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Structural Changes and Chemical Composition Changes during the Plasma Cutting Process

Abstract: Cutting is usually one of the initial and primary operations used when making welded structures and fabricating structural elements. Increasingly often, the preparation of elements involves the use of thermal, in particular plasma arc, cutting. The plasma arc cutting process consists in melting and ejecting liquid metal from the cut gap by highly concentrated plasma electric arc burning between a non-consumable electrode and a workpiece. The article presents results of tests concerning the influence of plasma gas on structural changes and chemical composition changes resulting from the cutting of unalloyed steel using air plasma arc. The tests revealed that the application of the air plasma arc cutting process led to the formation of an amorphous layer characterized by a very high nitrogen content (of approximately 1.6%) and a hardness of 750 HV 0.2. This high nitriding effect was triggered by the diffusion of nitrogen from the plasma gas. At the same time, the effect of air plasma arc gases on the liquid metal led to the carburising of the cut surface (up to approximately 0.5%) as well as to the burnout of alloying components (in accordance with the theory of selective oxidation of chemical elements). After the air plasma cutting process, the material structure revealed features intermediate between those of the structure formed through oxygen cutting and those of the structure formed as a result of nitrogen plasma cutting. The tests also revealed that the argon-hydrogen plasma cutting process had the lowest effect on the material subjected to cutting.

Keywords: Plasma, Plasma Arc, Plasma Gases, Structural Changes, Chemical Composition Changes

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Introduction

The cutting process involves the separation of a given material across its entire thickness and along the entire division line. The process is usually performed perpendicularly to the surface of a workpiece. Other variants of the cutting process include bevelling, grooving and punching. Cutting is typically one of the initial and primary operations during the fabrication of welded structures and structural elements. The preparation of elements increasingly often involves thermal cutting, usually performed using plasma. The plasma arc cutting process involves the melting and ejection of liquid metal from the cut gap by strongly concentrated electric plasma arc, burning between a non-consumable electrode and a workpiece. The above-named method is widely used in the thermal cutting of alloy steels and non-ferrous metals (impossible to cut with oxygen). In addition, the method is increasingly commonly used to cut carbon and low-alloy steels (instead of previously applied oxygen cutting). The plasma cutting process can be performed applying nearly all gases used in welding engineering, i.e. argon, nitrogen, hydrogen, helium, oxygen and mixtures containing hydrocarbons. During cutting, the above-named gases affect the material being cut, triggering chemical and structural changes in the surface adjacent to the material surface as well as affect operational properties of finished elements or properties of welded joints. The use of new materials in nozzles and electrodes (zirconium or hafnium seated in the housing made of copper or nickel-silver alloy)

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has enabled the use of air (or even oxygen) as the plasma gas and led to the obtainment of high cutting quality and favourable economic effects of the process. Air and oxygen belong to the group of active gases, significantly affecting, i.e. oxidising, surfaces subjected to cutting. Such an effect is particularly unfavourable when cutting alloy steels and aluminium alloys. In economic terms, air belongs to more favourable plasma gases. The heat affected zone (HAZ) formed during air plasma cutting is characterised by inferior properties and structure than those of edges made using other plasma gases (e.g. argon or argon + nitrogen, actively affecting the material being cut). The width, structure and hardness of the HAZ during plasma cutting depend on the thickness of the material subjected to cutting as well as on the cutting rate. In cases of structural carbon steels, regardless of a cutting environment, the structure located near the cut surface is martensitic-bainitic. The cutting of high-strength steels triggers the significant hardening of subsurface areas (up to approximately 850 HV). During the cutting of high-alloy (ferritic) steels, high heating and cooling rates generate high stresses and the hardening of the cut surface in the HAZ [1–15].

Individual study

Tests concerning the effect of plasma gas on the structure and chemical composition of a material subjected to cutting involved the use of 14 mm thick plates made of unalloyed steel S275JR subjected to air, nitrogen and argon-hydrogen plasma cutting. The cutting process was performed using a YUN-3000 plasma-gas cutting machine and a DP3a–100 plasma power supply.

The chemical composition of the plates was identified using an MC20 BAIRD emission spectrometer. The chemical composition of the test steel is presented in Table 1.

Table 1. Chemical composition of 14 mm thick steel S275JR

C	Si	Mn	Ni	Cr	Cu	Al	P	S
0.20	0.32	1.24	0.06	0.08	0.11	0.02	0.019	0.021

The identification concerning the effect of plasma arc gases on chemical and structural changes near the cut surface included the performance of a cutting process involving the use of the following gases:

- air used as the plasma gas; cutting process parameters:
  - cutting current: $I = 250$ [A]
  - plasma gas supply pressure: $p = 0.45$ [MPa]
  - cutting rate: $v = 700$ [mm/min],
- nitrogen used as the plasma gas; cutting process parameters:
  - cutting current: $I = 100$ [A]
  - plasma gas supply pressure: $p = 0.40$ [MPa]
  - cutting rate: $v = 300$ [mm/min]
- argon–hydrogen mixture (65% Ar + 35% H_2) used as the plasma gas; cutting process parameters:
  - cutting current: $I = 250$ [A],
  - gas flow rate: Ar – 40 [l/min], H_2 – 30 [l/min],
  - cutting rate: $v = 600$ [mm/min].

Tests

The cut surfaces were subjected to the following tests:

- microscopic metallographic tests performed using an Axiovert 405M light microscope (OPTON),
- hardness tests performed using an MVD1 hardness tester (Wilson Wolpert) and a load of 200 g,
- chemical composition analysis performed using an ICXA 733 electron microprobe X-ray analyser (Jeol), featuring an energy dispersive

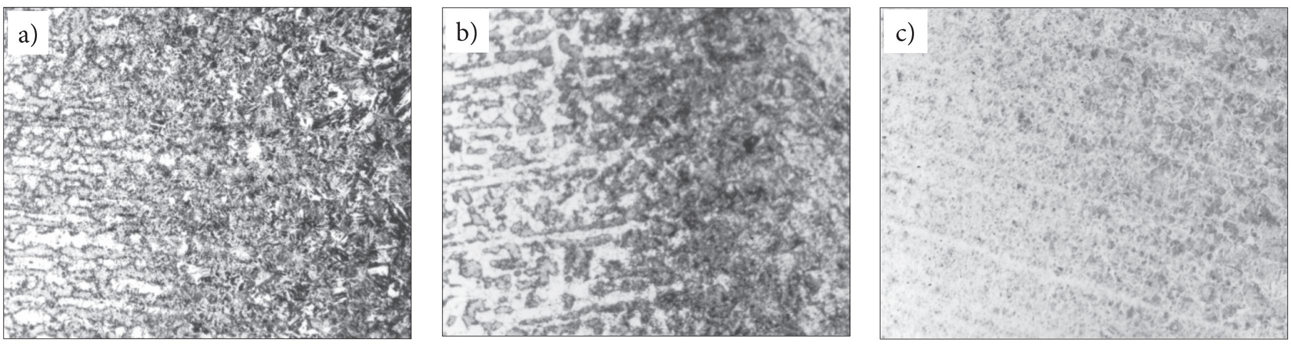

Fig. 1. Microstructure near the cut surface after; a) air plasma cutting, b) nitrogen plasma cutting; c) argon-hydrogen plasma cutting

spectrometer (EDS) connected with an ISIS 300 analytical system (OXFORD),
- analysis of phases formed on the cut surface and in the material subjected to cutting, performed using a PHILIPS PW 1050 X'Change machine operated in B-B (Bragg-Brentano) geometry.

Analysis of test results

Structural changes near the cut surface

Metallographic tests and hardness measurements concerning the cut surface made it possible to identity the HAZ width and determine the effect of the plasma gas on the width of the zone of structural changes taking place in the material subjected to cutting. During air plasma cutting, the width of the HAZ amounted to 0.7 mm, whereas during nitrogen plasma cutting, the width of the HAZ amounted to 1.2 mm. In turn, during argon-hydrogen plasma cutting, the width of the HAZ amounted to 0.9 mm. The differences in the HAZ width obtained during air, nitrogen and argon-hydrogen cutting resulted from differences in the enthalpy of applied plasma gases. The metallographic tests (Fig. 1) and hardness measurements of the specimens subjected to air, nitrogen and argon-hydrogen plasma cutting enabled the determination of structural changes taking place near the cut surface.

During the microscopic tests it was possible to observe that the layer of metal formed near the surface subjected to air plasma cutting was poorly etchable and revealed features of an amorphous material. The metal observed in the aforesaid layer melted during the cutting process and underwent recrystallisation on the cut surface. The hardness of the layer was restricted within the range of approximately 600 HV0.2 to 700 HV0.2. Below the amorphous layer it was possible to observe the bainitic structure, the hardness of which amounted to approximately 500 HV0.2. Along with the growing distance from the cut surface it was possible to observe the superheated Widmannstätten structure having a hardness of 400 HV0.2 as well as structures typical of welding processes (recrystallised zone, partially recrystallised zone and the base material). The argon-hydrogen plasma cutting process induced the smallest changes in the structure and width of the HAZ. Near the cut surface it was possible to notice hard layers after partial martensitic transformation (having a hardness of approximately 650 HV0.2). Below the hard layer, after partial martensitic transformation, it was possible to observe the martensitic-bainitic structure having a hardness of 450 HV0.2 and a width of approximately 0.3 mm. Underneath it was possible to observe structures characteristic of welding processes. The nitrogen plasma cutting process triggered changes in the material subjected to cutting similar to those induced by the air plasma cutting process. The layer near the cut surface was characterised by a high hardness of 720 HV0.2 and a width of approximately 0.1 mm. Below, there was a wide zone containing the bainitic structure having a width of approximately 0.4 mm and hardness restricted within the range of 400 HV0.2 to 500 HV0.2. Underneath it was possible to observe a wide layer of recrystallisation and partial recrystallisation. The distribution of hardness in the specimens subjected to air, nitrogen and argon-hydrogen plasma cutting is presented in Fig. 2.

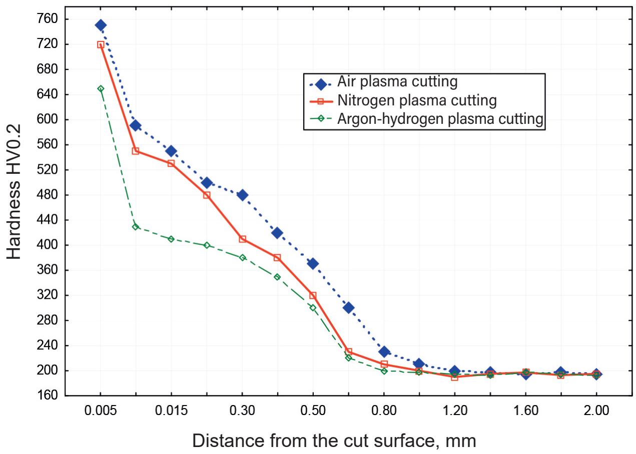

Fig. 2. Hardness distribution near the cut surface

Analysis of chemical composition changes near the cut surface

The phase analysis of the material subjected to air, nitrogen and argon-hydrogen plasma cutting confirmed the presence of oxide phases (Fe_3O_4, Fe_2O_3 and FeO) on the cut surface (Fig. 3). The width of the aforesaid layers was restricted within the range of 20 µm to 40 µm. The presence of the oxide layers after nitrogen and argon-hydrogen plasma cutting processes revealed that oxidation was triggered by oxygen sucked by arc plasma gases. The oxidised layers were easy to remove from the cut surface. During plasma cutting, the nitration of the cut surface can take place in two ways, i.e. it can be triggered by plasma gases (during nitrogen plasma cutting, air plasma cutting or plasma cutting, where mixtures used in the process

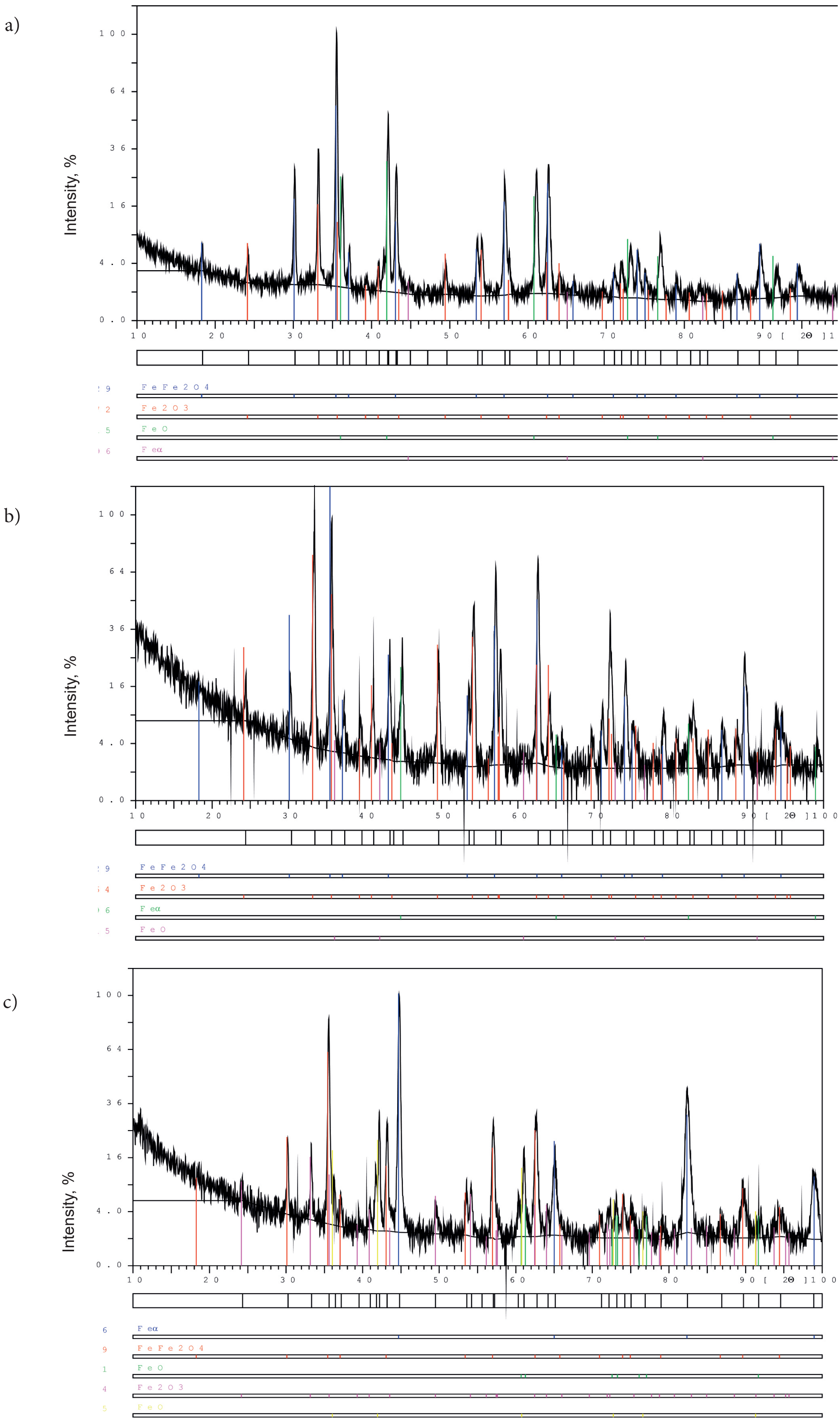

Fig. 3. X-ray analysis of the material subjected to cutting; a) air plasma cutting, b) nitrogen plasma cutting, c) argon-hydrogen plasma cutting

contain certain amounts of nitrogen) or by the atmosphere surrounding plasma arc (during oxygen or argon plasma cutting). Processes taking place in plasma arc include the dissociation and ionisation of nitrogen. In the presence of oxygen and alloying components, nitrogen can easily diffuse to the liquid metal.

In contact with oxygen, nitrogen undergoes oxidation in accordance with the following reaction (1):

$$N_2 + O_2 <=> 2NO \qquad (1)$$

The NO oxide dissolves easily in the liquid metal, increasing the content of nitrogen and that of oxygen (in the metal) (2):

$$Fe_c + NO -> [FeO] + [N] \qquad (2)$$

where
- Fe_c – liquid iron,
- [FeO] – concentration of FeO in the steel,
- [N] – concentration of N in the steel.

The solubility of nitrogen in iron depends on alloying components of steel. In liquid steel, nitrogen is present primarily in the solution, with nitrides forming only after the solidification of the steel. Nitrogen and iron can form such compounds as FeN (phase δ: 11.2% N_2), Fe_4N (approximately 6% N_2) and $Fe_{16}N_2$ (Fe_8N). The Fe_2N nitride is formed at a temperature of 450°C. Along with an increase in temperature, Fe_2N decomposes into Fe_4N. The exceeding of 550°C also leads to the decomposition of the Fe_4N nitride. Therefore, it could be concluded that, during the cutting process, the liquid metal layer contains nitrogen in the form of solution. Because of its properties, air plasma arc affected the cut surfaces in two ways. The microanalysis of the chemical composition revealed the significant enrichment of the subsurface layers with nitrogen (approximately 1.6% N) and carbon (approximately 0.6% C) and the substantial reduction of manganese and silicon contents. The intense nitration of the cut surface resulted from the effect of nitrogen (being a component of air plasma) on the liquid metal and the heating of the cut surface to high temperature. The area characterised by the most intense nitration was the (poorly etchable) layer of partly molten metal which had not been removed by the plasma beam. The phase analysis (Fig. 4) of the specimens subjected to air plasma cutting did not reveal the presence of nitride phases near the cut surface.

The foregoing could indicate that nitrogen was in the dissolved state. Probably, because of the very fast discharge of heat from the surface, nitrogen did not form compounds but remained in the metal in the form of the supersaturated solution. In turn, the phase analysis (Fig. 4) revealed the presence of carbide phases of variable carbon concentration, which confirmed the enrichment of the cut surface with carbon. The initial phase of air plasma cutting was accompanied by carbon oxidation, yet the above-named process finished when the thin layer of iron oxide was formed (carbon does not dissolve in liquid FeO). The fast oxidation of iron, manganese and silicon combined with the insolubility of carbon in liquid FeO were responsible

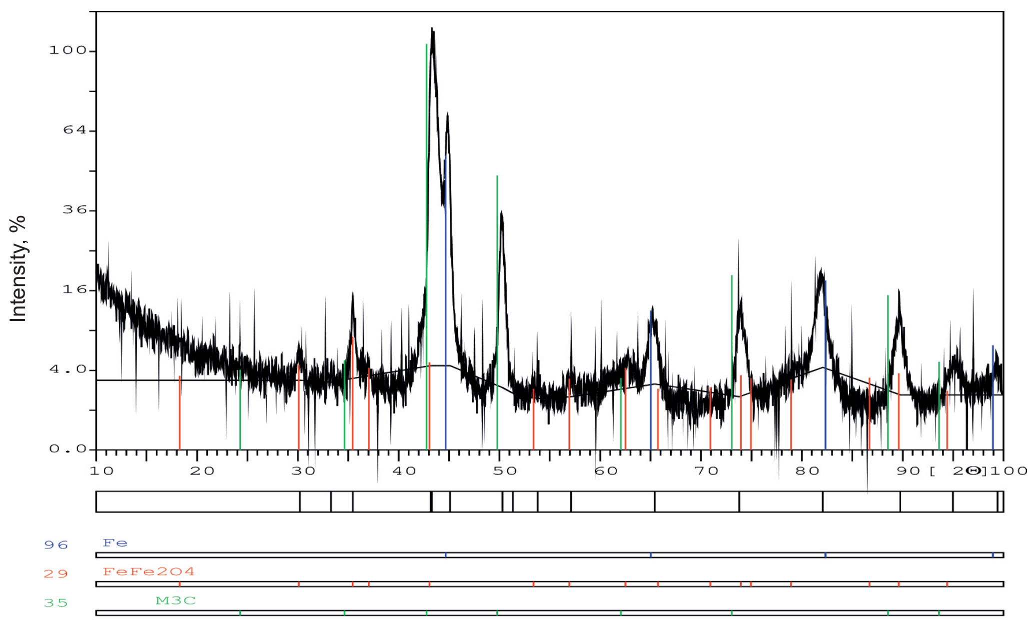

Fig. 4. Phase analysis of the layer subjected to air plasma cutting

for the enrichment of the molten steel with carbon and its diffusion from the metal surface deep inside the material. The diffusion of carbon in the liquid steel is fast. However, the aforesaid process is considerably slower in the solid solution. The intensive change of carbon concentration during the transfer from the partially molten area to the solid-state metal led to an increase in hardness in the cut surface. The burnout of manganese and silicon from the subsurface layer could be explained using the analysis of changes of Gibbs free energy in relation to oxide formation in the function of temperature. The results obtained in the tests were compatible with the view concerning the selective oxidation of alloying elements (Fig. 5).

The reduction of manganese and silicon contents was triggered by the higher affinity of the aforesaid chemical elements for oxygen than for iron at the temperature of the molten metal during the plasma cutting process. The air plasma cutting process burnt out up to 90% of silicon and 30% of manganese near the surface in comparison with contents of these chemical elements in the base material. The higher loss of silicon could be attributed to the fact that silicon is characterised by higher affinity for oxygen than manganese is. Nitrogen plasma cutting was responsible for the high nitration of the cut surface (up to 1.8%). The width of the nitrided zone amounted to approximately 60 µm. Similar to the air plasma cutting process, it was possible to observe the carburisation of the cut surface and the burnout of alloying components. However, it should be noted that the carburisation of the subsurface layers was lower than that observed during air plasma cutting and amounted to approximately 0.33% C. Also, the reduction of manganese and silicon contents was lower and amounted to approximately 50% in relation to the content of these elements in the base material. The argon-hydrogen plasma cutting process was characterised by the lowest effect on the chemical composition of the material subjected to cutting. The foregoing could probably be ascribed to the nature of the plasma arc gases. Argon-hydrogen plasma cutting was responsible for the low carburisation of the surface layer (approximately 0.29% C) and the reduction of manganese and silicon contents. The width of the zone where the changes of the chemical composition were observed amounted to 40 µm.

Summary

The plasma cutting process led to the obtainment of the layer of molten material which underwent recrystallisation on the cut surface. The layer was characterised by the properties of the amorphous and poorly etchable material. The width of the layer depended on the cutting rate and was restricted within the range of 10 µm to 40 µm. The layer hardness amounted to 750 HV0.2. In addition, the layer was characterised by a high nitrogen content of approximately 1.8% and that of carbon (amounting

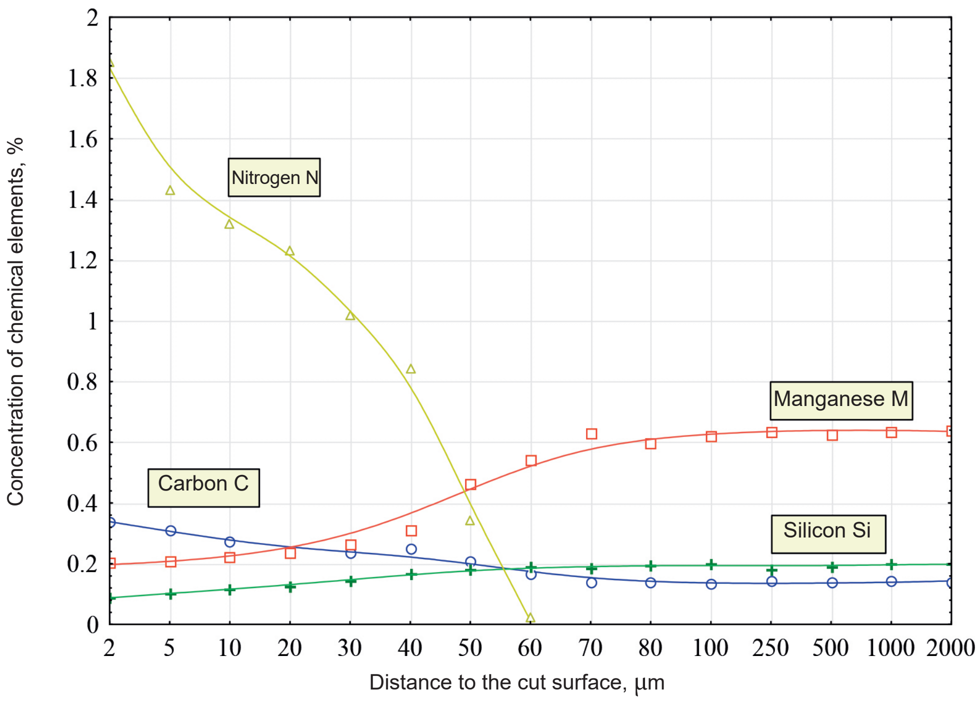

Fig. 5. Change of the chemical composition in the steel subjected to nitrogen plasma cutting

to approximately 0.5%). It is recommended that this layer should be removed mechanically before the welding of elements. The above-presented test results justified the formulation of the conclusion that the air plasma cutting process triggered changes in the cut material which were intermediate between those observed in the material subjected to argon-hydrogen plasma cutting and those observed in the material which underwent the nitrogen plasma cutting process. Nitrogen plasma cutting led to the significant nitration of the cut surface (up to 1.8%) and to an increase in hardness above 700 HV0.2. The HAZ| width formed during the nitrogen plasma cutting process amounted to approximately 1.2 mm in relation to cutting rate v = 300 mm/min. The lowest effect on the material was observed in relation to the argon-hydrogen plasma cutting process, which triggered only slight changes near the cut surface. The HAZ width formed during the argon-hydrogen plasma cutting process amounted to approximately 0.9 mm in relation to cutting rate v = 600 mm/min. The argon-hydrogen plasma cutting of steel S275JR led to a subsurface increase in hardness to approximately 650 HV0.2 and triggered the formation of small zones characterised by changes in the chemical composition.

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