SPT RESULTS EVALUATION

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Abstract

Small punch test (SPT) is known as a powerful NDT tool for material properties determination of existing structures. The paper presents a description and results of SPT computer simulations performed with the steels in a wide range of yield strength and tensile strength. The true tension diagrams of these steels are created by the Hollomon's formula. Conventional mechanical properties of the steels are verified from the results of computer simulation of tensile tests, too. True mechanical properties are used for SPT simulation of steels. Relationships of loads and puncher displacements are shown in the paper. Subsequently parameters SPT, i.e. the maximum load, puncher displacement at maximum load, plastic tangent at the initial stage of SPT and "yield load" are carried out. Intersection of plastic tangent and axis of load determines "yield load". Causal relations between the characteristics of static strength steels and SPT parameters are shown as graphic results. Quite notable is the influence of hardening exponent in causal relations and correlation of yield strength with "yield load". Two generally independent methods of estimating of yield strength and tensile strength from SPT results are presented. These methods are based either on causal relationships or derived regression models.

Key words: *simulation, small punch test, evaluation, mechanical properties of steel, finite element method*

1. Introduction

Small punch test (SPT) has been widely used for effective verification of mechanical properties related to steel elements in existing structures [1], [2] and [3]. SPT testing specimens are small in size. Thus, any imperfections of structure geometry developed during material sample extraction do not represent any significant factor with respect to overall structure strength. As a result, SPT ranks among NDT methods. Multiple procedures have been published that deal with innovative steel mechanical properties determination. This new approach includes computer-aided SPT simulation with controlled optimization of real stress/strain diagram [4] and [5]. Obviously, such methods are challenging with respect to technical equipment, software, and personnel as well. In common engineering praxis, the steel properties are estimated using simple empirical equations derived from available test results [6], [7], [8] and [9].

Commercial software programs based on finite element method allow for solution of complex tasks related to stress/strain computations. In such studies, elastic-plastic behavior of solid parts can be examined with focus on extensive deformation/friction scenarios. Results obtained from tensile test simulations and SPT simulations [10] and [11] indicate that such computer-aided simulation results may provide useful information about causal relationships between steel properties and SPT results.

Preparation phase included generation of true tensile diagrams [12] of model steels with pre-entered values of yield strength $R_{pO.2}$ and ultimate strength R_m. Then, simulation results were obtained for tensile tests and SPT with the same model steels. Information about relationships between material properties and SPT results were collected. The goal is to show that using this valuable data, yield strength and ultimate strength could be estimated directly from SPT results.

2. Model Steels

Model steel properties used in the simulation are described by Young modulus E = 210 000 MPa, Poisson ratio ν = 0.3, and true tensile test diagrams. The diagrams were

Table 1: *Mechanical properties of model steels*

k **[MPa]**	***n*** **[-]**	$R_{p0.2}$ **[MPa]**	R_m **[MPa]**	***A*** **[%]**	***Z*** **[%]**
931	0.05	682	761	19	74
1212	0.09	682	885	20	67
1530	0.13	682	1027	24	69
849	0.05	622	694	16	72
1105	0.09	622	806	20	68
1395	0.13	622	937	24	66
775	0.05	568	633	16	71
1010	0.09	568	737	21	68
1274	0.13	568	856	24	69
484	0.05	355	396	15	57
631	0.09	355	461	21	68
796	0.13	355	536	25	69

created using Hollomon's formula $\sigma = k \cdot \varepsilon_p^n$, where σ is true stress, ε_p is plastic strain, k is strength coefficient, and n is strain hardening exponent. Mechanical properties of model steels were calculated using computer simulation of tensile tests [11]. Elongation A and reduction of area Z correspond to point, where the HMH stress reached maximal specified value of true stress in 90% of the area within the cross-section of narrowed test specimen (see Table 1).

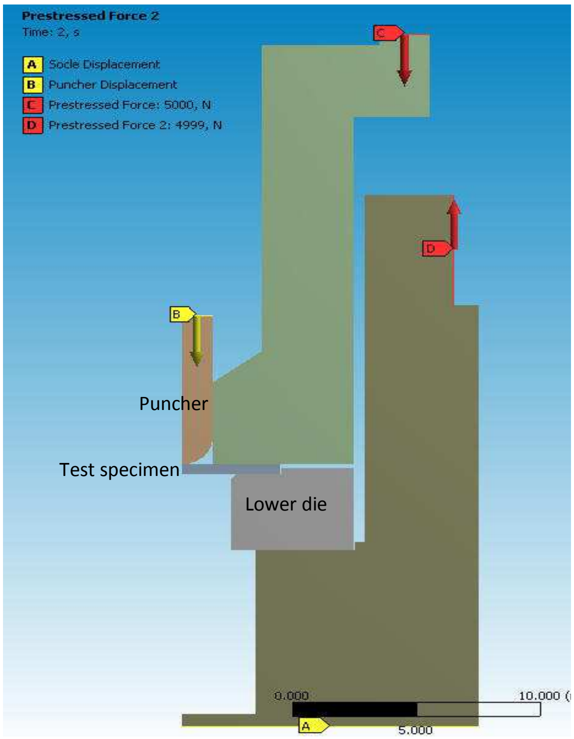

Fig. 1: *Geometric model of PD*

3. SPT Simulation

Geometric model of SPT includes punching device (PD) and test specimen. The specimen is a disc-shaped solid (diameter 8 mm, height 0.5 mm) [11]. Model of the PD with the specimen was created using rotational symmetry with respect to vertical axis of the PD. Friction coefficient f = 0.07 was applied onto the PD/specimen contacts. Specimen was "fixed" in the PD by means of C and D forces from union nut. Geometric model of the PD is shown in Figure 1. Material properties of individual PD parts, for example steels, lower die (INCONEL625), and puncher (corundum) have corresponding values of Young modulus and Poisson ratio. Model of the lower die (INCONEL625) includes additional parameters of isotropic hardening. In the first step of the SPT, the test specimen disc is fixed in the PD using the C and D forces. In the second step, the specimen is gradually loaded due to displacement of the puncher up to value of 2.1 mm.

4. Relations between Material Properties and SPT Simulation Results

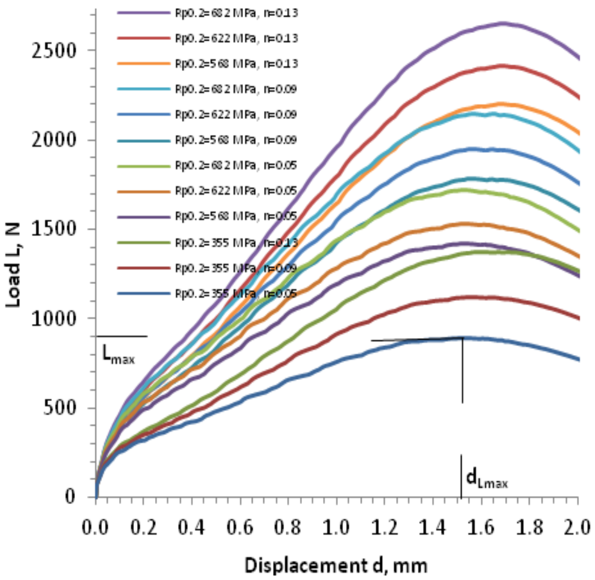

Fig. 2: Load-displacement curve for model steels

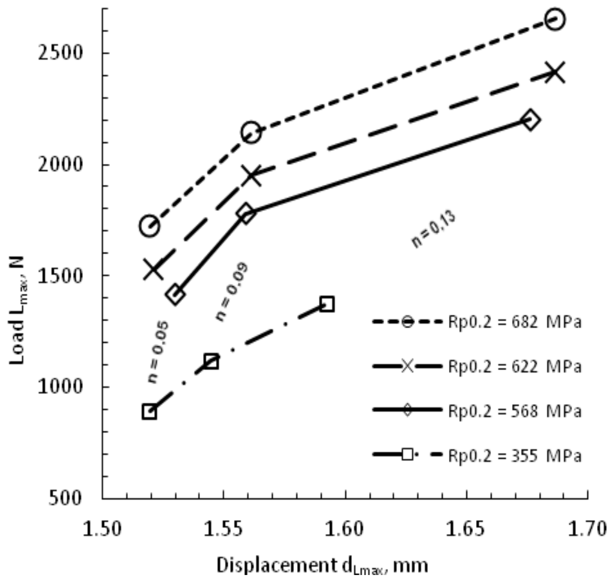

***Fig. 3:** Effect of yield point and hardening on SPT results*

Figure 2 shows loading diagrams of simulated SPT model steels marked with yield strength and hardening exponent. This represents relationship of loading force *L* and puncher displacement *d*.

Figure 3 shows maximum load L_{max} related to displacement d_{Lmax} for model steels with yield strength $R_{p0.2}$ and hardening exponent *n*. Maximum load L_{max} and displacement d_{Lmax} increases with yield strength and hardening exponent of the steel.

Figure 4 shows dependences of model steel ultimate strength values and maximum load L_{max} for hardening exponent values of $n = 0.05$, 0.09 and 0.13. With constant values of hardening exponent, the dependences are linear and pass through the coordinate system origin. Ultimate strength increases with growing maximum load values. When the maximum load is constant, the ultimate strength shows increase along with decrease of the hardening exponent. Figure 5 shows dependency of yield strength and maximum load L_{max} for model steels. With constant values of hardening exponent, the dependences are linear and pass through the coordinate system origin. Yield strength increases with growing maximum load values. When the maximum load is constant, the yield strength shows increase along with decrease of the hardening exponent. Figure 5 shows dependency of yield strength and maximum load L_{max} for model steels. With constant values of hardening exponent, the dependences are linear and pass through the coordinate system origin.

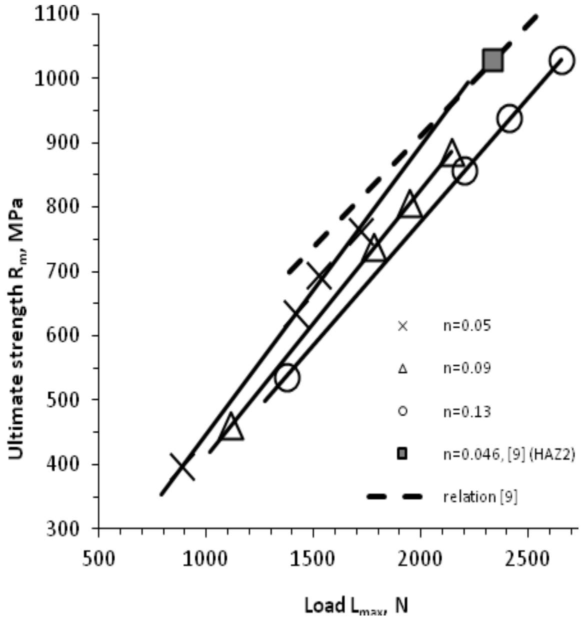

Fig. 4: Dependency of ultimate strength and maximum load

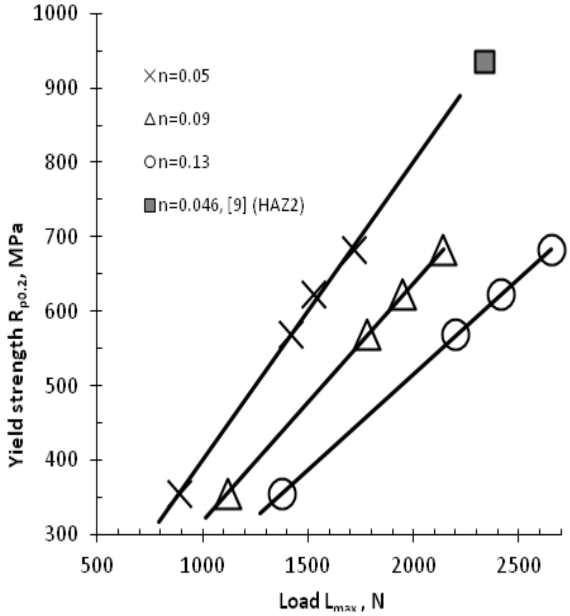

Fig. 5: Dependency of yield strength and maximum load

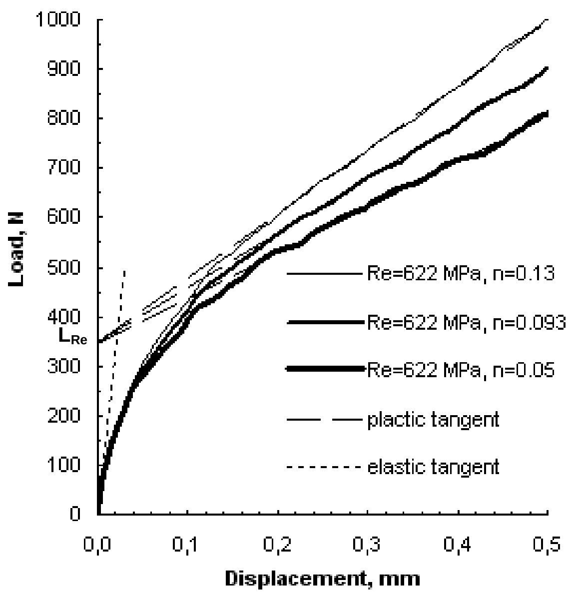

Fig. 6: Procedure of "yield load" L_{Re} assessment

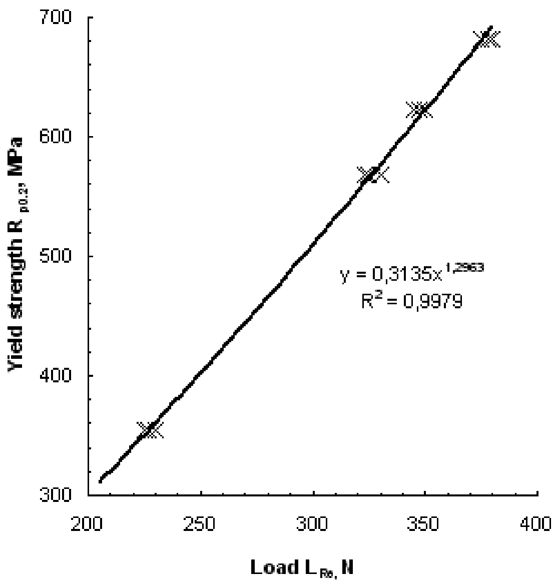

Fig 7: Yield strength – "yield load" L_{Re} relation

Yield strength increases with growing maximum load values. When the maximum load is constant, the yield strength shows increase along with decrease of the hardening exponent.

Incline of plastic tangents constructed in loading diagram at the start of the SPT, i.e. shortly after reaching of the yield strength in test specimen shows strong increasing trend with growing hardening exponent *n* (see Figures 2 and 6). Plastic tangents constructed for given yield strength intersect for examined values of hardening exponent at the axis of load. They determine value of the property „yield load“ L_{Re}, see Figure 6.

Figure 7 shows dependency of yield strengths of model steels and values of „yield load“ L_{Re} .

The dependency can be approximated using a linear or power law relation. When the power law approximation is used, the determination coefficient R^2 reaches value of 0.9979.

5. Estimation of Yield Strength and Ultimate Strength from SPT Results

Analysis of relationships between mechanical properties of steels and computer-simulated SPT results makes it possible to establish improved methods for estimation of yield strength and ultimate strength using graphic-calculation methodic and multidimensional linear regression (MLR).

A. Graphic-calculation Methodic

Plastic tangent is constructed in the loading-displacement diagram provided by the SPT. The tangent's intersection with the axis of load of the diagram marks the loading value L_{Re} (see Figure 6). The yield strength is either read out from the diagram showing the dependence of yield strength and „yield load“ L_{Re} or can be calculated using regression function (see Figure 7). The hardening exponent n can be estimated using dependency of yield strength and measured maximum load L_{max} (see Figure 5). Then, ultimate strength value is either calculated using a equation $R_m = R_{pO.2} \cdot (500 \cdot n)^n / (n+1)$ derived from Hollomon’s formula or it can be read out from the diagram showing the dependence of ultimate strength and maximum load L_{max}, (see Figure 4).

B. Multidimensional Linear Regression (MLR)

SPT simulation results (maximum load L_{max} and displacement at maximum load d_{Lmax}, or their squared values and mutual products) are considered to be independent variables (so called regressors). Yield strength and ultimate strength values are randomly dependent variables. Linear regression model in matrix notation was applied to SPT simulation results. The model is described by $\boldsymbol{y} = \boldsymbol{X\beta} + \boldsymbol{\varepsilon}$ equation, where $\boldsymbol{X}$ is a matrix of regressors, $\boldsymbol{\beta}$ is a regression coefficient vector, and $\boldsymbol{\varepsilon}$ is a random error vector [13]. It is presumed that components for the random error vector have normal distribution of probability with zero mean value. Also, they have the same variation σ^2 and they are uncorrelated. Estimation of the regression coefficient vector $\boldsymbol{b}$ was performed using the least square method. This method relies on minimization of residual sum of squares for the exact value deviations y_i with respect to theoretical values of Y_i. Thus, regression coefficient vector represents solution of normal linear equations $\boldsymbol{b = (X^TX)^{-1}X^TY}$ provided that symmetric matrix $\boldsymbol{X^TX}$ is regular. Regression coefficient vectors are estimated with yield strength and ultimate strength. The vectors can be described using the following functions: linear function, quadratic function without mixed member or quadratic function of SPT results. Table 2 contains estimated equation of yield strength $R_{pO.2}$, ultimate strength R_m, and corresponding values of determination coefficients R^2. The determination coefficients R^2 related to ultimate strength are higher than those related to yield strength. It is worth noting that determination coefficients reach the highest values for the quadratic relation.

Table 2: *Regression relations of yield strength/ultimate strength and SPT parameters*.

Function	Regression Relations	R^2
Linear	$R_{p0.2} = 2753.2 - 1794.1 \cdot d_{L\max} + 0.36121 \cdot L_{\max}$	0.926
	$R_m = 1126.9 - 732.80 \cdot d_{L\max} + 0.42931 \cdot L_{\max}$	0.994
Quadratic without mixed-member	$R_{p0.2} = 40448 - 49364 \cdot d_{L\max} + 14911 \cdot d_{L\max}^2 + 0.62184 \cdot L_{\max} - 0.00008 \cdot L_{\max}^2$	0.993
	$R_m = 16616 - 20312 \cdot d_{L\max} + 6143.3 \cdot d_{L\max}^2 - 0.04411 \cdot L_{\max} - 0.00004 \cdot L_{\max}^2$	0.999
Quadratic	$R_{p0.2} = 33649 - 39736 \cdot d_{L\max} + 11493 \cdot d_{L\max}^2 + 0.67330 \cdot d_{L\max} \cdot L_{\max} - 0.29960 \cdot L_{\max} - 0.00012 \cdot L_{\max}^2$	0.994
	$R_m = 12212 - 14077 \cdot d_{L\max} + 3929.8 \cdot d_{L\max}^2 + 0.43606 \cdot d_{L\max} \cdot L_{\max} - 0.04411 \cdot L_{\max} - 0.00001 \cdot L_{\max}^2$	0.999

6. Discussion

Determination of steel yield strength using ordinate of elastic and plastic tangent intersection as described in commonly used methodic [9] does not take into account the dependency of plastic tangent incline and hardening exponent. Another methodic uses elastic tangent re-positioned at specified displacement value [7]. However, this approach results in even higher error of yield strength estimation.

Plastic tangents are determined in a specific area of the SPT diagram, where the plastic strain is quite small and fitting of Holloman’s formula to true tensile diagram is satisfactory. SPT simulation provided dependencies of loading L on displacement d (Figure 6) and of yield strength on the L_{Re} value (Figure 7). These dependencies are realistic and correspond to result of actual SPT procedures.

Relations between yield strength, ultimate strength, maximum load L_{max}, and displacement d_{Lmax} acquired using SPT simulation can be affected by the construction method used to get true tensile diagrams, especially for greater strain conditions. However, this presumption was not supported by the SPT results carried out with steel specimens in the heat-affected zone of the weld joint [9], see Figure 4 and Figure 5. Simulation results correspond to SPT experiment for steel with hardening exponent of approximately 0.05.

It worth noting, that based on our results, linear equation $R_m{=}a{\cdot}{+}b{\cdot}L_{max}$ (where a and b are constants) used by Rodrigez [9] may be considered valid only for steels with higher strength values. It is ergo possible to presume, that this linear relationship is established for higher-strength steels without taking into account the hardening. It is logical expect that curve of dependency of yield strength and „yield load“ L_{Re} goes through the origin of coordinates. These considerations were confirmed by our results of the SPT simulation (see Figure 4).

Estimation of yield strength from SPT using graphic-calculation methodic works with different data than estimation using MLR. As a result, the both approaches may be considered independent. Evaluation of yield strength and ultimate strength using relation established by MLR is straightforward with no personnel influence factor. On the other hand, values of determination coefficient predict greater estimation errors, especially for yield strength estimation.

Validity range for relations among yield strength, ultimate strength, and SPT results should be verified by experiment (tensile testing, SPT) followed by a SPT simulation. Applied normalization of loading L_{max}, L_{Re}, and displacement d_{Lmax} with specified specimen height v [13] does not affect either conclusions referring to relations between material properties of steels and results of SPT simulation or proposed evaluation methodic. With SPT evaluation, normed loads L_{max}/v^2, L_{Re}/v^2 and normed displacements d_{Lmax}/v are used in the procedure.

7. Conclusions

SPT simulation results for model steels featuring specific values of yield strength (from 355 MPa to 682 MPa) and ultimate strength (from 396 MPa to 1027 MPa) made it possible to establish empirical relationships between mechanical properties of the steels and SPT results. Significant findings include influence of hardening exponent onto dependency of yield strength/ultimate strength and maximum load of the SPT. The hardening exponent proved to affect the incline of the plastic tangent constructed in the load/displacement diagram as well. Strong correlation of yield strength and the „Yield load“ value established in the intersection of plastic tangent and load axis is considered an important feature, too. This knowledge was crucial for the development of an improved SPT result evaluation methodic. Two generally independent methods for estimation of yield strength and ultimate strength from SPT results are presented.

8. References

1. KUPČA, L. -BŘEZINA, M. -PETZOVÁ, J. -BAĽÁK, M.: Evaluation of the reactor pressure vessel material properties degradation due to the irradiation by SPT method, 1st International Conference SSTT, Ostrava, 2010
2. KUPČA, L. -BŘEZINA, M.: Možnosti využitia systému na odber malých vzoriek z prevádzkových zariadení pri hodnotení vlastností materiálov, Chem. Listy 105, s167-s170 (2011)
3. ŠŤASTNÝ, R. -PAVLÍK, V.: Application of SPT in CEZ, 1st International Conference SSTT, Ostrava, 2010
4. EGAN, P., et al.: Small punch test: An approach to solve the inverse problem by deformation shape and finite element optimization, Comput. Mater. Sci. 40 (2007) pp33-39
5. IVÁN, L. –DYMÁČEK, P.: Optimalizace materiálových parametrů při simulaci protlačovací zkoušky na miniaturních vzorcích, ANSYS konference 2010, Frymburk, Czech Republic, 2010
6. Abdul Salam Ali zidan,-LI, W. -BROOKFIELD, D. J.: The FE analysis and aplication of the small punch test, Int. Conf. on STISWB, Mahasarakham University, Thailand, 2009

7. AUTILLO, M., A. et al.: Utilización del ensayo miniatura de punzonamiento (Small Punch Test) EN LA Caracterización mecanica de aceros, Anales de Mecanica de la Fractura Vol. 1 (2006), 77-83
8. KLEVTSOV I. et al.: Using of small punch test for determination of tensile properties for power plant steels, 6th Int. DAAAM Baltic Conf. INDUSTRIAL ENGINEERING, Tallinn, 2008
9. RODRÍGUEZ, C. et al.: Mechanical Properties Characterization of Heat-Affected Zone Using the Small Punch Test, Welding Journal,Vol. 88 (2009) 188-192
10. HŮLKA, J. - KUBÍK, P. - PETRUŠKA, J.: Sensitivity analysis of small punch test, 18th Int. Conf. ENGINEERING MECHANICS 2012, Svratka, Czech Republic, 2012
11. VARNER, M. – KOULA, - V. VOLÁK, J.: Influence of instrumentation imperfections on SPT results, 43rd International Conference NDE for Safety 2013, Olomouc, 2013
12. DOWLING, N. E.: Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture, and Fatigue, Prentice Hall, Englewood Cliffs, New Jersey, 1993
13. KROPÁČ, O.: Náhodné jevy v mechanických soustavách, Praha, SNTL, 1987
14. CAMPITELLI, E. N.: Assessment of mechanical properties in unirradiated and irradiated zircaloys and steels with non-standard tests and finite element calculations, These No 3304, EPFL, Lausanne, Switzerland , 2005

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