at different temperatures along any loading direction can be predicted when the flow curve along the rolling direction and anisotropic parameters at RT are given. In order to improve the accuracy, especially considering the evolving features during plastic deformation, flow curves at RT along three loading directions as well as the corresponding strain dependent thermal parameters are taken as input data in this study to achieve the accurate prediction of flow stresses at different temperatures along other loading directions, proving the high accuracy of the evolving plasticity model not only in the description of thermal effects but also the anisotropy effects. However, it is noted that the materials parameters are calibrated based on experimental results within a certain temperature range and strain level. Therefore, the accuracy of this plasticity model applied in other loading conditions needs further validations. The major aim of the study is not to comprehensively calibrate the model in various loadings for specific applications but it is aimed to propose a new constitutive model and develop a methodology in the description of thermal effects on anisotropy while considering the effects of dynamic strain ageing. The proposed approach is proven to be accurate and efficient by comparing with the experimental data.

CONCLUSIONS

The current study aims to develop a constitutive model to describe the thermal effects on anisotropy based on uniaxial tensile tests of a high-strength steel. The following conclusions can be drawn:

- In addition to the typical thermal softening phenomena, the dynamic strain ageing effects have also been observed in the investigated material along all three loading directions.
- Based on the results of uniaxial tensile tests at different temperatures along different loading directions, the thermal effect on the anisotropic behaviour is not significant but evident for the investigated material.
- The developed thermal-dependent enHill48 model provides high accuracy and efficiency in describing the anisotropic flow behaviour in a wide temperature range with both deformation mechanisms of thermal softening and dynamic strain ageing.

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