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Deformation analysis of ZnMgAl coated steel sheet using digital image correlation (DIC) system

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Abstract. Protective metallic coatings may be applied to the finished tubes and pipes using the hot dip method or may be applied to cold rolled sheet that is then used in the roll forming process of tubes manufacturing. In the latter case applied coating must ensure the proper adhesion and lack of cracks during deformation. In this work, the main objective is to assess the plastic deformability of steel sheets covered with an advanced ZnMgAl coating. The assessment of the susceptibility of the ZnMgAl coatings to plastic deformation was carried out using three-point bending tests, supported by the digital image correlation technique. A standard bending test of a steel sheet with a ZnMgAl coating at different bending angles was also used. The comparison of the results of the tests carried out allowed for the formulation of conclusions for direct use in industrial practice.

Introduction

Optimization and control of the processes of industrial metal forming of steel products requires an understanding of the behavior of the charge material under deformation conditions similar to those, in which it will be formed. Pipes with open-joints are produced from steel sheet in the rolling process, so the accompanying deformations in the bending process are significant [1]. The steel sheet used in the production process should be characterized by good mechanical properties and formability. It should also be remembered that in a pipe manufactured using the open-joint method, the weakest point is the joint/weld. The protective coating can also be used to protect the weld. There are many types of protective coatings on the market today. Many of them are based on zinc. Galvanized steels produced by hot-dip galvanizing find many applications, e.g. in the construction and automotive industries [2-4]. By introducing aluminum and magnesium into a standard zinc coating, a ZnAlMg coating was obtained, which provides excellent corrosion and wear resistance [5]. One of them is the Zn Al3,5Mg3 (Trade name: Magnelis®) coating patented by ArcelorMittal. This coating is characterized by the great corrosion resistance and wide range of possible applications. Compared to standard Zn coatings, Magnelis provides similar level of corrosion resistance protection with much thinner layer of coating. So far, this coating has not been widely studied in terms of its ductility. The coated ZnAlMg steel plate can be used to the production process of the open-joint tubes. This however requires high cracking resistance both of the steel sheet and coating during the roll-forming process. Even a micro damage of the coating may lead to cracking in the most deformed areas and may be the cause of the deteriorations in the in-service corrosion resistance [5-7]. Thus, obtaining the information of the correlation between microstructure and mechanical properties during the roll forming of open-joint tube process is necessary. This knowledge will allow to improve the quality of the coating and to optimize the parameters of the deformation process. Therefore, the main purpose of the presented work was to

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assess the properties of ZnMgAl coated steel sheet used for the production of tubular products where it is subjected to the process of deformation by bending.

Materials

Three types of steel sheets were used in the tests. The base material was hot-rolled steel sheet, the chemical composition of which is shown in Table 1. The base material was E220 steel sheet with a ZnMgAl coating with a total thickness of 1.4 mm. The other two steel sheets of the S235 grade were taken as the reference material - one with a standard Zn coating and the other without this coating. The thickness of both sheets was 1.5 mm.

First, the quality of every coating was investigated using the Nova NanoSEM FEI scanning electron microscope (SEM). Additionally, the thickness and homogeneity of the surface was measured (Fig.1).

Table. 1. Based chemical composition of the steel sheet (% wt.).

Material	C	Mn	Si	P	S	Al	Cu	Sn
E220	0,049	0,20	0,004	0,023	0,015	0,032	0,021	0,002
S235JRH	0,15	0,12	0,030	0,020	0,025	0,01	0,55	-

Fig. 1a and b present the initial microstructure of the cross – section of specimen with standard Zn coating (as received). Analysis of the sheet steel with Zn coating showed good coating adherence to the base sheet. The mean thickness of the Zn coating was approximately 98 µm. During the microstructural analysis the cracks of the Zn coating were not observed.

A similar analysis was performed for the ZnMgAl-coated sample (Fig. 1c, d). In the case of the main research material, the measurement of the coating thickness showed that the ZnMgAl layer is smaller than in the case of the standard Zn layer and is about 38 - 40 µm. Its microstructural analysis showed good adhesive properties and cracks were also not visible.

Based on the microstructural analysis of steel sheets coated with Zn and ZnMgAl it can be concluded that the initial quality of both samples is sufficient for their use in the rolling process.

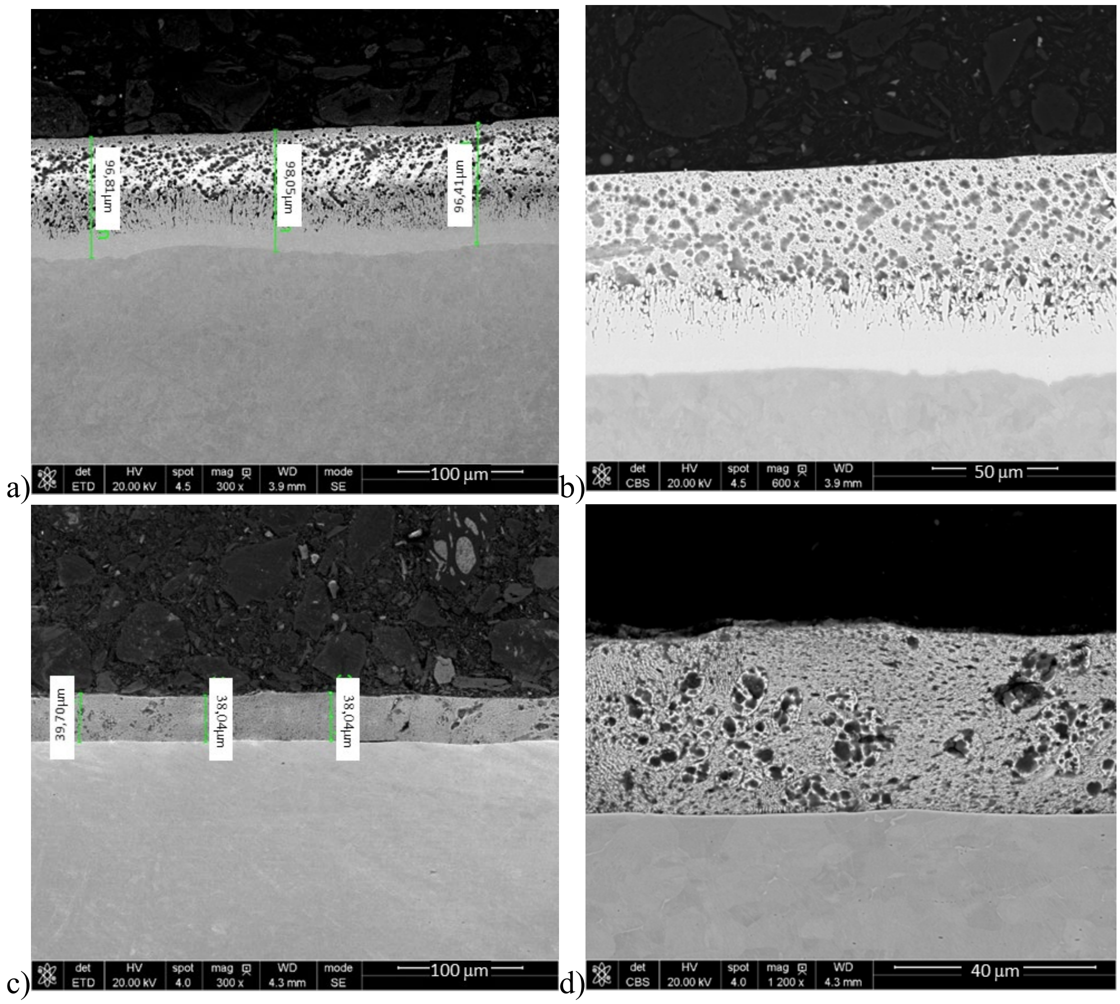

Fig. 1. The example of the cross – section of the steel sheet with standard Zn coating – a); b) and ZnMgAl coating – c); d).

Experimental Procedure

In order to obtain the data for the analysis of deformation susceptibility of steel sheet with ZnMgAl coating, the experimental procedure was divided into two steps. The first stage included the three-point bending test. The radius of the upper tool was equal 5 mm. In this part of work, the three different sheets were deformed: 1) base material (with no coating) 2) sheet with standard Zn coating, and 3) sheet with ZnMgAl coating. The experiments were performed at room temperature with the velocity of the bending load of 1mm/min. The experimental procedure was combined with Digital Image Correlation (DIC) analysis. The DIC system consist of high resolutions CCD 5mpx camera. In order to obtained the accreted results, the DIC analysis was made using two different lenses. In first case the whole surface of the samples were analyzed ale for this the lens of 2.8/50 was used. In the second case only most deformed area was analyzed. and for this measurement the stereo microscope was used as a lens. Postprocessing of the obtained images was made using Istra4D software. The second stage of the investigation was focused only on the steel sheet with ZnMgAl coating. In this stage, the bending test based on the ISO 7438:2016 standard was applied. The bending angle ranging between 90 and 180 deg was used. Similarly, like in the pervious test, the bending test was made at the room temperature, but the angle on the upper tool was equal 30 deg.

Results and Discussion

In the presented work, the DIC strain measurement was applied to analyze deformation of coated sheets subjected to the three-point bending test. During the test, DIC method was applied to track the strain distribution during the deformation process [8-9]. The upper tool displacement was kept the same for the all analyzed specimens. Results obtained for the one-time step before end of the deformation process with the stress–strain curve are presented in the Fig. 2. DIC strain distribution maps show typical strain accumulation for the three-point bending test localized in the lower part of the specimen. The highest strain accumulation was observed in the sample with standard zinc coating and the lowest value was obtained for the sample with ZnMgAl coating. In the case of sheet with zinc coating the additional strain concentration can be observed in the upper part of the specimen (under the upper tool), what suggests the possibility of the zinc coating crack occurrence in this area.

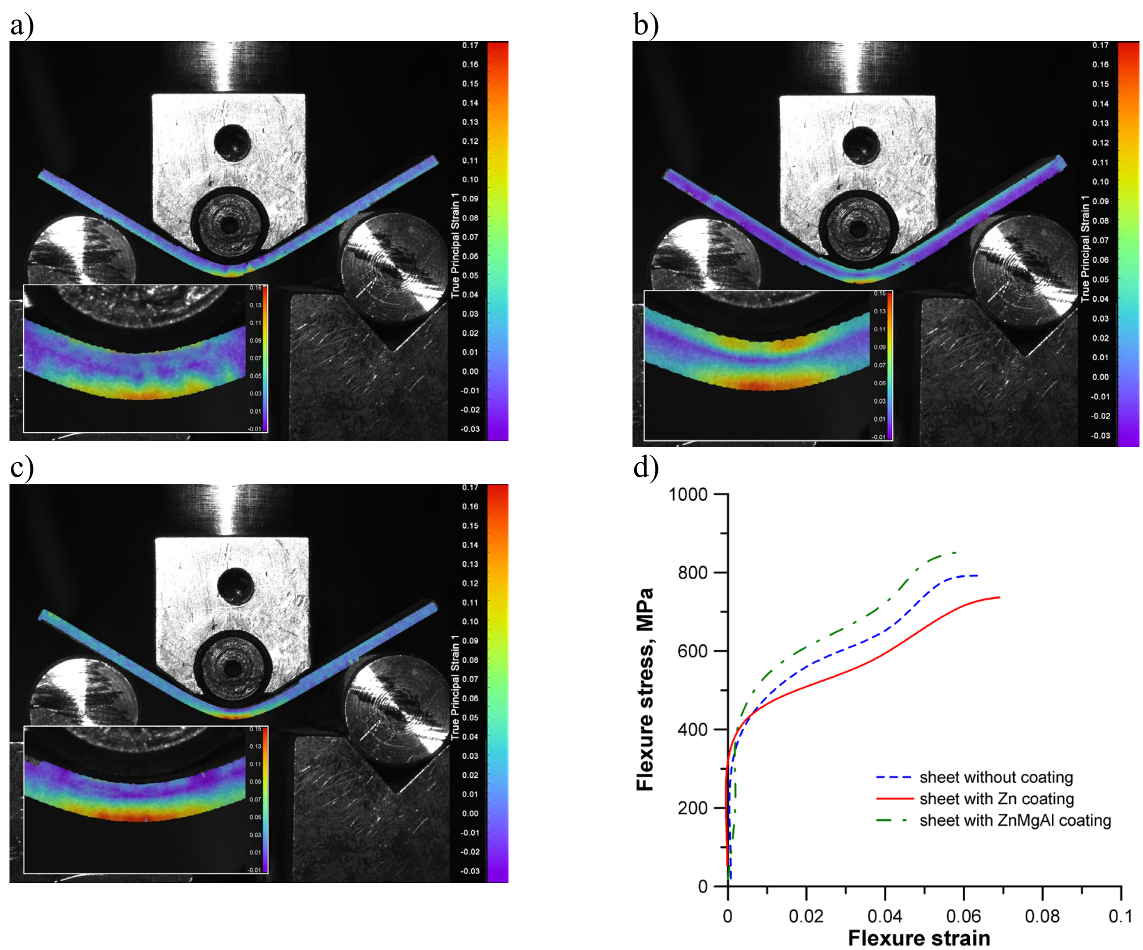

Fig. 2. The true principal strain distributions maps obtained in DIC analysis for sheet plate without the coating – a); with standard zinc coating – b); with ZnMgAl coating – c); and the stress – strain curve obtained in the three – point bending test using two type of the lenses.

The main aim to use the DIC analysis was the estimate the local deformation value on the sample thickness during the bending test in order to related these values with the coating deformation susceptibility in related to the open join tube production process.

Additionally, based on the obtained DIC results, it can be expected that on the sheet with the zinc coating the cracks will appear in the external and internal surfaces of the specimen. For the specimen without coating the cracking of the oxide scale also took place. For confirmation, all specimens after the three-point bending test were analyzed using Zeiss optical microscope (Fig. 3). Observations were carried out on the outer and inner surfaces, where the accumulation of deformations was the greatest (Fig. 3a).

The obtained micrographs revealed the flaking of the oxide scale layer - especially on the internal surface of the specimen with no coating (Fig. 3b). In the case of the second specimen with zinc coating clear cracking both at external and internal surface was visible. A digital crack assessment was made and compared with patterns based on the PN-EN ISO 4628-4:2004(U) standard. It was found that the internal cracks can be assigned to the ASTM 4 group and external cracks to the ASTM 2 group. For the last analyzed specimen, with the ZnMgAl coating, no visible cracks were found at any of the analyzed surfaces (internal and external).

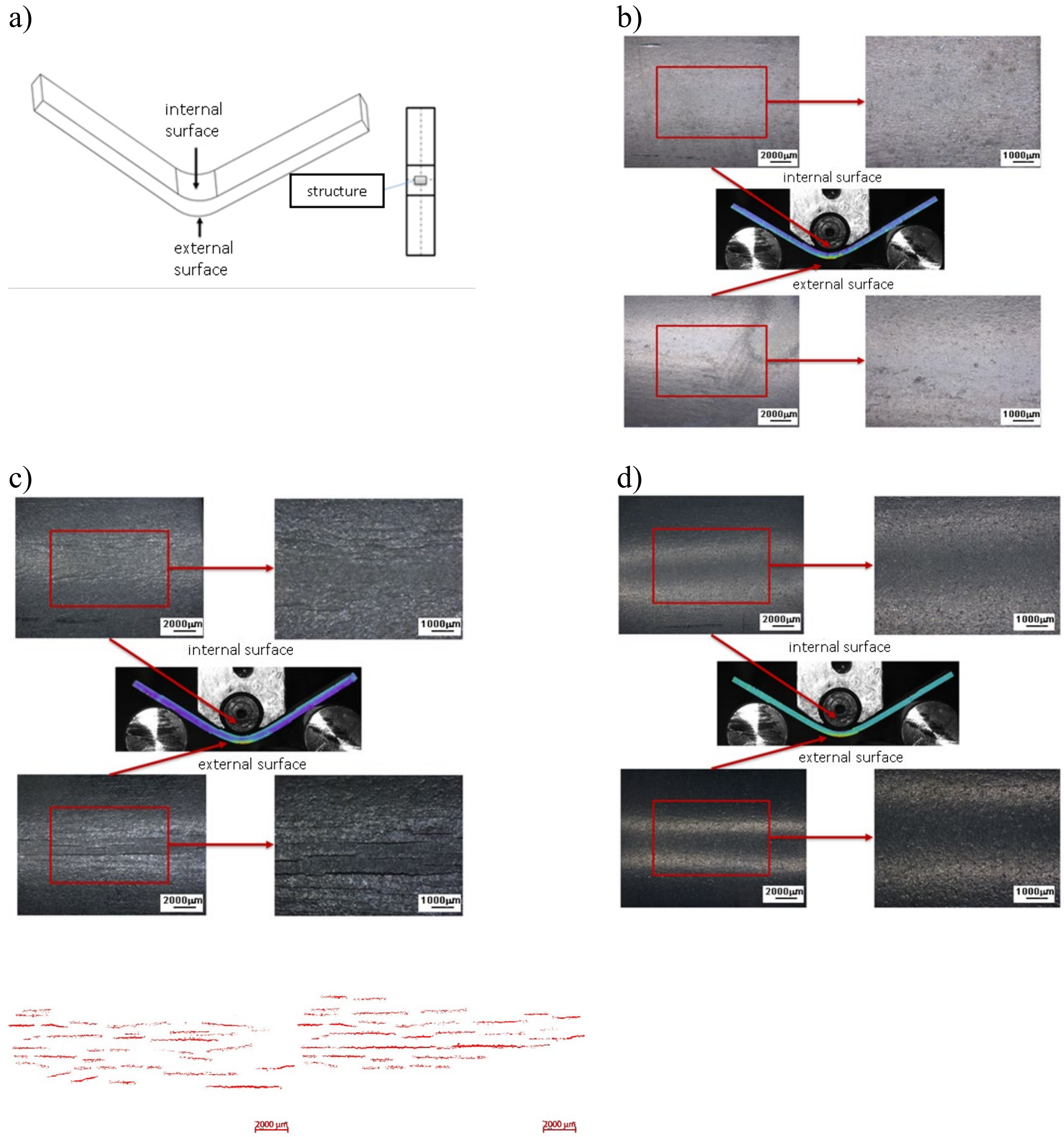

Fig. 3. Position of the optical microscope analysis of surface quality bending sample on the internal and external surface - a). Obtained results for the specimen without the coating - b); with standard zinc coating with comparison to the patterns from PN-EN ISO 4628-4:2004(U) standard - c) and with ZnMgAl coating - d).

The surface that was observed using DIC system was subjected to the scanning electron microscope observation using FEI Nova Nano SEM. For the analysis the specimen with zinc coating and ZnMgAl coating was used. Fig. 4 shows that in the case of the specimen with standard zinc coating the coating detachment and cracking (marker with the red arrows) can be observed. On the second analyzed specimen the any layer damage was not found.

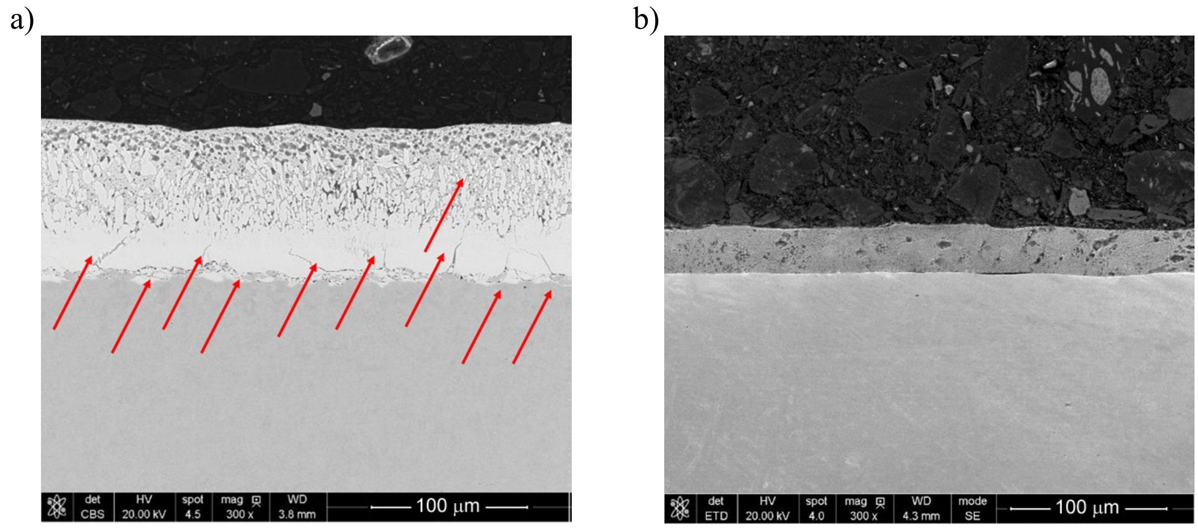

Fig. 4. The SEM image for specimen with Zn coating – a) and ZnMgAl coating – b).

The analysis of the three-point bending test results confirmed that the steel sheet with ZnMgAl coating is suitable to the deformation process.

Additionally, in order to design the roll-forming process, bending test is usually performed to check the springback angle and select the roll forming pass design. In the current study this test was also performed but its aim was more focused on the analysis of the ZnMgAl coating adhesion. The obtained results for the bending test with angle equal to 90deg are presented in the Fig. 5. Additional analysis performed after bending shows that, similarly to the previous test, the cracks were not visible either of the surface (internal and external).

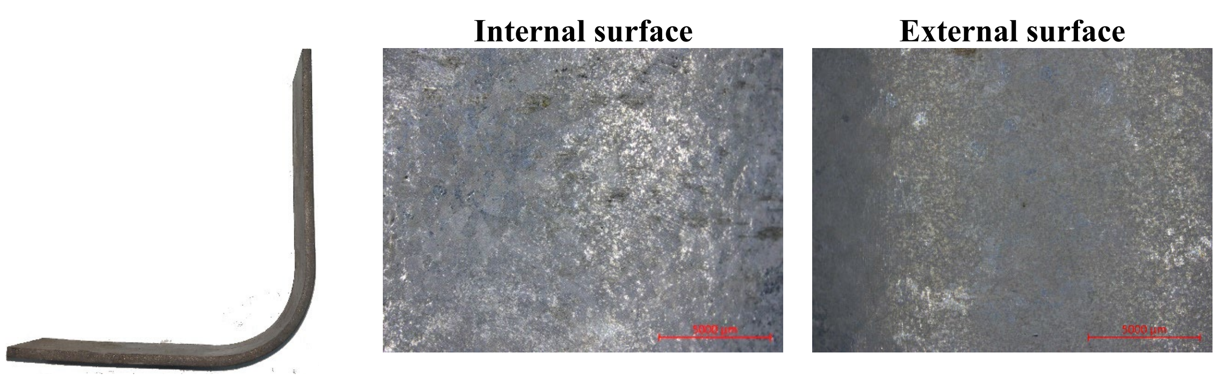

Fig. 5. The shape of the specimen after bending test with microstructure of internal and external surface.

Summary
The tests carried out and the analysis of their results allowed for the assessment of the suitability of the steel sheet with the ZnMgAl coating for the process of forming pipes with an open joint. For this purpose, a standard bend test and a three-point bend test combined with a digital image correlation system were used. In the case of the three-point bending test, the test results of a steel sheet without a protective coating and with a standard zinc coating were taken as the starting point. Based on the DIC analysis, areas of strain concentration were determined where the protective coating could crack. Both bending tests, i.e. standard and three-point bending, showed that the tested material with ZnMgAl coating can be successfully used in the pipe production process.
Based on the presented results, the following conclusions can be drawn:

- The microstructural analysis of the sheet steel with coating shows good adherence to the base steel for both analyzed coatings.
- In the case of the sheet plate without the coating strain distribution analysis showed the points localization at maximum strain value. Additional microstructure analysis showed that in this area the flaking of scale layer occurred.
- The DIC analysis of steel sheet with standard zinc coating showed the highest strain concentration both at internal and external surface. Microstructural analysis showed significant cracks. Based on the ISO standard was coating cracking was assigned to the ASTM 4 group for the internal surface and ASTM 2 group for the external surface.
- Based on the DIC analysis of the plate with ZnMgAl coating the strain concentration (beside standard strain localization characterized for the three-point bending test) was not observed. The microstructure analysis confirmed lack of the visible cracks on the surface.

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