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Analysis of the strength difference effect on tailor welded blanks' springback

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Abstract. Tailor welded blanks (TWBs) are becoming widespread in the automotive industry due to their advantages, such as the possibility of weight reduction or the material usage optimising, resulting from the application. However, their main disadvantage is that the construction design and the simulation of the mechanical processes (like weld line movement, sheet springback, etc) are more complex. Predicting the mechanical response can only be done by accurately estimating the weld properties, which greatly increases the material testing requirements. Moreover, it often does not coincide with the matter of the field of material forming. In this study we focus on the simplified description of the springback of TWBs, to reveal which parameters have the primary influence on this process. Three kinds of DP steels with different strengths were welded to a mild steel grade one by one. Using these pairs we have varied both the strength difference between each sides and the average strength of the blanks, too. Uniaxial tensile tests were performed for the mechanical characterisation of each material, as well as right-angled bends perpendicular to the weld line were carried out to monitor the springback tendency of the samples. Our results show that a transition zone develops near to the weld line, independently from the strength difference between the TWB's components. This zone is well-defined by linear functions, in which, the parameters are consistent with the physical content of the springback phenomenon.

1. Introduction

Tailor Welded Banks (TWBs) were developed for the most ideal use of materials in the engineering structures, and their application is still spreading today. The TWBs are primary manufactured by laser beam welding, specifically for subsequent forming operations. Namely, the welding is not the final operation in the assembly sequence plan, contrary to the ordinary sense of this technology [1].

The most popular variants of TWBs are made by sheets of different thickness and/or strength to meet the lightweight requirements and retain the structural rigidity at the same time. Besides, different coatings can also be observed in certain cases. In order to distinguish the pre-welded blanks for forming purpose from the traditional sheets, the EN 10359:2015 standard contains certain specifications for the manufacturing conditions.

Figure 1 shows the ideal material distribution of a complex car body panel, both in the sense of the material grade and the thickness. Due to this geometrical and structural complexity, the manufacturing of this part from a simple blank is neither economically nor technically reasonable. It can be seen that if the complete part would be manufactured by the thickest or the highest strength material, the structure will be oversized and the lightweight pursuits are no longer met. On the other hand, if the complete part would be manufactured by the thinnest or the lowest strength material, the structure will be undersized and additional elements should be used for strengthening the critical points. In addition, the geometry

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of the initial blank can be simplified and accordingly the material usage can be improved if more, simpler banks are included. Another advantage of TWBs is that the welding happens on in-plane sheets, which is easier than for spatial cases [2,3].

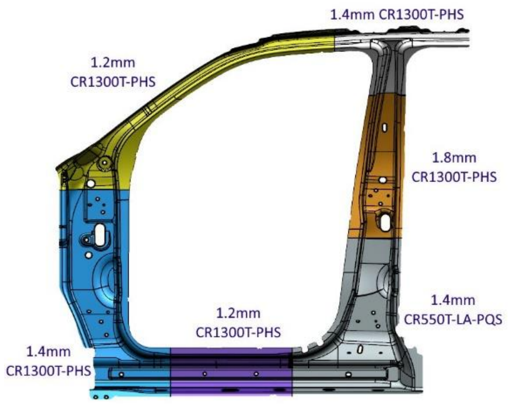

Figure 1. An example for a complex car body panel, made by different grades of materials and thicknesses [2].

Nevertheless, thanks to the interaction of the different elements as well as the weld line, the forming operation is more complicated than for simple blanks. Both the difference of the applied materials' properties (strength, formability, anisotropy, thickness, etc.) and the loading circumstances (the weld line position in relation to the loading or the straining direction) influence the behaviour of the workpiece during forming. In this sense, Korouyeh et al. [4] introduced the limit thickness ratio to describe the formability of TWBs with different thicknesses. The formability ratio was established by Bandyopadhyay et al. [5] for direct characterization of the drawability and the stretchability of TWBs. The deep-drawability was also intensively studied by Padmanabhan et al. in [6,7].

Fundamental springback approximation, which calculates the angle deviation after tools' release (θ^*) is generally defined in the form of equation (1). Marciniak et al. [8] derived that formulation from the moment equilibrium. Lange et al. [9] adopted the fundamentals of mechanic to obtain the resisting moment of the sheet against bending. Pearce [10] and the ASM Handbook of Metal Forming [11] simply communicate the formula, in which expression $\bar{\sigma}$ indicates the flow stress, E refers to the Young modulus and ρ and t_0 are the bending radius and the nominal (initial) thickness of the sheet. The bending angle is $\theta°$.

$$\theta^* = \frac{3\bar{\sigma}}{E} \cdot \frac{\rho}{t_0} \cdot \theta. \tag{1}$$

Due to the complexity of the TWBs, authors certainly do not know any simplified formula for analytical evaluation of the TWBs' springback. Although, it is worth noting that the present results only applies to this case of bending, and work on how this can be generalised is still ongoing.

This study presents the experimental results and the theoretical analysis on the springback behaviour of TWBs, considering the interaction of each sides made by different strength steels. The results show that the interaction can be described by a transition zone, which strength difference dependent mathematical description meets the physical content of the springback phenomenon.

2. Applied materials

Four grades of commercial, automotive, thin sheets in 1 mm nominal thickness (t_0) were used in this research work. The basic mechanical properties of the applied dual phase (DP) steels and the DC04 mild steel were determined by tensile tests, according to the ISO 6892-1:2019 standard's prescription. Five parallel experiment were done on each material, with 20 mm/min constant crosshead speed. The measurement of the r-values were carried out by a non-contact Instron AVE video-extensometer at Ag-1 (%) engineering strain level. The mean values in each direction are listed in table 1.

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The applied three types of DP steels, DP600, DP800 and DP1000 have contained varying amounts of the ferrite-martensite phases. Basically, the higher the martensite ratio, the higher the tensile strength, which is indicated in the materials' number. The hard martensite and the soft ferrite together provide the relatively high strength and good formability of these materials at the same time [3]. Such as, DP steels are widely used in the automotive industry for car body panels, thanks to the abovementioned benefits as well as their favourable weldability and solderability [12,13].

The DC04 is also a widespread material for both the automotive and the kitchen utensils industry, since it has excellent formability and high anisotropy coefficient (i.e. good resistance to thinning). Its microstructure is ferritic for the most part, and thus the deformation is relatively homogenous on the microscopic scale [14].

Table 1. Basic, average material properties and the r-values of the applied materials.

	YS (MPa)	UTS (MPa)	Ag (%)	r_0	r_{45}	r_{90}
DC04	238	336	20.4	1.79	1.33	2.39
DP600	444	656	12.8	0.80	0.91	1.12
DP800	570	879	10.2	0.64	0.79	0.77
DP1000	758	1099	6.7	0.74	0.71	0.79

In the case of the TWBs, the DC04 mild steel was constantly coupled to each grade of DP steels by laser beam welding. Thereby, three variable strength ratios were available. Next to it, the average strength of the welded blanks was also varied with the usage of the different pairings.

The TWBs were manufactured by laser beam welding using a Rofin DY 027 Nd:YAG machine. The shielding gas was Ar 99.996 on the crown side of the weld. The welding has happened without additives. There was no particular requirement for the weld line, except that it should not open up under the bending stress.

3. Bending experiments

Simple, rectangular, free-bending in V-die was performed on square shaped TWBs, the illustration of which can be seen in figure 2 (right). The illustration contains the relation of the weld line to the rolling- and the bending directions, too. The final angles after the tools' release were measured by a workshop angle meter on the edges of the blanks. With increasing the length of the initial blanks (100…600 mm), the springback (θ^*) could be determined in the function of the distance from the weld line. All the bending experiments were repeated three times.

30° bending tools (figure 2 left and mid) made by the Eurostamp GmbH were installed on an AMADA HFE 50-20 CNC controlled bending machine. The final angle (90°) was adjusted by the punch movement, which had a constant 20 mm/min speed. The sheets were not lubricated.

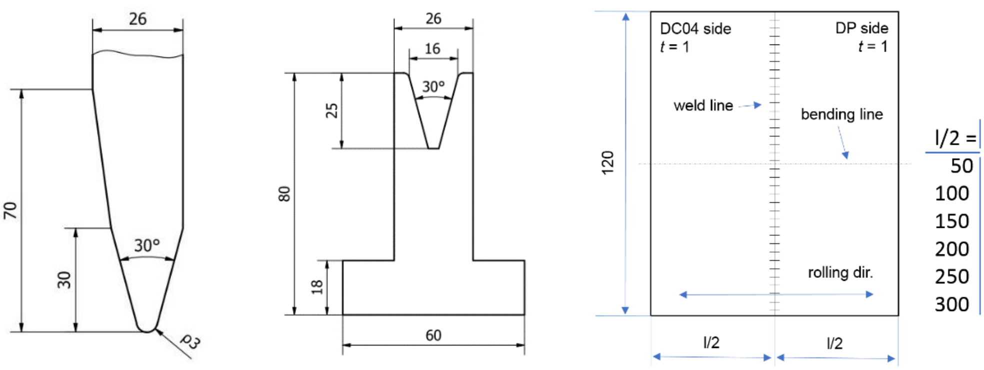

Figure 2. Schematic view of the applied bending tools and the initial blank, indicated the rolling-, the bending-, and the welding directions.

4. Results and discussion

4.1. Experimental springback results

The average difference between the measured and the nominal bending angle (90°) has given the value of free springback and is depicted in figure 3 for the three cases of TWBs. The angle deviation was measured in every 50 mm from the weld line. Therefore, six measurement points depending on the distance from the weld line were determined on each sides.

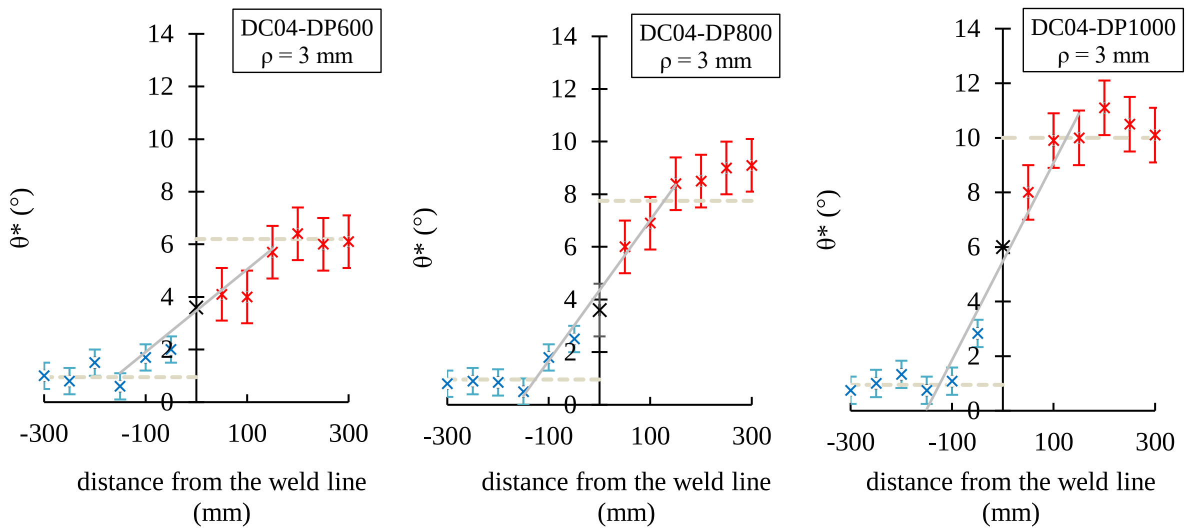

Figure 3. Experimental springback angles of the DC04-DP600, DC04-DP800 and DC04-DP1000 pairs.

Seeing the components' interaction in the figure above, it can be observed that a transition zone is developed near to the weld line, independently from the strength difference of the creating elements. Before and after the transition zone, the springback fits the components' separately characteristic values. The character of the transition zones, which can be properly described by linear functions is varying with the change of the strength differences ($\Delta\sigma$). Increasing the strength difference enhances both the steepness (m) and the point of intersection with the vertical axis (b) of the linear functions. The mentioned two parameters are indicated in table 2.

Table 2. Characteristic values (steepness and the point of intersection with the vertical axis) of the transition zones.

	m (-)	b (-)
DC04-DP600	0.0157	3.67
DC04-DP800	0.0267	4.25
DC04-DP1000	0.0361	5.59

4.2. Theoretical analysis

According to equation (1), the expected springback values only depend on the strength difference between theoretical *A* and *B* blanks in a steel-steel TWB, since the other influencing parameters are the same on both sides. Our assumption was that two theoretical cases should be existed in this manner:

- case one (i): the components have symmetrical influence on the springback, i.e. the welded blank behaves in the same way in both sides;

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- case two (ii): the components have asymmetrical influence on the springback, i.e. the effect of one side is more pronounced.

Figure 4-6 show the appearances of both cases theoretically, if the strength difference is infinitely large, or infinitely small, or if it is between them. (The strength difference is indicated by $\Delta\sigma_{ps}$ in the following figures, where *ps* abbreviation refers to the plane strain state.) Provided that the strength difference is infinitely large (figure 4), the linear function should lie into the vertical axis in (i), since the *m* and *b* parameters should be infinitely large, too. In (ii), when the effect of the sides is inhomogeneous, the higher strength component should distort the TWB, since it validates its effect on the softer side.

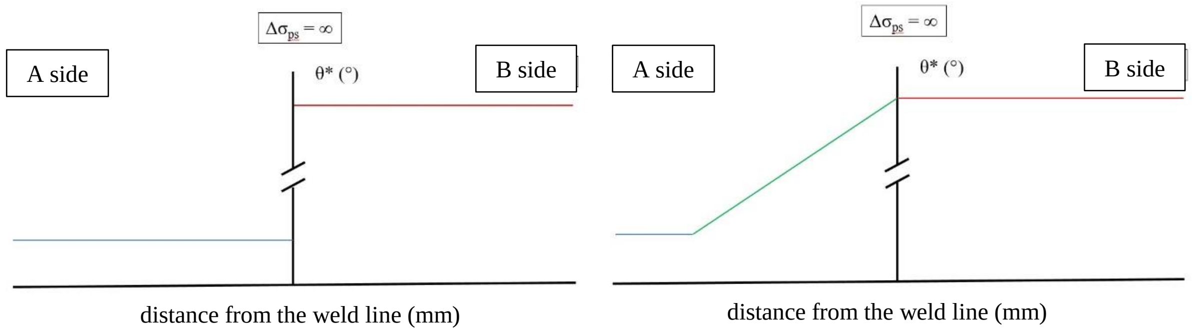

Figure 4. Theoretical interaction between the TWB’s sides with infinitely large strength-difference: the effect of each components is symmetric (left) or asymmetric (right).

As long as the strength difference is infinitely small (figure 5), there is no discrepancy between case (i) and (ii), and the blank behaves like a non-welded sheet.

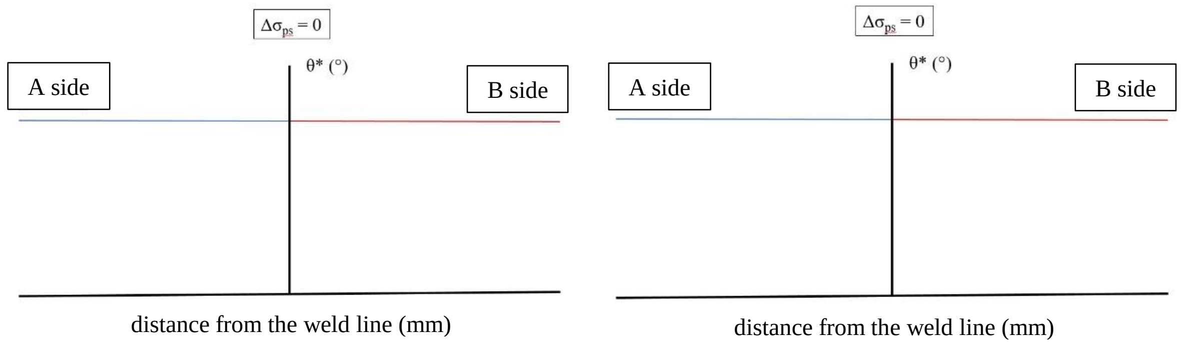

Figure 5. Theoretical interaction between the TWB’s sides with infinitely small strength-difference: the effect of each components is symmetric (left) or asymmetric (right).

In the cases we investigated practically, when the strength difference is neither infinitely large nor infinitely small (figure 6), the transition zone should develop symmetrically (i), or asymmetrically (ii). We suppose that this kind of strength difference could have the most common occurrence in the practice. Our results (figure 3) show that the symmetrical behaviour (i.e. case (i)) is an acceptable approximation in the tested range, since there is no observable shift of the linear functions in figure 3.

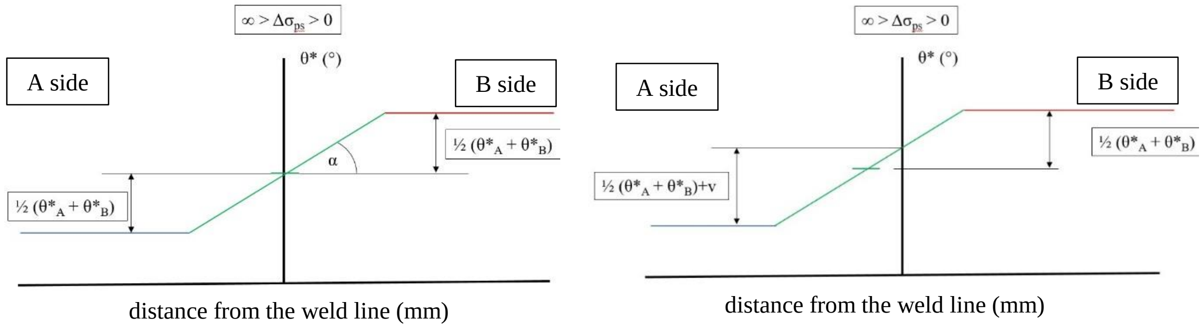

Figure 6. Theoretical interaction between the TWB's sides with a given (practical) strength-difference: the effect of each components is symmetric (left) or asymmetric (right).

If we accept the assumption that the TWBs behave as shown in figure 6 left side, then we can consider influencing parameters, which affect the steepness and the intersection point of the linear functions. The fact that both the steepness and position of the intersection point have grown in figure 3 is explained schematically by figure 7. It becomes visible from this figure that the steepness only depends on the strength difference itself, however, the intersection point is influenced by both the strength difference and the average strength. In other words, if $\Delta\sigma_{ps}$ is increasing, both the *m* and *b* parameters increase, too (figure 7 left). On the other hand, the average strength only has an effect on the intersection point, as it can be seen in figure 7 right, thus the average strength does not change the steepness.

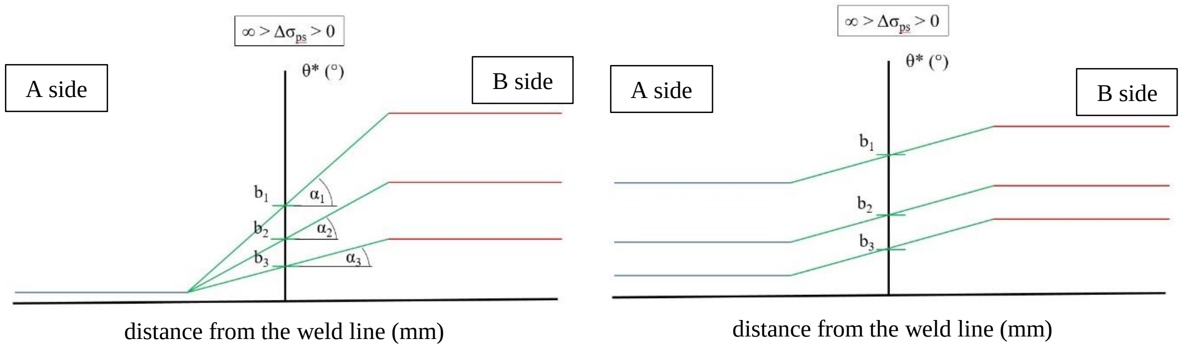

Figure 7. Theoretical interaction of given strength-difference sides, considering the effect of the strength difference (left) and the average strength (right).

The above mentioned facts can be mathematically described in equations (2) and (3)

$$m = f\left(\Delta\sigma_{ps}\right) \tag{2}$$

$$b = f\left[\left(\frac{\sigma_A+\sigma_B}{2}\right);\ \left(\Delta\sigma_{ps}\right)\right] \tag{3}$$

as well as depicted in figure 8 and 9.

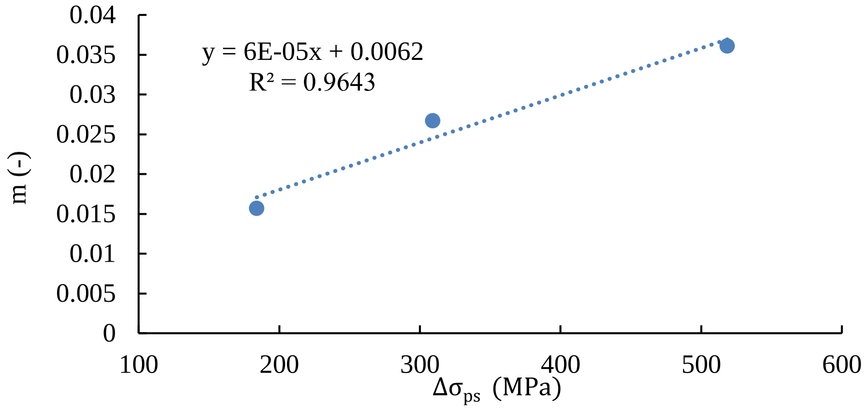

Figure 8. The changing of the m parameter in the function of the plane strain yield strength difference.

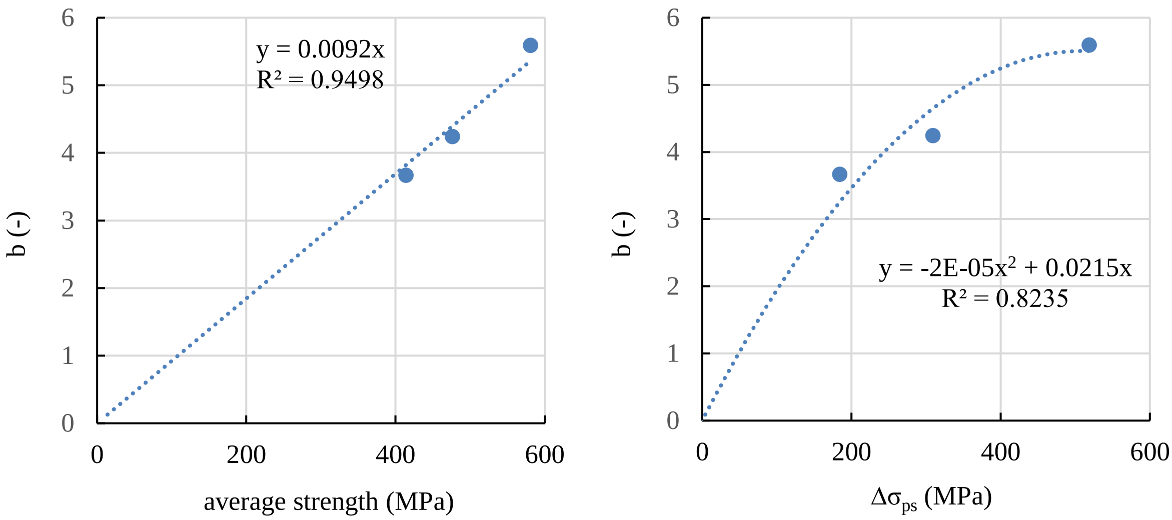

Figure 9. The changing of the b parameter in both the function of the yield strength difference in plane strain state and the average yield strength.

5. Summary

In this study we investigated the springback tendency of tailor welded blanks. Different pairs were manufactured by using constantly the same DC04 mild steel jointed to different kinds of DP steels. This have given three different types of blanks regarding the strength difference between the components and the average strength. In this way, the effect of the constituent materials' strength on the springback was even better revealed, since the elastic modulus, the sheet thickness and the bending geometry were the same in both sides of the blanks.

From the results it can be observed that a transition zone develops near to the weld line, in which the springback can be defined by linear functions. Theoretical analysis showed that parameters of the obtained functions have physical meaning in line with the phenomenon of springback, and is clearly aligned with the strength difference as well as the average strength of the components.

6. References

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