Shanguo Han[a], Detao Cai[b], Ziyi Luo[c], Yaoyong Yi[d]

Research on water-air plasma cutting process of carbon steel

Istraživanje procesa rezanja ugljeničnog čelika plazmom voda-vazduh

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Adresa autora / Author's address:
High-energy beam welding R&D center, Guangdong Welding Institute (China-Ukraine E.O.Paton Institute of Welding), Guangzhou, China
[a]*shanguohan@163.com,*
[b]*caidt@gwi.gd.cn,*
[c]*luozy@gwi.gd.cn,*
[d]*yiyy@gwi.gd.cn*

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Abstract

The principle and equipment of water-air plasma cutting has been introduced in this paper. Especially, the function of water is not only to prevent the cutting pool from oxidizing in the form of a water curtain, but also to generate plasma in the center of arc. The Numerical Model of Low-temperature Plasma has been eatablished with equation of energy, status, motion and chemical dynamic equation. Working process, mechanical properties and micro-structural features of 20 mm carbon steel processed by water-air plasma cutting and air plasma have been investigated, which choose the same parameters. The voice of plasma arc and dust of pool are being limited in the area of water curtain, so that the noise and dust of water-air plasma cutting can be compared favorably with under-water plasma cutting. Lower temperature of water-air cutting plates is due to the fluent water taking off energy of metal pool during cutting. It is impossible to find oxide layer on the incisions surface of water-air plasma cutting, and the heat affected zone is so thin that welding can be carried out directly after cutting without any else process. So inclusion also can be avoided in the weld. But for air plasma cutting, lot of time is waste to remove oxide layer by mechanical polishing before welding. With the help of addition plasma arising from water, the water-air plasma arc becomes stronger, so smooth and high flatness cutting surface can be

Rezime

U ovom radu je predstavljen princip rada i oprema za sečenje plazmom voda-vazduh. Funkcija vode nije samo sprečavanje oksidacije kupke za rezanje formiranjem vodene zavese, već i stvaranje plazme u središtu luka. Numerički model niskotemperaturne plazme je definisan jednačinom energije, statusa, kretanja i hemijske dinamičke jednačine. Istraženi su radni proces, mehanička svojstva i mikrostrukturne karakteristike ugljeničnog čelika od 20 mm obrađenog rezanjem voda-vazduh plazmom. Takođe je analizirana vazdušna plazma sa istim parametrima. Zvuk luka plazme i prašina kupke su bili ograničeni područijem vodene zavese, tako da se buka i prašina sečenja voda-vazduh plazmom mogu uporediti sa podvodnim rezanjem plazmom. Niža temperatura ploča koje se režu vodom i vazduhom je posledica tečnja vode koja preuzima energiju metalne kupke tokom sečenja. Nije pronađen oksidni sloj na površini reza pri sečenju voda-vazduh plazmom, a zona pod uticajem toplote je toliko tanka, da se zavarivanje može izvršiti neposredno nakon sečenja bez ikakvog drugog postupka pripreme. Time se izbegavaju nečistoće u zavarenom spoju. Pri rezanju vazdušnom plazmom, pre zavarivanja je neophodno uklanjanje oksidnog sloja mehaničkim poliranjem što zahteva određeno vreme. Uz pomoć dodatno stvorene plazme od vode, luk voda-vazduh plazme postaje snažniji, tako da se može dobiti glatka i velika ravna površina rezanja. U poređenju

acquired. Compared with the technology of air plasma cutting, water-air plasma cutting has benefits of friendly working environment, higher quality incision and lower cost.

sa tehnologijom vazdušnog rezanja plazmom, rezanje voda-vazduh plazmom ima prednosti povoljnijim radnim okruženjem, kvalitetnijim rezom i nižim troškovima.

1. Introduction

The method of metal cutting can be classified into thermal cutting and cold cutting, depending on whether the metal is melted, and the plasma cutting is belongs to thermal cutting. But it is necessary to consider the cutting quality and cutting cost before choosing cutting methods. With excellent incision quality and cutting efficiency, laser cutting and high-pressure water cutting have been introduced to many industries. But these equipment cost are too high to be widely used. Due to roughness cutting surface, oxygen-acetylene and mechanical cutting are applied in unimportant applications. Considering economic and performance of cutting, plasma cutting can be used in most of machinery factories.

There are several kinds of plasma cutting, such as air plasma cutting, under-water plasma cutting and fine plasma cutting. The fine plasma cutting can be choice when desires high quality cutting which similar to laser cutting. With the benefits of low noise and dust, the under-water plasma cutting provides a friendly working environment. However, neither fine plasma cutting equipment nor under-water cutting equipment is more expensive than the cost of air plasma cutting machine. Water-air plasma cutting have the benefits of low cost and high cutting quality, which have a great future.

Based on the air plasma cutting power, the water-air plasma cutting has a unique design producing surround water curtain and additional plasma. A water injection port is located on the top of the torch, and water channel is arranged inside the torch, isolating from generation gas and protecting gas channels.

Under the gas pressure, the water flows out of the nozzle in the style of water curtain. An enclosed space surrounding by the torch nozzle, the work piece surface and the water curtain can prevent cutting metal pool from oxidation during cutting. The plasma arc is formed at the center of the nozzle under the action of high pressure and high temperature air. And the water will transfer to plasma when entering into the plasma region already existing.

1. Uvod

Način rezanja metala može se klasifikovati na termičko i hladno rezanje, u zavisnosti od toga da li se metal topi, pa tako rezanje plazmom pripada termičkom rezanju. Pre odabira metode sečenja neophodno je uzeti u obzir zahtevani kvalitet i troškove sečenja. Sa odličnim kvalitetom reza i visokom efikasnošću rezanja, lasersko sečenje i rezanje vodom pod visokim pritiskom primenjuju se u mnogim industrijama. Troškovi opreme su previsoki da bi se pomenute metode mogle široko koristiti. Za široku primenu se koristi mehaničko sečenje ili kiseonik-acetilen plazma. Uzimajući u obzir ekonomičnost i performanse sečenja, rezanje plazmom se može koristiti u većini mašinskih postrojenja.

Postoji nekoliko načina rezanja plazmom, kao što su vazdušno, podvodno i fino rezanje plazmom. Fino rezanje plazmom može biti izbor kada se želi visokokvalitetno rezanje slično laserskom rezanju. Uz prednosti niskog nivoa buke i prašine, rezanje pod vodom pruža prijatno radno okruženje. Međutim, oprema za fino rezanje plazmom i oprema za rezanje pod vodom nisu skuplje od troškova mašina za rezanje vazdušnom plazmom. Rezanje voda-vazduh plazmom ima prednosti zbog niske cene i visokog kvaliteta rezanja i zato ima sjajnu budućnost.

Zasnovano na snazi rezanja vazdušnom plazmom, rezanje voda-vazduh plazmom ima jedinstveni dizajn koji stvara vodena zavesa koja ujedno doprinosi i dodatnoj plazmi. Priključak za ubrizgavanje vode nalazi se na vrhu gorionika, dok je vodeni kanal postavljen unutar gorionika, izolujući od radnog gasa i štiteći gasne kanale.

Pod pritiskom gasa, voda izlazi iz mlaznice u vidu vodene zavese. Zatvoreni prostor koji okružuje mlaznica gorionika, površina radnog predmeta i vodena zavesa mogu sprečiti oksidaciju metalnog kupatila tokom sečenja. Luk plazme se formira u središtu mlaznice pod dejstvom visokog pritiska i vazduha visoke temperature. Voda prelazi u plazmu prilikom ulaska u već postojeći region plazme.

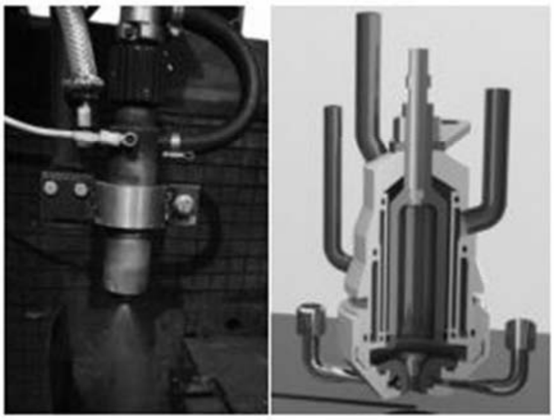

Figure 1. *The water-air plasma torch and its schematic diagram*

Slika 1. *Voda-vazduh plazma gorionik i njegov šematski diagram*

The water-air plasma cutting machine is consisting of power supply, control system, plasmatrons, water tank and motion mechanism. The range of power supply currents is 50 - 200A. The control system is used for controlling parameters of water-air cutting and process on the basis of the PLC-controller. The device has the capability to alternately switch on and operation of the plasma-tron on direct polarity with thermo-chemical cathode and plasmatron for operation on the reverse polarity with copper hollow "cold" electrode, which controlled by switching system integrated in control system.

It also can be regulate the exact dosage of water that as a plasma-forming medium to influence the energy and chemical parameters of the plasma, and regulate the exact dosage of water, to protect the reactive zone of the cut from atmospheric gases, to cool the edges, to reduce the cast zone of the cut, to reduce the harmful factors of the process. In order to implement an emergency stop algorithm, real-time analysis of emergency conditions is necessary.

2. Numerical model of water-air plasma cutting

The physical and chemical characteristics of low-temperature plasma (the temperature range of 103 to 2×104 ℃), a high- temperature air system consisted by atoms, free radicals, ions, electrons and free molecules with same temperature, are rapidly accelerating. The plasma producing during water-air plasma cutting is a kind of low-temperature plasma. The change laws of chemical composition of the reaction components over time can be reflected by founding chemical kinetic equations, which described the flow and interaction air of multi-component under static condition as follows.

Mašina za rezanje voda-vazduh plazmom se sastoji od napajanja, kontrolnog sistema, plazmatrona, rezervoara za vodu i mehanizma za kretanje. Raspon struja napajanja je od 50 do 200 A. Upravljački sistem se koristi za kontrolu parametara rezanja na bazi PLC-kontrolera. Uređaj ima mogućnost naizmeničnog uključivanja i rada plazmetrona na direktnom polaritetu sa termohemijskom katodom i rad na obrnutom polaritetu sa šupljom bakarnom “hladnom” elektrodom, gde se kontrola vrši preklopnim sistemom integrisanim u sistem upravljanja.

Takođe se može regulisati tačna količina vode, koja kao medij za formiranje plazme utiče na energetske i hemijske parametre plazme, radi zaštite reaktivne zone reza od atmosferskih gasova, zatim za hlađenje ivica, za smanjenje istopljene zone reza i za smanjenje drugih štetnih faktora procesa. Da bi se primenio algoritam hitnog zaustavljanja, neophodna je analiza hitnih stanja u realnom vremenu.

2. Numerički model sečenja voda-vazduh plazmom

Fizičke i hemijske karakteristike niskotemperaturne plazme (opseg temperatura od 10^3 do 2×10^4 °C) vezane su za visokotemperaturni vazdušni sistem koji se sastoji od atoma, slobodnih radikala, jona, elektrona i slobodnih molekula sa istom temperaturom, koji se velikom brzinom ubrzavaju. Plazma nastala tokom sečenja voda-vazduh plazmom je niskotemperaturna vrsta plazme. Promena sastava reakcionih komponenti tokom vremena može se objasniti postavljanjem kinetičkih jednačina višekomponentnih hemijskih reakcija pod statičkim uslovima koje opisuju protok i interakciju vazduha na sledeći način.

$$\frac{d(\rho WF)}{dx}=0 \quad (1)$$

$$\rho W\frac{dW}{dx}+\frac{dP}{dx}=0 \quad (2)$$

$$\rho W\frac{du}{dx}+\frac{d(PW)}{dx}+\rho W^2\frac{dW}{dx}+\frac{dQ}{dx}=0 \quad (3)$$

$$PV=\sum n_i RT \quad (4)$$

$$\frac{d(n_i W)}{dx}=\frac{dn_i}{dt} \quad (5)$$

Where ρ- air flow density; W- air flow velocity; x- air flow motion path coordinates; Fair flow (channel) cross-sectional area; Ppressure; U- the system internal energy; Q- the heat flow of reaction channel wall; nicomposition moles unit time passage channel cross-section.

When boundary value x=0, a set of new equations have acquired:

$$\rho WF=MG \quad (6)$$

$$\rho W^2+P=L \quad (7)$$

$$L=\rho_0 W_0+P_0 \quad (8)$$

Where G- integral constant, M- mass flow of gas, L- integral constant determined by initial conditions;

When the integral value transfer to total cross-sectional area, energy equation described by energy flow density in unit cross-sectional area as follow:

$$\rho WF\left(U+\frac{P}{\rho}+\frac{W^2}{2}\right)+QF=Q_0 \quad (9)$$

Where Q_0 - the integral constant represents the total energy of the system at the initial moment, $\left(U+\frac{P}{\rho}\right)$ the gas entropy of unit mass, which can be included by the following equation:

$$\rho WF\left(U+\frac{P}{\rho}\right)=\sum_{i=1}^{i} n_i\mu_i\left(U+\frac{P}{\rho}\right)=\sum_{i=1}^{i} n_i h_i(T) \quad (10)$$

Where n_i, $h_i(T)$, and μ_i - the molar fraction, enthalpy and density of components.

When use G $\sum_{i=1}^{i} n_i\mu_i$ which has no heat exchange with the reactor wall, the energy equation can be show as follow:

$$\sum_{i=1}^{i} n_i h_i(T)+\frac{GW^2}{2}=Q_0 \quad (11)$$

$$\frac{d(\rho WF)}{dx}=0 \quad (1)$$

$$\rho W\frac{dW}{dx}+\frac{dP}{dx}=0 \quad (2)$$

$$\rho W\frac{du}{dx}+\frac{d(PW)}{dx}+\rho W^2\frac{dW}{dx}+\frac{dQ}{dx}=0 \quad (3)$$

$$PV=\sum n_i RT \quad (4)$$

$$\frac{d(n_i W)}{dx}=\frac{dn_i}{dt} \quad (5)$$

gde je ρ - gustina protoka vazduha; W - brzina protoka vazduha; x - koordinate putanje kretanja vazdušnog toka; F - površina poprečnog preseka protoka vazduha (kanala); P - pritisak; U - unutrašnja energija sistema; Q - protok toplote kroz zid reakcionog kanala; n_i - molska koncentracija po jedinici vremena na poprečnom preseku.

Kada je granična vrednost x=0, dobija se set novih jednačina:

$$\rho WF=MG \quad (6)$$

$$\rho W^2+P=L \quad (7)$$

$$L=\rho_0 W_0+P_0 \quad (8)$$

gde je G - konstanta integrala, M - maseni protok gasa, L - konstanta integrala određena početnim uslovima.

Kada se integralisana vrednost prenese na ukupnu površinu poprečnog preseka, dobija se jednačina energije opisana gustinom protoka energije po jedinici površine poprečnog preseka:

$$\rho WF\left(U+\frac{P}{\rho}+\frac{W^2}{2}\right)+QF=Q_0 \quad (9)$$

gde je Q_0 integralna konstanta koja predstavlja ukupnu energiju sistema u početnom trenutku, $\left(U+\frac{P}{\rho}\right)$ entropija gasa jedinične mase, koja se može izrazizi sledećom jednačinom:

$$\rho WF\left(U+\frac{P}{\rho}\right)=\sum_{i=1}^{i} n_i\mu_i\left(U+\frac{P}{\rho}\right)=\sum_{i=1}^{i} n_i h_i(T) \quad (10)$$

Gde su n_i, $h_i(T)$ i μ_i molarna frakcija, entalpija i gustina komponenti.

Ako se sa G zameni izraz $\sum_{i=1}^{i} n_i\mu_i$ koji podrazumeva da nema razmene toplote sa zidom reaktora, jednačina energije može se prikazati na sledeći način

$$\sum_{i=1}^{i} n_i h_i(T)+\frac{GW^2}{2}=Q_0 \quad (11)$$

When consider the cross section of passageway (F) , the gas flow tare (W), and the flow continuity of each element, the volume of the reaction system changeing due to temperature, the changing of reaction moles, and ρ replaced by ratio $\frac{\sum n_i \mu_i}{V}$

$$\frac{dn_i}{dx} = \sum_{j=1}^{j} V_{ij} \left(\frac{1}{W}\right)^{q_j} \left(\frac{1}{F}\right)^{q_{j-1}} K_j(T) \prod_j (n_i) \qquad (12)$$

Where Vij- the stoichiometric coefficient of reaction equation when component i entering j ('+' indicates the reaction product and '-' indicates the starting material; $\prod_j (n_i)$ - the molar number product of reaction component during reaction *j* ; for cylindrical channels F = *const*.

When the initial conditions uslovi $n_i(0)=n^0_i$; $W(0)=W_0$; $P(0)=P_0$; $T(0)=T_0$; $F=Const$, which representing airflow velocity, pressure, and temperature, respectively, i i i a ,b ,c - the approximate coefficient of entropy depending temperature.

$$W(x) = \frac{L}{2G} - \sqrt{\left(\frac{L}{2G}\right)^2 - \sum n_i \cdot \frac{R \cdot T}{G}} \qquad (13)$$

$$P(x) = L - \frac{F}{G \cdot W} \qquad (14)$$

$$T(x) = \frac{-\sum b_i n_i + \sqrt{\left(\sum b_i n_i\right)^2 - 4\left[\sum a_i n_i - \frac{G}{2}\left(\frac{\sum n_i R}{PF}\right)^2\right]\left(\sum c_i n_i - Q_0\right)}}{2\left[\sum a_i n_i - \frac{G}{2}\left(\frac{\sum n_i R}{P \cdot F}\right)\right]} \qquad (15)$$

3. Materials and experimental procedure

In this study, 20 mm thick carbon steel was used as experimental metal. With the same cutting parameters (show in Tab. 1) and other situations, air plasma cutting and water-air plasma cutting had been implemented.

Kada se uzme u obzir poprečni presek prolaza (F), protok gasa (W) i kontinuitet protoka svakog elementa, zapremina reakcionog sistema koja se menja zbog temperature, promena koncentracije reagujućih substanci, i ρ zamenjen odnosom $\frac{\sum n_i \mu_i}{V}$, dobija se:

$$\frac{dn_i}{dx} = \sum_{j=1}^{j} V_{ij} \left(\frac{1}{W}\right)^{q_j} \left(\frac{1}{F}\right)^{q_{j-1}} K_j(T) \prod_j (n_i) \qquad (12)$$

gde je V_{ij} stehiometrijski koeficijent jednačine reakcije kada komponenta *i* ulazi u *j* gde '+' označava proizvod reakcije, a '-' označava polazni materijal; $\prod_j (n_i)$ je broj molarnih produkata reakcionih komponenti tokom reakcije *j*; za cilindrične kanale *F* je konstantno.

Kada su početni uslovi $n_i(0)=n^0_i$; $W(0)=W_0$; $P(0)=P_0$; $T(0)=T_0$; $F=Const$, što predstavlja brzinu protoka vazduha, pritisak, i temperaturu, respektivno. a_i, b_i, c_i su aproksimativni koeficijenti entropijski zavisne temperature.

$$W(x) = \frac{L}{2G} - \sqrt{\left(\frac{L}{2G}\right)^2 - \sum n_i \cdot \frac{R \cdot T}{G}} \qquad (13)$$

$$P(x) = L - \frac{F}{G \cdot W} \qquad (14)$$

$$T(x) = \frac{-\sum b_i n_i + \sqrt{\left(\sum b_i n_i\right)^2 - 4\left[\sum a_i n_i - \frac{G}{2}\left(\frac{\sum n_i R}{PF}\right)^2\right]\left(\sum c_i n_i - Q_0\right)}}{2\left[\sum a_i n_i - \frac{G}{2}\left(\frac{\sum n_i R}{P \cdot F}\right)\right]} \qquad (15)$$

3. Materijali i eksperimentalni postupak

U ovom istraživanju, kao eksperimentalni metal je korišćen ugljenični čelik debljine 20 mm. Sa istim parametrima sečenja (prikazano u Tab. 1) primenjeno je sečenje vazdušnom plazmom i voda-vazduh plazmom u različitim situacijama.

Table 1. *Cutting process parameters*

Tabela 1. *Parametri procesa sečenja*

Parameters name/Parametar	Air Cutting/ Vazdušno sečenje	Water-air Cutting/ Voda-vazduh sečenje
Cutting Current/Struja sečenja, A	70	70
Cutting velocity/Brzina sečenja, m min-1	0,16	0,16
Plasma-forming gas (air) pressure/Pritisak plazma formirajućeg gasa (vazduh), MPa	0,8	0,8
Plasma-forming gas (air) flow rate/Protok plazma formirajućeg gasa (vazduh), m3/min	25	25
Water flow rate /Protok vode, g/min	-	100

In order to evaluate the cutting quality, the perpendicularity of the cut, the surface roughness and the depth of the heat affected zone are choice as the main basis. The first parameter reflects the cutting accuracy, and the latter two parameters show the cleanliness of the cut surface, the tissue and chemical changes in the metal. With the help of macroscopic microscope, the cutting verticality of two kinds of incisions without any treatment had been researched. The tests of surface roughness of cutting were conducted by roughness meter.

To examine the microstructures of heat affect zone, the samples had to cut off in the transverse direction. Samples were first polished by using silicon carbide waterproof electro coated abrasive paper from CW400 to CW2000, and were then polished in 3.5μm diamond polishing liquid for 1 min, followed by etching in Concentrated nitric acid for 5 seconds. But to analysis the microstructures and chemical composition of incision, the tests of SEM and energy spectrum were necessary. The type of SEM equipment is FEI QUANTA 250.

4. Results and Discussion

The surface morphology of water-air plasma cutting is shown in Fig. 2

Izabrani parametri za procenu kvaliteta sečenja su okomitost reza, hrapavost površine i dubina zone pod uticajem toplote. Prvi parametar odražava tačnost sečenja, a sledeća dva parametra pokazuju čistoću površine reza, strukturu i hemijske promene u metalu. Uz pomoć makroskopskog pregleda svetlosnim mikroskopom istražena je vertikalnost rezanja dve vrste rezova bez dodatnog tretmana. Ispitivanja površinske hrapavosti rezanja izvedena su meračem hrapavosti.

Da bi se ispitale mikrostrukture zone uticaja toplote, uzorci su odsečeni u poprečnom smeru. Uzorci su prvo polirani upotrebom silicijum-karbid-vodootpornog elektro-obloženog abrazivnog papira od CW400 do CW2000, a zatim su polirani sa dijamantskom tečnošću za poliranje od 3,5 μm u trajanju od jednog minuta, nakon čega je sledilo pet sekundi nagrizanja u koncentrovanoj azotnoj kiselini. Za analizu mikrostruktura i hemijskog sastava reza bile su primenjene skening elektronska analiza - SEM i testovi energetskog spektra. Tip SEM opreme je FEI QUANTA 250.

4. Rezultati i diskusija

Morfologija površina voda-vazduh sečenja je prikazana na Sl. 2.

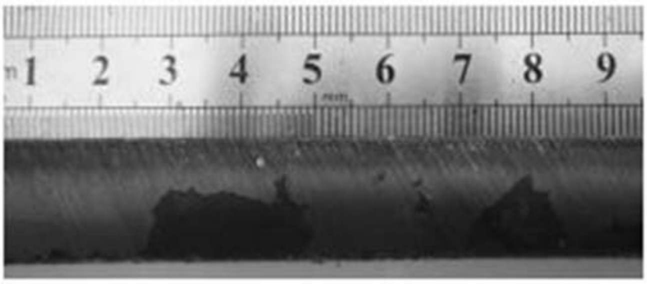

Figure 2. *The surface morphology of water-air plasma cutting*

Slika 2. *Morfologija površine voda-vazduh plazma sečenja*

The cutting sample section is show in Fig. 3 (a), and the cutting surface located at the top of sample is show in Fig. 3 (b). The length of straight section (L), the offset distance (D), the tilt angle (α) and the deflection angle (β) have been used for revealing cutting verticality. As we know from Tab. 2, the similar value has been acquired with two cutting methods, in other words, the main influencing factors of incision verticality are cutting current, cutting velocity, plasma-forming gas pressure and flow rate, but the function of water is limited which can be inferred from α and β. It can be concluded that only few water will transfer to plasma when cutting, and most of water keep the original status.

Deo sečenog uzorka prikazan je na slici 3(a), a presečena površina koja se nalazi na vrhu uzorka prikazana je na slici 3(b). Dužina ravnog preseka (L), udaljenost odstupanja (D), ugao nagiba (α) i ugao skretanja (β) su korišćeni su za određivanje vertikalnosti sečenja. Kao što se vidi iz Tabele 2, slične vrednosti su ostvarene za obe metode sečenja, drugim rečima, glavni faktori uticaja vertikalnosti reza su struja sečenja, brzina rezanja, pritisak gasa i protok gasova koji formiraju plazmu. Funkcija vode je ograničena, što se može zaključiti na osnovu rezultata za ugao nagiba (α) i ugao skretanja. Može se zaključiti da će se samo mali deo vode razgraditi u plazmu prilikom sečenja, a većina će se zadržati u prvobitnom stanju.

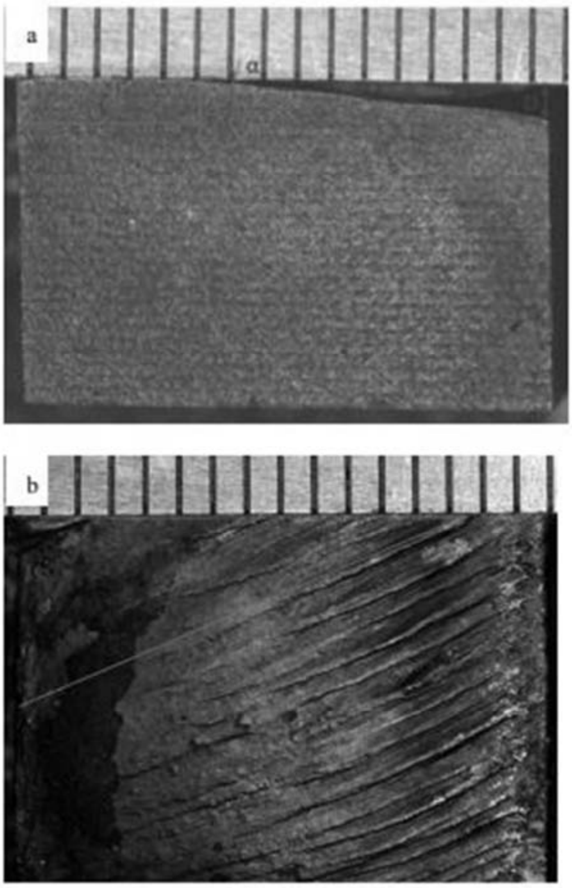

Figure 3. *The cutting sample section (a) and surface (b)*

Slika 3. *Deo sečenog uzorka (a) i površina (b)*

The incision surface roughness of air plasma cutting is Ra=24.19μm, but the incision surface roughness of water-air plasma is Ra=3.16μm which is more smoother than air plasma cutting. So the water vapor and its transformed plasma have an important interaction with cutting molten metal to improve the incision surface roughness. For further study, microstructure and elemental composition of incision surface had been studied by SEM.

Hrapavost površine reza pri sečenju vazdušnom plazmom je Ra = 24,19μm, dok je hrapavost površine reza vodeno-vazdušne plazme Ra = 3. 16 μm što je viša vrednost ravnosti u poređenju sa rezanjem vazdušnom plazmom. Vodena para i plazma formirana od vodene pare, imaju važnu interakciju sa istopljenim metalom tokom rezanja i utiču na smanjenje hrapavosti površine reza. Mikrostruktura i elementarni sastav površine reza je dalje analiziran pomoću SEM-a.

Table 2. *The verticality parameters*

Tabela 2. *Parametri vertikalnosti*

	Air cutting /Vazdušno sečenje	Water-air cutting/ Voda-vazduh sečenje
L/mm	5.5	5.3
D/mm	1.6	1.3
α/°	6.7	5.4
β/°	21.5	17.5

The incision surface results of specimens examined by SEM and energy spectrum (EDS) are shown in Fig. 4 and Fig. 5. The surface of the slit is relatively flat, and there is little difference between the parts' microstructure. In order to reflect the actual situation of water-air plasma cutting more accurately, three locations were picked up for EDX analysis (Fig. 4(a)), where contain at 9.09% ～ 10.32% C, at 48.97%～59.39% O and at 29.44%～40.76% Fe with atomic measurement, similar to the composition of base material.

It indicates that the surface of the cutting surface was less affected by oxidation under the protection of water curtain (Fig. 4(b)). The incision surface microstructure of air plasma cutting consists of rugged areas that attached with small particles (Fig. 5(a)). The position of point 2, which has universal characteristics, contains at 24.65% C, at 53.46% O and at 12.1% Fe show in Fig. 5(b). Compared with base material, there is a huge discrimination. It makes sure that oxide had formed on the surface of the slit. Some oxide will transfer to oxide inclusions in welds which was consider crack source when welding, and other oxide can increase the oxygen content leading pores during welding.

Rezultati analizirane površine reza uzoraka ispitivanih SEM-om i energetskim spektrom (EDS) su prikazani na slikama 4 i 5. Površina reza je relativno ravna i postoji mala razlika u mikrostrukturi. Da bi se tačnije prikazala stvarna situacija posle sečenja voda-vazduh plazmom, tri lokacije su uzete za EDX analizu (slika 4 (a)), gde je hemijski sastav analiziranih lokacija sledeći: 9,09 ～10,32 %C, 48,97～59,39 %O, i 29,44～40,76 %Fe u atomskim procentima, što je slično sastavu osnovnog materijala.

To ukazuje da je rezna površina pod zaštitom vodene zavese bila manje pod uticajem oksidacije (slika 4 (b)). Mikrostruktura površine reza pri rezanju vazdušnom plazmom sastoji se od neravnih područja sa prisustvom malih čestica (slika 5 (a)). Položaj tačke 2 na slici 5 (b), koja ima univerzalne karakteristike, sadrži 24,65% C, 53,46% O i 12,1% Fe. U poređenju sa osnovnim materijalom postoji velika razlika. To ukazuje na formiranje oksida na površini reza. Neki oksidi će preći u oksidnu nečistoću zavarenog spoja, što se smatra izvorom prslina prilikom zavarivanja, dok drugi oksidi mogu povećati sadržaj kiseonika u porama tokom zavarivanja.

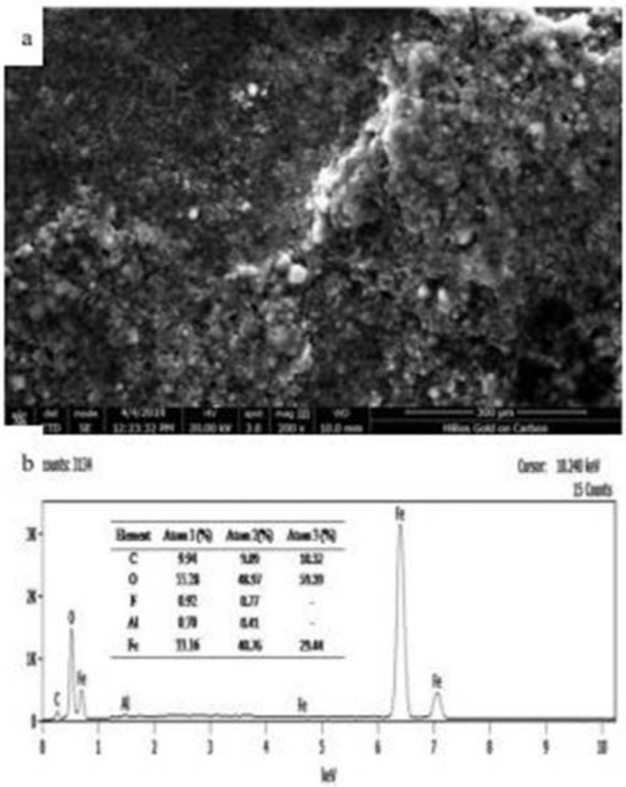

Figure 4. *The water-air plasma cutting sample surface microstructure (a) and Energy spectrum (b)*

Slika 4. *Površinska mikrostruktura (a) i energetski spektar (b) uzorka presečenog voda-vazduh plazmom*

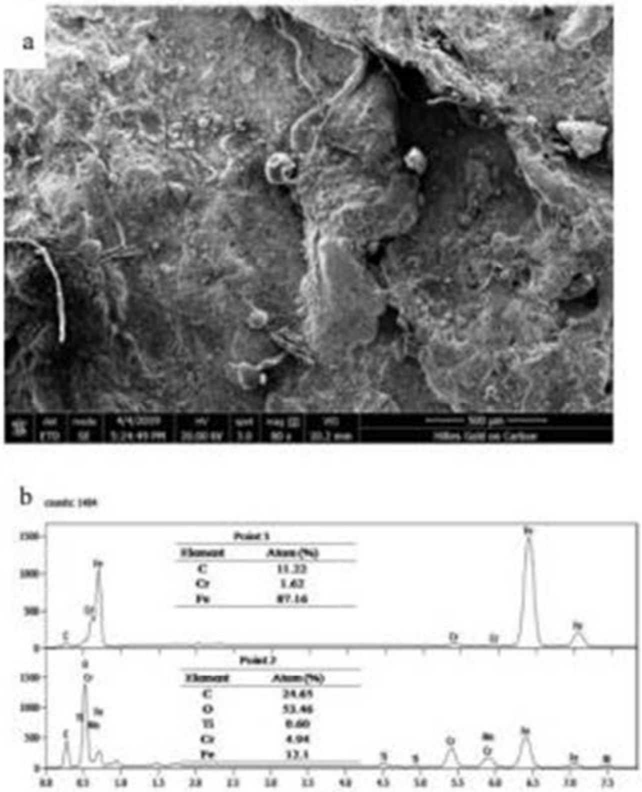

Figure 5. *The air plasma cutting sample section microstructure (a) and Energy spectrum (b)*

Slika 5. *Mikrostruktura (a) i energetski spektar (b) uzorka presečenog vazdušnom plazmom*

Through the analysis of the metallographic of the cut section, the results show that the thickness of nitride layer produced by air plasma cutting is 0.016 mm, while no nitride layer has been found after water-air plasma cutting; the thickness of heat affected zone caused by air plasma cutting is more than 0.65 mm, and the thickness of heat affected zone resulting in water-air plasma cutting is less than 0.45 mm. With the additional water vapor, it effectively avoids the formation of nitride layers and reduces the extent of the heat affected zone. The nitrogen content exceeds the partial pressure of nitrogen in the gas, even exceeding the solubility of nitrogen in the metal. Because the solubility of nitrogen in the molten metal during cutting is high, nitrogen cannot overflow from the metal in time under rapid cooling conditions, and nitrogen is stay in the solidified metal. This is an important factor leading to the production of pores. When choice the plates cutting by water-air plasma method, no additional processing required before welding, which decrease the time of processing and cost.

Metalografska analiza preseka rezne zone pokazuje da je debljina sloja nitrida proizvedenog vazdušnim rezanjem plazmom 0,016 mm, dok nakon rezanja voda-vazduh plazmom nije pronađen nijedan sloj nitrida. Debljina zone pod uticajem toplote dobijena rezanjem vazdušnom plazmom je veća od 0,65 mm, a debljina zone pod uticajem toplote koja je dobijena rezanjem voda-vazduh plazmom je manja od 0,45 mm. Sa dodatnom vodenom parom efikasno se izbegava stvaranje nitridnih slojeva i smanjuje se veličina zone uticaja toplote. Sadržaj azota premašuje parcijalni pritisak azota u gasu, čak premašujući rastvorljivost azota u metalu. Pošto je rastvorljivost azota u rastopljenom metalu tokom sečenja velika, azot ne može na vreme da disocira iz metala usled velike brzine hlađenja, pa azot ostaje u očvrslom metalu. Ovo je važan faktor koji dovodi do stvaranja šupljina. Pri izboru rezanja ploča metodom vodeno-vazdušne plazme, nije potrebna dodatna obrada pre zavarivanja, što smanjuje vreme obrade i troškove.

5.Concluding remarks

We investigated carefully the differences of incision surfaces used air plasma cutting and water-air plasma cutting, and revealed that: (a) only little water transfer to plasma when water-air plasma

5. Zaključne napomene

Pažljivo su istražene razlike na reznim površinama koje su nastale rezanjem vazdušnm plazmom i voda-vazduh plazmom i otkriveno je da: (a) samo malo vode prelazi u plazmu kod rezanja voda-cutting and most of water keeps the original status, which have almost no influence on the cutting verticality, but significant to incision roughness; (b) the surface of the water-air plasma cutting surface was less affected by oxidation under the protection of water curtain, but a lot of oxide had formed on the surface of the air plasma incision; (c) it effectively avoids the formation of nitride layers and reduces the extent of the heat affected zone

vazduh plazmom, dok većina vode zadržava prvobitno stanje. To nema gotovo nikakav uticaj na vertikalnost sečenja, ali je značajno za hrapavost reza; (b) površina uzorka presečenog voda-vazduh plazmom pod zaštitom vodene zavese je bila manje izložena oksidaciji, ali je na površini reza uzorka presečenog vazdušnom plazmom nastalo puno oksida; (c) voda-vazduh plazma efikasno sprečava stvaranje nitridnih slojeva i smanjuje veličinu zone pod uticajem toplote.

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