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Thermal cutting of thermomechanically rolled S700MC and heat-treated S690QL steels

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Abstract. The article describes the impact of oxygen, HD air plasma and laser beam cutting processes on structural changes and quality of the surface of thermomechanically treated S700MC and heat-treated S690QL steels. Taking into account good quality of obtained cut surface, particular attention shall be attached to the structural and chemical changes due to the impact of the heat cycle. Those modern steels are especially susceptible to a loss of their properties during the heat interaction in thermal cutting processes. The quality of the surfaces after thermal cutting processes were evaluated in accordance to ISO 9013:2017 (bevel angle, surface roughness, rectangularity tolerance). Also, measurements of cut widths and breakthrough holes diameters were accomplished. In the next stage the hardness measurements and metallography examination were performed. The following devices were used for this purpose: metallographic light stereoscopic microscope Olympus SZX9 and Wilson Wolpert 401 MVD for Vickers's hardness measurements.

1. Introduction

More and more companies in these days are using fine grained steels obtained in quenching and tempering or thermo-mechanical rolling processes for welded constructions. Modern steels for building industry obtain their high strength properties and good plasticity due to the complex manufacturing process which must be strictly supervised, figure 1 [1-4]. Taking into account that the thermal cutting process is often the first technological operation, from which the whole process of manufacturing begins, its influence on structural changes in cut material can have an important impact on the obtained quality and strength properties of final product. The growing requirements affect to the continuous development of thermal cutting methods, starting from straight line to 2D or 3D cut allowing to obtain complicated shapes [5]. Application of the appropriate cutting process depend on the documentation requirements and possibilities of each of the cutting method, i.e. type and thickness of material, shape of the part, dimensional tolerances, cutting quality, cutting speed, rectangularity deviation, and economic factors which takes into account investment, operating and utilization costs or efficiency of the process [6-7].

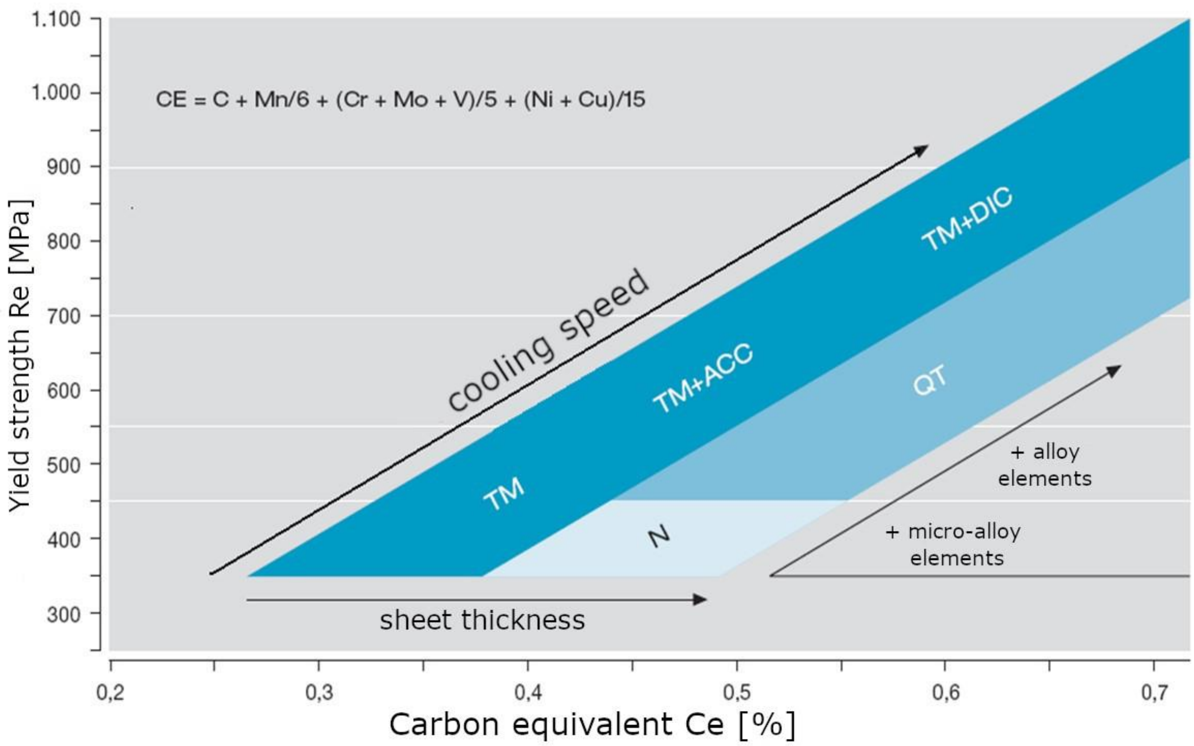

Figure 1. Correlation between carbon equivalent and yield strength Re of steels obtained in various manufacturing processes: N – normalized or normalized rolled steels, QT – quenched and tempered steels, TM - thermomechanically rolled steels, TM+ACC - thermomechanically rolled steels with accelerated cooling, TM + DIC - thermomechanically rolled steels with direct intensive cooling [4].

2. Experimental

The main purpose of the research was to determine the influence of oxygen stream, High Definition air plasma and laser beam cutting processes on surface quality of 10 mm thickness thermomechanically rolled S700MC and heat-treated S690QL steels. The mechanical properties and chemical composition of the tested materials are shown in table 1. The structure of the investigated steels has been presented in figures 2 and 3.

Table 1. The mechanical properties and chemical composition of thermomechanical rolled S700MC and heat-treated S690QL steels.

	Concentrations of elements, [%]											
	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Nb**	**V**	**Ti**	**Ni**	**Mo**	**Ce***
S700MC	0.06	0.17	1.68	0.008	0.003	-	0.047	0.006	0.122	-	0.006	0.36
S690QL	0.20	0.50	1.60	0.02	0.02	1.0	-	0.10	-	1.50	0.60	0.94

	Mechanical properties		
	Tensile strength, Rm, [MPa]	**Yield point, Re, [MPa]**	**Elongation A_5, [%]**
S700MC	822	768	19
S690QL	810	730	14

* Ce – carbon equivalent, %

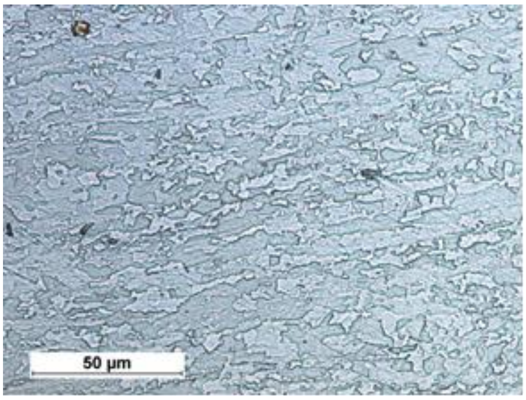

Figure 2. Ferritic-bainitic structure of thermomechanical rolled S700MC steel.

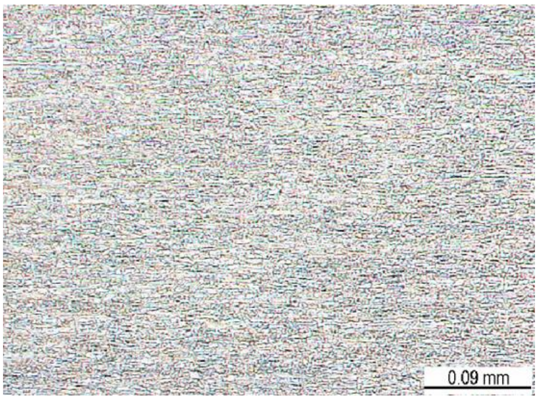

Figure 3. Tempered martensite structure of S690QL steel.

2.1. Cutting process

To determine the quality of the surface, the investigated materials were cut on a length of 200 mm. The cutting process was performed with the optimal parameters determined on the basis of initial tests for the sheet thickness of 10 mm, table 2. Oxygen cutting process was conducted on a Global Control Plus workstation equipped with a Messer OmniMat, equipped with an Alpha torch. Air plasma cutting was performed on a HD 3070 HYPERTHERM plasma cutter integrated with the VANAD Proxima CNC device. Laser cutting was carried out on a workstation equipped with a Trumpf TruLaser 5060 (L10), whose maximum continuous rated power is up to 5000W. In this process oxygen was used as a gas for laser cutting.

Table 2. Parameters of conducted cutting processes.

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

Plasma cutting						
Intensity of current, [A]	**Voltage of arc, [V]**	**Cutting speed, [m/min]**	**Pressure of plasma gas, [MPa]**	**Type of electrode**	**Diameter of cutting nozzle, [mm]**	**Nozzle clerance, [mm]**
100	150	3.0	0.8	Ziroconiated	1	4

Laser beam cutting				
Power of laser beam, [W]	**Cutting speed, [m/min]**	**Pressure of gas, [MPa]**	**Gas type**	**Laser head distance, [mm]**
4800	2.4	0.8	Oxygen	1.5

2.2. Surface quality assessment of cut surfaces

Surface quality assessment after following processes: oxygen cutting, air plasma and laser beam cutting were carried out on the basis of the ISO 9013:2017 standard, where the rectangularity tolerances, surface roughnesses and bevel angles are assessed. Surface roughness 'Rz' measurements were performed in five places on the cut surface in accordance with the cutting direction. The length of the measurement section was 12.5 mm, while the length of the elemental section was 2.5 mm. For this purpose, the Surytest 402 profilometer produced by Mitutoyo was used. The bevel angle measurements were performed using optical protractor, table 3. The squareness deviation evaluations 'u' were carried out in 3 places on the sample with 20 mm intervals between measuring points, table 3.

Table 3. Evaluation of cut surface quality of S700MC and S960QL steels 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 9013:2017**		**Bevel angle [º]**	
	MC	**QL**	**MC**	**QL**	**MC**	**QL**	**MC**	**QL**	**MC**	**QL**
Oxygen	0.45	0.30	3	3	15.83	20.80	1	2	2º30'	1º25'
HD plasma	0.82	0.49	4	3	9.20	6.40	1	1	2º20'	25'
Laser	0.12	0.12	1	1	13.52	18.30	1	2	1º	30'
Note: MC – S700MC steel, QL – S690QL steel										

For the purposes of the comparison geometric features of the obtained cut surfaces, the diameter of the breakthrough hole, bevel angle and geometry of the cut groove (bottom and top kerf widths) were measured, table 4.

Table 4. Geometrical features evaluation of S700MC and S690QL cut surfaces.

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**	
	MC	**QL**	**MC**	**QL**	**MC**	**QL**	**MC**	**QL**	**MC**	**QL**
Oxygen	1.65	1.63	1.78	1.59	-	-	-	-	Small	Small
HD plasma	1.85	2.1	1.27	1.08	4.62	5.21	2.85	3.37	Large	Small
Laser	0.43	0.57	0.45	0.45	4.09	4.18	3.73	3.90	No dross	No dross
Note:	MC – S700MC steel, QL – S690QL steel									

2.3. Metallographic examinations

Using stereoscopic microscope Olympus SZX9 the macroscopic examination was performed to determine the size of the heat affected zone obtained after process of thermal cutting, figure 4. The assessment of influence of the thermal cycle caused by cutting processes on the obtained material structure was performed on the Olympus PME 3. Microscopic examinations were conducted in three investigated areas: in the lower, middle and upper part of the sample surface, figure 5.

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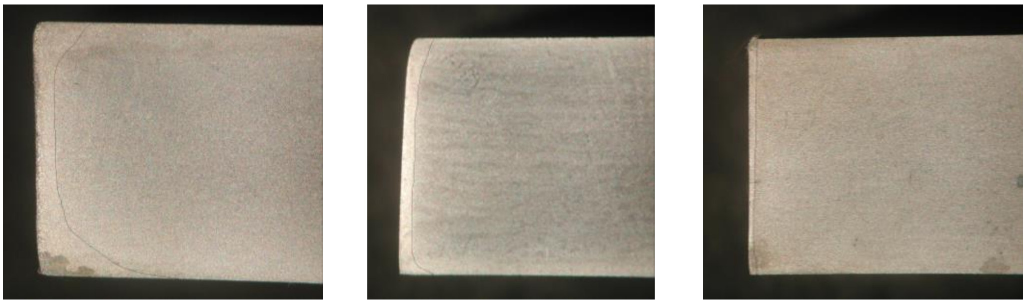
Oxygen cutting process	**HD plasma cutting process**	**Laser cutting process**

S700MC steel



S690QL steel

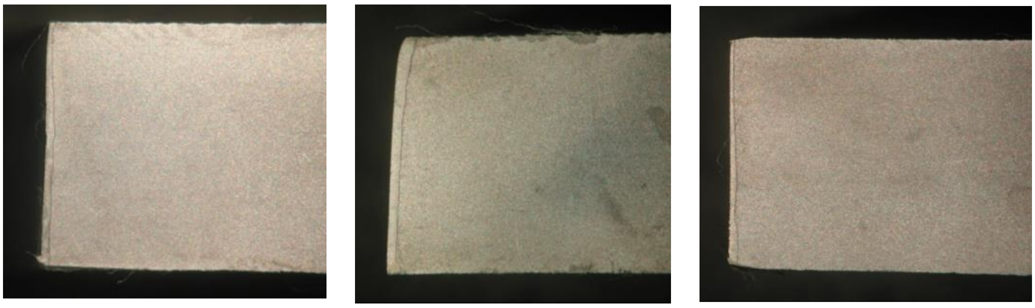
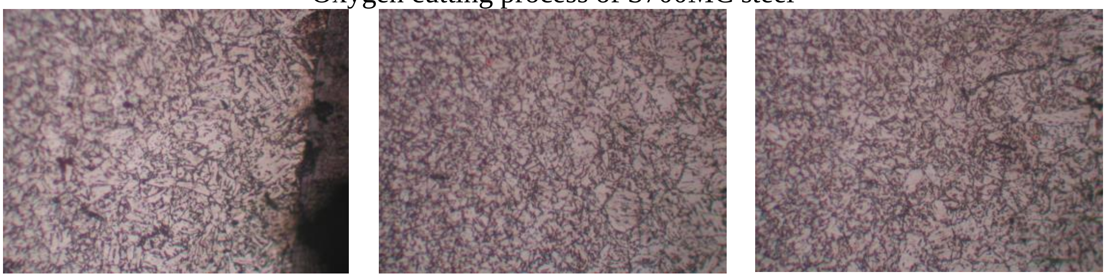


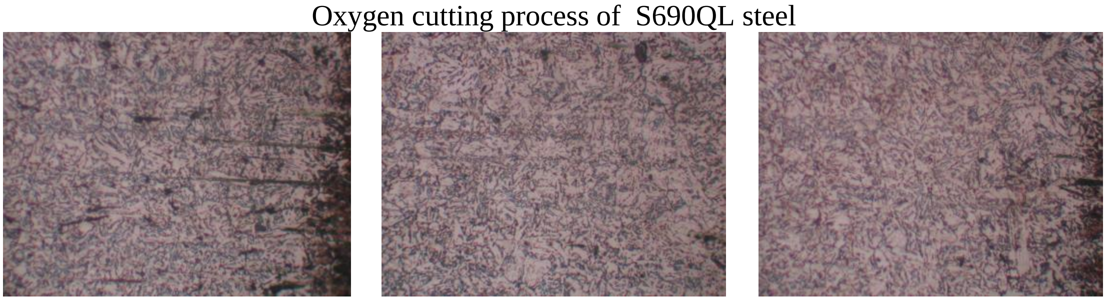
Figure 4. Microstructure at the surface after oxygen, HD plasma and laser cutting processes of S700MC and S690QL steels; etching - Adler Etchant.

Microstructure at the upper part of the cut surface	**Microstructure in the middle part of the cut surface**	**Microstructure at the bottom part of the cut surface**

Oxygen cutting process of S700MC steel



Oxygen cutting process of S690QL steel



HD plasma cutting process of S700MC steel

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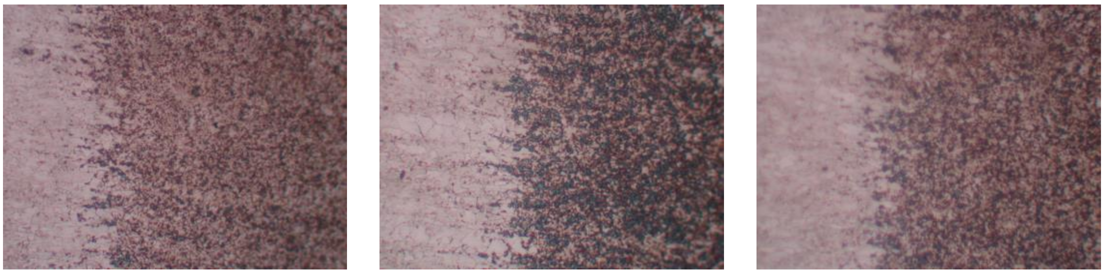
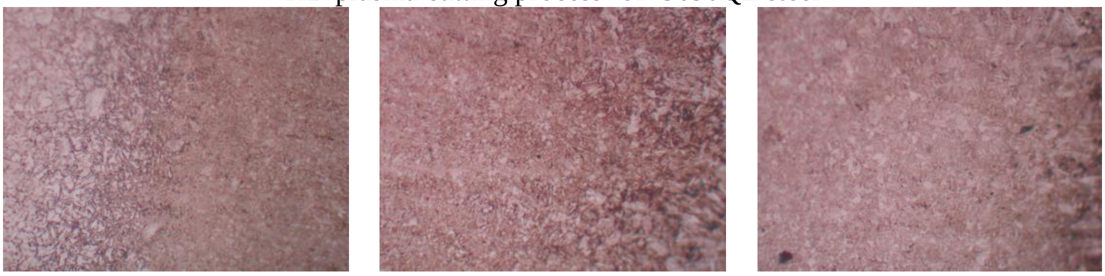
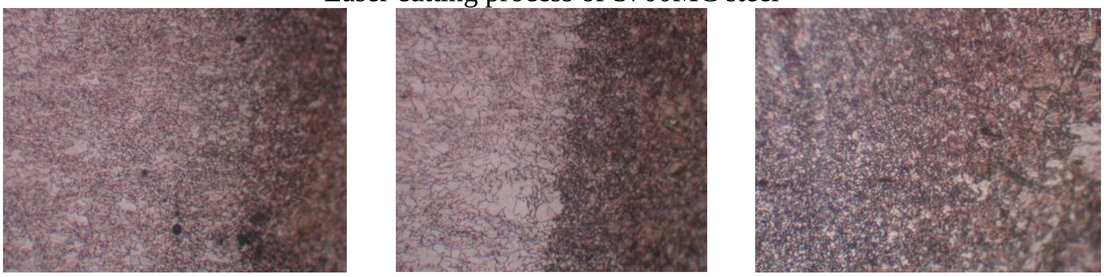


HD plasma cutting process of S690QL steel



Laser cutting process of S700MC steel



Laser cutting process of S690QL steel

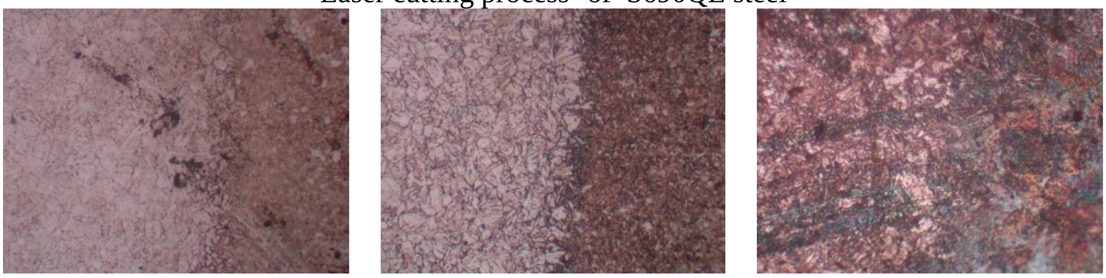


Figure 5. Microstructure of the surface after oxygen, High Definition plasma and laser cutting processes of S700MC and S690QL steels, etching – Adler Etchant, magnification – 200x.

2.4. Hardness measurement

Measurements of the hardness of investigated materials after cutting process were carried out using the Vickers hardness method on 401 MVD Wilson Wolpert device with load of 100g. The tests were carried out in three measuring lines which were perpendicular to the cutting surface. The method of conducting hardness test is shown in figure 6. Indenter loading time: 15 seconds. The results of hardness measurements are shown in tables 5, 6.

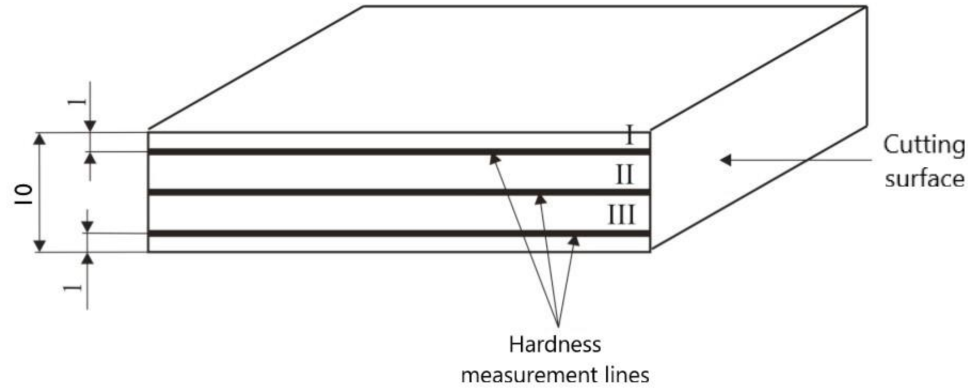


Figure 6. Hardness measurement lines.

Table 5. Vickers hardness results (HV 0.1) after cutting process of S700MC steel.

Distance from cut surface [mm]	**Oxygen cutting process**			**HD plasma cutting process**			**Laser cutting process**		
	Measurement line according to figure 6								
	I	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0.1	295	299	283	356	367	386	403	372	385
0.2	279	273	275	351	355	347	336	374	341
0.3	269	267	263	318	319	329	315	340	297
0.4	287	249	275	301	295	308	287	329	298
0.5	267	257	267	304	297	295	279	285	283
0.6	265	247	259	274	286	287	275	284	277
0.7	265	286	257	283	281	275	-	-	-
0.8	274	287	271	277	275	273	-	-	-
0.9	279	301	295	-	-	-	-	-	-
1.0	284	299	283	-	-	-	-	-	-
1.1	277	291	292	-	-	-	-	-	-
1.2	278	284	283	-	-	-	-	-	-
1.3	281	282	277	-	-	-	-	-	-
1.4	283	277	276	-	-	-	-	-	-
1.5	282	275	273	-	-	-	-	-	-

Table 6. Vickers hardness results (HV 0.1) after cutting process of S690QL steel.

Distance from cut surface [mm]	**Oxygen cutting process**			**HD plasma cutting process**			**Laser cutting process**		
	Measurement line according to figure 6								
	I	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0.1	297	283	275	416	414	399	453	467	456
0.2	278	266	273	381	452	435	436	447	453
0.3	273	268	265	415	457	438	343	328	369
0.4	228	248	257	391	419	389	286	287	285
0.5	223	227	243	328	297	313	278	283	288
0.6	218	227	245	293	287	295	286	276	284
0.7	217	216	237	295	287	283	-	-	-
0.8	205	203	228	269	274	275	-	-	-
0.9	189	212	213	-	-	-	-	-	-
1.0	217	225	210	-	-	-	-	-	-
1.1	223	228	231	-	-	-	-	-	-
1.2	257	254	261	-	-	-	-	-	-
1.3	234	285	277	-	-	-	-	-	-
1.4	268	283	264	-	-	-	-	-	-
1.5	281	283	278	-	-	-	-	-	-

3. Result and discussion

The thermal cutting (oxygen, High Definition plasma and laser beam cutting processes) of 10 mm thick S960QL and S700MC steel sheets were performed after preliminary tests, using optimal parameters, which were shown in table 2. Obtained surfaces after cutting process have been assessed in accordance to ISO 9013:2017, which takes into account rectangularity tolerance and surface roughness. In next stage the following values have been measured: kerf widths and breakthrough holes. Then hardness measurements, microscopic and macroscopic metallography examinations were performed.

3.1. Quality of cut surfaces and analysis of kerf widths

The international standard ISO 9013:2017 when assessing the obtained quality surface after thermal cutting processes takes into account the following parameters: perpendicularity tolerance and roughness of cut surface. Other geometrical parameters i.e. diameter of breakthrough hole, bevel angle kerf width are qualified as auxiliary. Evaluating obtained quality of the surface after thermal cutting processes based on the ISO 9013:2017 international standard and taking into account the values of surface roughness and average perpendicularity deviation it has been determined that the quality of cut surfaces for S700MC steel is contained in the area: 1-1 for laser beam, 4-1 for HD air plasma and 3-1 for oxygen cutting processes. For S690QL steel the following surface quality area results were obtained: 1-2 for laser beam, 3-1 for HD air plasma and 3-2 for oxygen cutting processes. Analysing values of surface roughness after cutting of S700MC and S690QL it has been stated that obtained data are divergent depending on the thermal cutting process. None of the thermal cutting methods made it possible to obtain the lowest parameter of surface roughness for cut S690QL and S700MC metal sheets. The lowest values of surface roughness have been observed for process of High Definition air plasma cutting. Measurements of perpendicular deviation showed that the maximum value of this parameter was registered during High Definition air plasma cutting process – 0.5 mm for S690QL and 0.82 mm for S700MC. The minimum perpendicular deviation was obtained during laser beam cutting, where the value for both tested materials was about 0.1 mm. For oxygen cutting process the medium

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values of perpendicularity deviation were registered– from 0.3 to 0.45 mm. Kerf width measurements showed that the largest values were obtained during process of oxygen and High Definition air plasma cutting processes and were characterized by large V-shaped bevel. Analysing bottom and top kerf widths it has been stated that High Definition air plasma cutting process is characterized by much larger values of this parameter comparing to the laser cutting process. The obtained values of top kerf widths in High Definition air plasma cutting process of S690QL and S700MC steels were about 2mm, while after oxygen cutting process they were about 1.7 mm. For comparison, minimum values of kerf width (0.5 mm) were registered for laser beam cutting process. Achieved cut surfaces in this process were almost parallel for S690QL and S700MC steels. Obtained differences between the bottom and top kerf widths for laser cutting were 0.07 mm for S690QL and 0.03 mm for S700MC steels.

3.2. Structure changes on cut surfaces

Microscopic and macroscopic metallographic examination as well as Vicker's hardness tests of investigated materials after oxygen, High Definition air plasma and laser cutting processes were performed in order to determine the size of heat affected zone and type of structural changes that occurred on the surface after thermal cutting. On surface after laser cutting process of S690QL steel a layer of low carbon martensite was formed with a Vicker's hardness of up to 460 HV0.1 The obtained width of this layer was 0.3 mm. When cutting S700MC steel, a bainitic layer with a hardness 360 – 405 HV0.1 was created. Behind this layer with a width of 0.6 mm, a fine grained bainitic-ferritic structure (native material) with a hardness of 280 HV0.1 was registered. After HD plasma cutting of S690QL steel, a low-carbon martensite layer with a hardness of up to 467 HV0.1 was formed - similar to the process of laser cutting, but the measured width of this layer was much bigger - about 0,6 mm. Similarly, in the case of cutting S700MC steel, the hardness of bainite layer was about 360 – 375 HV0,1. Oxygen cutting process of S690QL steel caused a reduction of heat affected zone hardness to 185 HV0.1 (tempering process), the size of this zone with was 1.3 mm. In the case of cutting S700MC steel the minimum hardness value of the heat affected zone was about 235 HV0.1 (partial recrystallization) with the size of this zone about 1.2 mm. The influence of the thermal cutting processes on obtained structural changes at the surface are shown in table 7.

Table 7. Obtained **m**icrostructure of investigated materials after thermal cutting processes.

Type of material	Base material	Material structure on cut surface		
		Upper part	Middle part	Bottom part
Oxygen cutting process				
S700MC	Ferrite + fine grained bainite	Ferrite + bainite	Ferrite + bainite	Ferrite + bainite
S690QL	Tempered martensite	Low-carbon martensite	Low-carbon martensite	Low-carbon martensite
High Definition air plasma cutting process				
S700MC	Ferrite + fine grained bainite	Fine grained bainite	Fine grained bainite	Fine grained bainite
S690QL	Tempered martensite	Low-carbon martensite	Low-carbon martensite	Low-carbon martensite
Laser beam cutting process				
S700MC	Ferrite + fine grained bainite	Fine grained bainite	Fine grained bainite	Fine grained bainite
S690QL	Tempered martensite	Low-carbon martensite	Low-carbon martensite	Low-carbon martensite

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4. Conclusions

When evaluating the surface quality after processes of thermal cutting, not only surface parameters (roughness and perpendicular deviation) should be assessed. Other parameters i.e. bevel angle, size of breakthrough hole, top and bottom kerf widths are also very important. Paying particular attention to the chemical and structural changes after processes of thermal cutting it is possible to obtain the minimum loss of mechanical properties which is very important in case of heat-treated steels. In those materials during impact of thermal cycle may occur a loss of mechanical properties which were acquired in processes of complicated process of heat treatment. It was stated that High Definition air plasma and laser beam cutting processes steels have a significant impact on increase of hardness of the surface layers up to 460 HV0.1 for heat-treated steels. The oxygen cutting process in the areas of heat affected zone causes tempering of martensite for quenched and tempered S690QL steels and in the case of thermomechanically rolled S700MC steel leads to partial recrystallization and grain growth. The consequences of these changes may affect to the operational properties of finished elements or quality of welded joints prepared for joining by thermal cutting processes.

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