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The influence of thermal cutting on the properties and quality of the cut surfaces toughened steel S 960QL

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Abstract. In this paper results of investigation of air plasma, oxygen, laser beam cutting processes on quenching and tempering S 960QL steel surface quality were shown. In most cases a cutting process is the first technological operation from which the manufacturing process begins. In that case changes in the material during this process have a significant effect on the final quality of the manufactured parts. The choice of cutting method depends on the requirements and technical capabilities i.e. type and thickness of material, dimensional tolerances, economic factors, cutting speed or shape of the element. The main goal of this study was to investigate the effect of cutting processes to the surface quality. The obtained cut surfaces have been subjected to ISO 9013:2017 (surface roughness, rectangularity tolerance), as well as cut widths and breakthrough holes diameters have been measured. In the last stage the metallography examination and hardness measurements were accomplished. Hardness measurement of samples after cutting was done by Vickers's method on Wilson Wolpert 401 MVD at load 100g. Macroscopic studies to determine the heat affected zone were performed using a metallographic microscope light stereoscopic Olympus SZX9. Focusing on operating properties of the cut material, attention should be paid to the structural and chemical changes that occur due to the influence of the heat cycle. A heat-treated steel is particularly susceptible to a loss of material properties acquired during heat treating and hardening of the surface layer.

1. Introduction

There is a continuous increase in the global share of welded constructions made of high-strength steel. The quality requirements have been set in many branches of industry, such as shipbuilding, road and bridge construction, hydropower and nuclear energy, construction of drilling platforms, pipelines and construction machines. It has led to the development and implement of the new technologies, in the field of steel metallurgy, allowing to obtain final products in the form of high strength sheet and pipes without lowering their plastic properties. The large increase in demand and a competition on the the construction machines' market (especially lifting devices) caused that the leading manufacturers of these had to increase the load capacity while maintaining the same mass of the structure. It was possible only through the use of the construction materials with higher strength. The S 960QL (Weldox 960), S 1100QL (Weldox 1100) and S 1300QL (Weldox 1300) with a yield in the range of 960÷1300 MPa appeared on the market [1-9]. Despite the much higher purchase costs, the use of fine-grained steel in the construction machinery allows to increase the load capacity while maintaining the same weight of the structure. In most cases a cutting process is the first technological operation from which the manufacturing process begins. In that case changes in the material during this process have a significant effect on the final quality of the manufactured parts. The development of cutting methods takes place in response to the increasing demands, which are placed on them, starting from straight cuts, through 2D cutting to 3D cutting. The choice of cutting method depends on the requirements and technical capabilities i.e. type and thickness of material, dimensional tolerances, economic factors, cutting speed or shape of the element [10-16].

2. Experimental

The aim of the research was to determine the impact of air plasma, oxygen and laser beam cutting processes on surface quality of quenched and tempered S960QL steel. The actual chemical composition and properties of S960 steel are presented in table 1 and its structure – in figure 1.

Table 1. The chemical composition and mechanical properties of S960 steel.

Concentraction of elements, [%]											
C	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**	**Al**	**Ti**	**V**	**Nb**	**B**
0.17	0.22	1.26	0.008	0.001	0.21	0.05	0.061	0.003	0.041	0.015	0.001

Mechanical properties			
Tensile strength, Rm, [MPa]	**Yield point, Re, [MPa]**	**Elongation A_5, [%]**	**Impact value, K, [J] -40 ^{o}C**
1020	1070	14	78

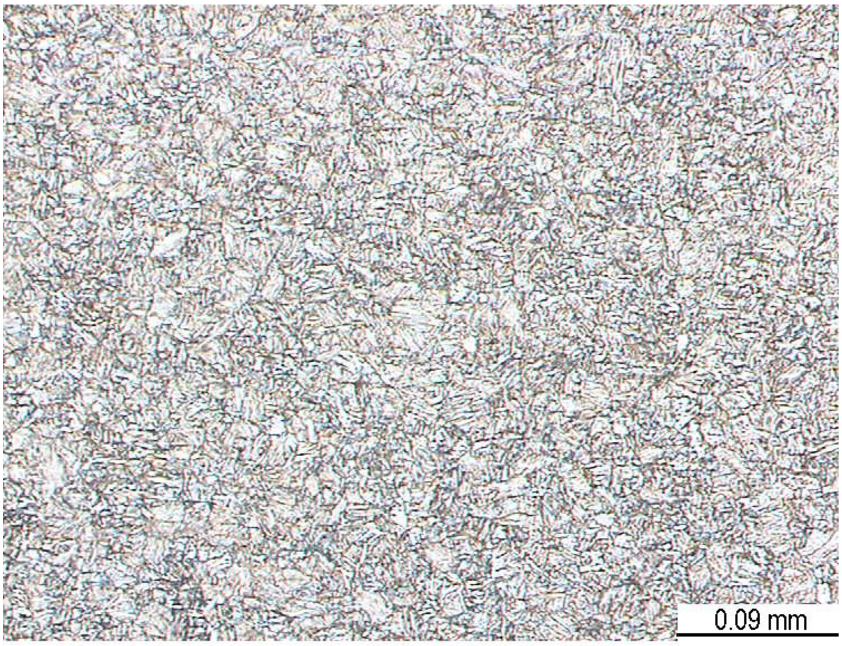


Figure 1. The martensite structure of tempered S960QL steel.

2.1. Cutting process

The cutting process was carried out with the optimal parameters selected on the basis of preliminary tests for the sheet thickness of 10 mm, table 2. In order to evaluate the quality of the surface, the samples were cut at length of 200 mm, figure 2. Oxygen cutting was carried out in a workstation equipped with a Messer OmniMat. The machine was controlled using a Global Control Plus device equipped with an Alpha torch. Plasma cutting was carried out on a HYPERTHERM plasma cutter type HD 3070 cooperating with the VANAD Proxima machine. It is a transferred arc device with narrowed plasma stream type HTPAC, cutting range of this plasma cutter is up to 12.7 mm. Laser cutting was done on a station geared with a Trumpf TruLaser 5060 (L10) with a maximum power up to 5000 W. The gas used for a laser cutting was oxygen.

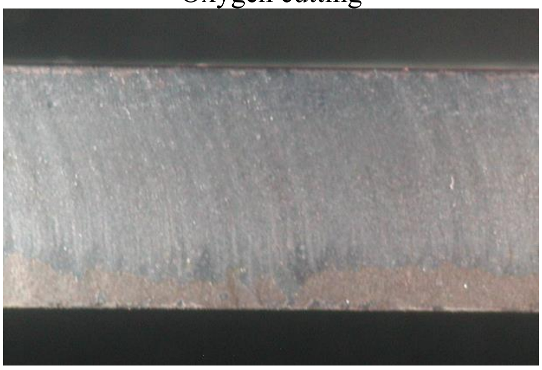
Table 2. Parameters of the oxygen, air plasma and laser cutting processes.

Oxygen cutting process				
Cutting oxygen pressure, [MPa]	**Pressure of acetylene, [MPa]**	**Cutting speed, [m/min]**	**Oxygen nozzle, [mm]**	**Nozzle clerance, [mm]**
0.5	0.045	0.57	7-15	8

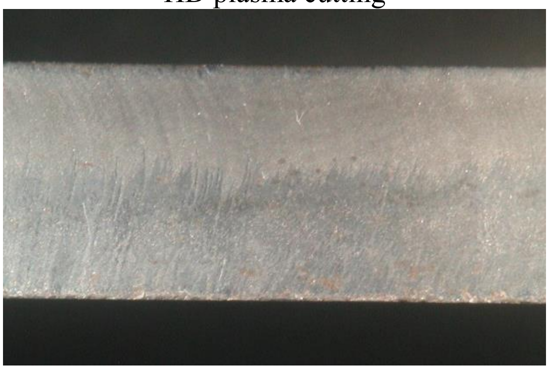
HD plasma cutting process						
Current intensity, [A]	**Arc voltage, [V]**	**Cutting speed, [m/min]**	**Plasma gas pressure, [MPa]**	**Electrode type**	**Diameter of the cutting nozzle, [mm]**	**Nozzle clerance, [mm]**
100	150	3.0	0.8	Ziroconiated	1	4

Laser beam cutting process				
Laser beam power, [W]	**Cutting speed, [m/min]**	**Gas pressure, [MPa]**	**Gas type**	**Laser head distance, [mm]**
4800	2.4	0.8	Oxygen	1.5

Oxygen cutting



HD plasma cutting



Laser beam cutting

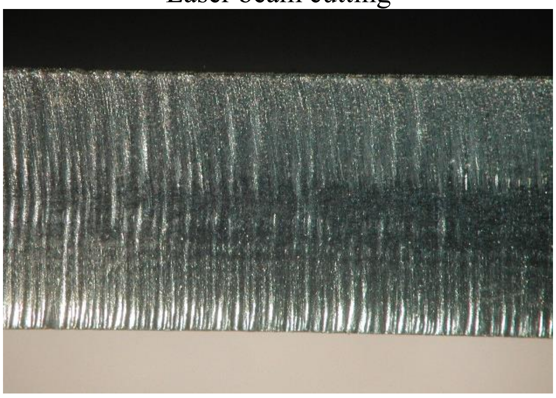


Figure 2. View of the surface after cutting process.

2.2. Surface quality evaluation after cutting process

The obtained cut surfaces after oxygen, HD air plasma and laser beam cutting processes have been subjected to ISO 9013:2017 in which the following aspects have been assessed: surface roughness, rectangularity tolerance, bevel angle. Measurement of surface roughness "Rz" was carried out in the cutting direction in five places of the sample. The length of the measuring section was 12.5 mm, while the length of the elementary section was 2.5 mm, table 3. The device used to measure the surface roughness was the Surytest 402 profilometer produced by Mitutoyo. The measurement of squareness deviation "u" was carried out at 20 mm intervals in three places of the sample, the bevel angle was measured with an optical protractor, table 3.

Table 3. Evaluation of cut surface quality of S 960QL steel with a thickness of 10 mm according to ISO 9013: 2017.

Cutting method	Perpendicularity deviation u_{avg} [mm]	Area „u" according to ISO 9013: 2013	Surface roughness Rz_{avg} [µm]	Area „Rz" wg ISO 9013:2013	Bevel angle [°]*
Oxygen cutting process	0.3	3	20.8	2	3
HD plasma cutting process	0.49	3	14.5	1	5
Laser cutting process	0.12	1	17.6	1	0.5

* - values in relation to the inferior surface after cutting

In order to compare the geometric features of the cutting surface, the diameter of the breakthrough hole, geometry of the cut groove (top kerf width, bottom kerf width) and bevel angle were measured, table 4.

Table 4. Evaluation of the geometrical features of the cut surface for 10 mm thick S 960QL steel.

Cutting method	Top kerf width [mm]	Bottom kerf width [mm]	Upper diameter of the breakthrough hole [mm]	Bottom diameter of the breakthrough hole [mm]	Formation of dross on the bottom edge
Oxygen cutting process	3.25	1.69	5.40	4.32	Small
HD plasma cutting process	3.08	1.56	5.02	4.18	Small
Laser cutting process	0.37	0.39	3.20	0.98	No dross

2.3. Metallographic examinations

In order to determine the width of the heat affected zone after cutting process, macroscopic examination was carried out using an Olympus SZX9 stereoscopic microscope, figure 3. The assessment of the impact of a cutting processes on structural changes was made on the light microscope Leica MeF4M and the Buehler OMNIMET Express program. Microscopic examinations were carried out in three places of the sample: at the upper cutting surface, in the middle of the sample and at the bottom cutting surface, figure 4.

Oxygen cutting process | HD plasma cutting process | Laser cutting process

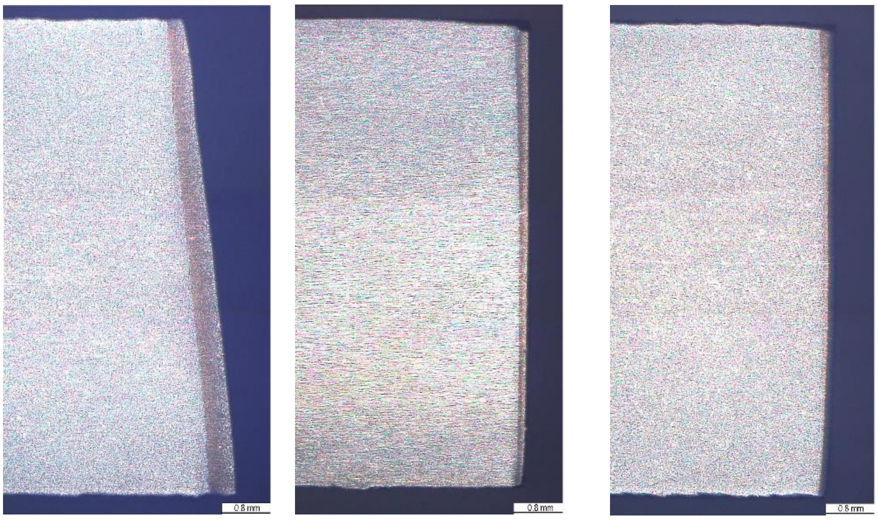
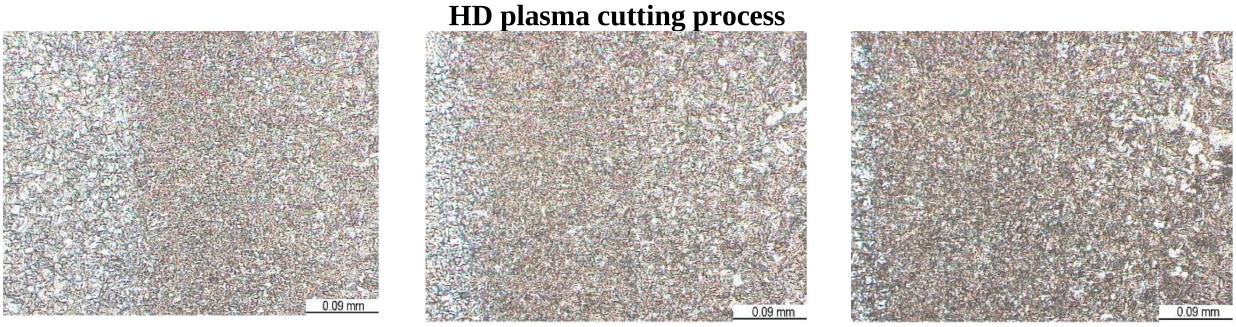


Figure 3. Macrostructure at the surface after oxygen, HD plasma and laser cutting processes.

Microstructure at the upper cutting surface | **Microstructure in the middle of the sample** | **Microstructure at the bottom cutting surface**

Oxygen cutting process

HD plasma cutting process



Laser cutting process

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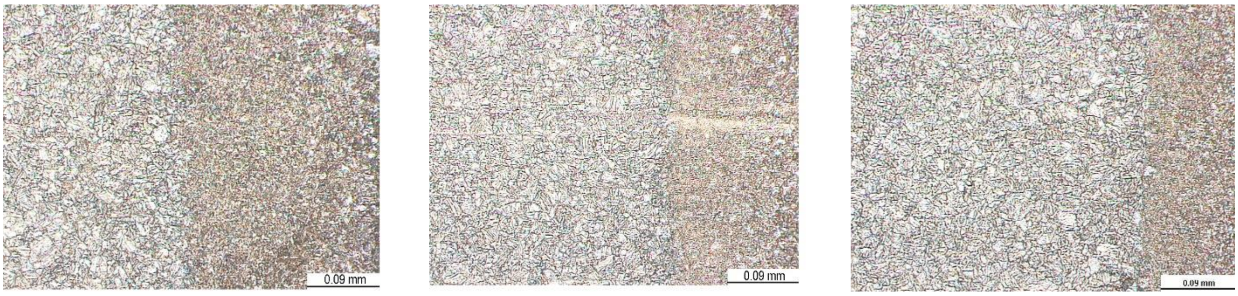

Figure 4. Microstructure at the surface after oxygen, HD plasma and laser cutting processes of S960QL steel, etching – nital.

2.4. Hardness measurement

Hardness measurement of the tested samples after cutting process was made using the Vickers method on a Wilson Wolpert 401 MVD with load of 100g – indenter working time – 15 seconds. The measurement was carried out along three measuring lines which were perpendicular to the cutting surface. The method of hardness testing is shown in figure 5. The results of hardness measurements are presented in table 5.

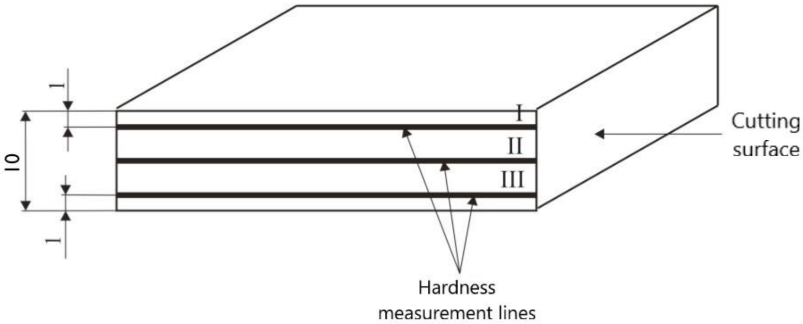

Figure 5. Hardness measurement lines.

Table 5. Results of the HV 0,1 Vickers hardness after cutting process.

Distance from cutting surface [mm]	**Hardness HV 0.1 after oxygen cutting process**			**Hardness HV 0,1 after HD plasma cutting process**			**Hardness HV 0.1 after laser cutting process**		
	Measurement line according to figure 5								
	I	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0.1	292	287	273	455	432	492	441	463	445
0.2	298	267	272	442	417	467	472	408	439
0.3	283	258	263	427	427	451	341	434	431
0.4	227	238	255	407	421	417	280	286	429
0.5	233	229	242	390	423	391	275	280	395
0.6	208	225	240	374	407	364	279	276	276
0.7	216	214	247	348	382	321	-	-	-
0.8	201	200	238	305	302	294	-	-	-

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0.9	190	202	223	293	284	273	-	-	-
1.0	216	220	216	282	275	270	-	-	-
1.1	228	222	241	278	274	275	-	-	-
1.2	267	244	251	-	-	-	-	-	-
1.3	274	275	258	-	-	-	-	-	-
1.4	278	280	274	-	-	-	-	-	-
1.5	284	285	280	-	-	-	-	-	-

3. Result and discussion

The oxygen, HD air plasma and laser cutting processes of 10mm thickness S960QL steel were carried out with the optimal parameters shown in table 2. The obtained cut surfaces have been subjected to ISO 9013: 2013 (surface roughness, rectangularity tolerance), as well as kerf widths and breakthrough holes diameters have been measured. In the last stage the metallography examination (microscopic and macroscopic) and hardness measurements were accomplished.

3.1. Analysis of surface quality and kerf width

The ISO 9013:2017 standard when assessing the surface quality after thermal cutting takes into account the roughness and the perpendicularity tolerance of cutting surface. Other geometrical parameters (kerf width, bevel angle, diameter of breakthrough hole) are treated auxiliary. Evaluating 10mm S 960QL steel after cutting process based on the ISO 9013:2013 standard taking into account the averaged perpendicularity deviation and the surface roughness it is stated that the quality of cutter surfaces is contained in the area: 1-1 for laser, 3-1 for HD plasma and 3-2 for oxygen cutting processes. The analysis of surface roughness after cutting showed that achieved quality depends on the cutting process and its parameters. The lowest values of surface roughness - 14 µm were obtained during HD plasma cutting process. During other cutting processes roughness values were between 15-22 µm. The analysis of perpendicular deviation showed that the maximum deviations were obtained during HD plasma cutting process - in that case it was about 0.5 mm. The minimum perpendicular deviation was obtained during laser cutting, where the value was about 0.1 mm. Average values of perpendicularity deviation were obtained in oxygen cutting process and their values were between 0.2 to 0.3 mm. Analysis showed that the kerf width is the largest in the case of oxygen and HD plasma cutting processes and is characterized by large V-shaped bevel. When analysing the top and bottom kerf widths it should be noted that HD plasma cutting is characterized by much higher widths differences than the laser cutting process. The top kerf widths in oxygen and HD plasma cutting processes were about 3 mm. For comparison, the size of kerf width as a result of laser cutting process was only 0.4 mm. Obtained cut surfaces during laser cutting were almost parallel. The difference between the top and bottom kerf width was 0.02 mm.

3.2. Structural changes occurring at the cutting surfaces

Macro and microscopic metallographic examination as well as hardness testing of samples after oxygen, HD plasma and laser cutting processes allowed us to determine the heat affected zone width and type of structural changes that occurred at the cutter surface. During laser cutting of S 960QL steel, a layer of low-carbon martensite with a hardness of 460 HV 0.1 is formed at the cutting surface. The width of this layer is approximately 0.3 mm. After cutting with HD plasma, a low-carbon martensite layer with a hardness of up to 490 HV 0.1 is formed at the cutting surface – similar to the laser cutting process, however the width of this layer is much higher (about 0.6 mm). Oxygen cutting process of S 960QL steel resulted a reduction of hardness of the heat affected zone to 190 HV 0.1

(tempering process) with the size of this zone approximately 1.3 mm. The influence of the cutting process on the change of hardness at the surface is shown in figure 6.

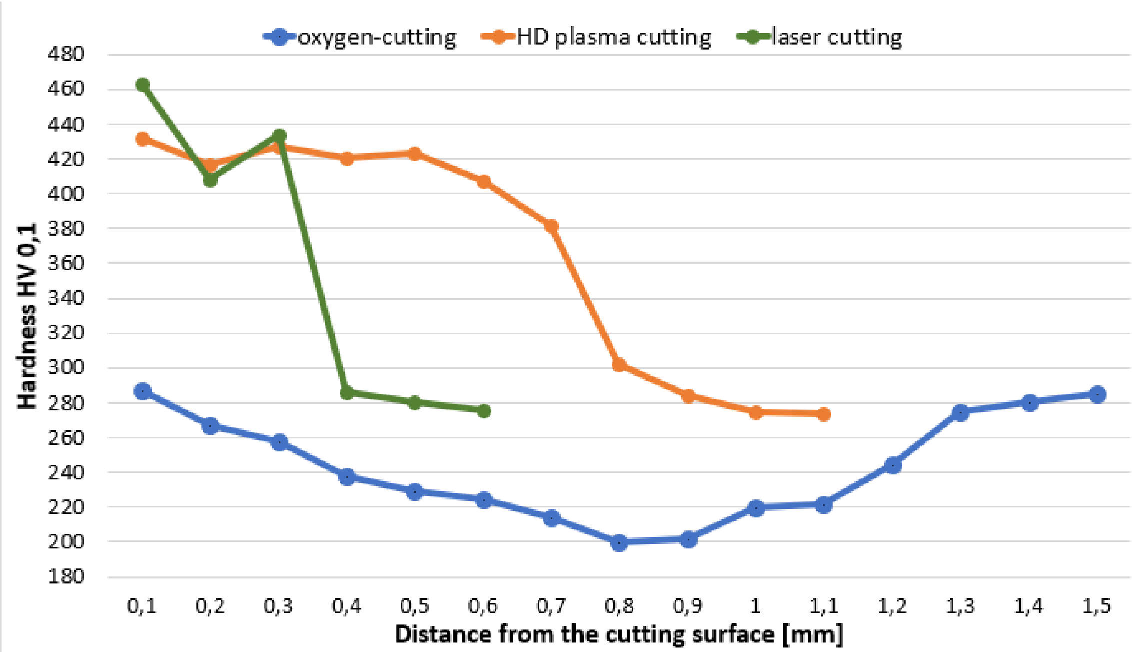

Figure 6. Impact of the cutting process on the change of hardness at the surface of S 960QL steel.

4. Conclusions

When assessing the quality surface after cutting process, not only surface parameters should be taken into account (roughness and perpendicular deviation). Other parameters like bevel angle, breakthrough hole, top and bottom kerf width are also very important. Considering the operational properties of elements after cutting, attention should also be paid to the impact of cutting processes on the possible structural and chemical changes caused by the heat, especially in case of heat-treated steels where as a result of thermal cycle may occur loss of properties acquired during heat treatment and hardening of the surface layer. The process of cutting with laser and HD plasma causes a particular increase of hardness in the surface layer up to 490 HV. The oxygen-cutting process in the areas of heat affected zone causes tempering of martensite. The consequences of these changes may affect the final product quality.

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