APEM journal
Advances in Production Engineering & Management
Volume 12 | Number 2 | June 2017 | pp 105–114
https://doi.org/10.14743/apem2017.2.243
ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Analysis of corrosion resistance when turning martensitic stainless steel X20Cr13 under chilled air-cooling

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ABSTRACT

Amongst different methods of cooling in machining, application of air is considered to be the cleanest and most environmentally friendly one. The aim of this paper was to explore the possibility of chilled air-cooling considering the corrosion resistance when turning martensitic stainless steel X20Cr13. Thus, a comparison between an alternative cooling technique where compressed air is refrigerated and jetted to the cutting zone by means of Ranque-Hilsch counter-flow vortex tube and the conventional flood cooling with oil-in-water emulsion was done. The corrosion resistance was determined by electrochemical testing and the surface condition was analysed with both Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS). From the results presented herein, it can be concluded that the specimen cooled with chilled air has better resistance to corrosion activity after a certain longer time in relation to the specimen cooled with emulsion. In addition, the specimen cooled with chilled air has lower surface roughness, which has a positive effect on the corrosion resistance. Hence, in the scope of environmentally friendly machining the vortex tube based chilled air-cooling can be successfully applied when turning difficult-to-cut martensitic stainless steel.

ARTICLE INFO

Keywords:
Turning
Stainless steel X20Cr13
Corrosion resistance
Chilled air-cooling
Vortex tube

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Article history:
Received 3 February 2017
Revised 20 April 2017
Accepted 24 April 2017

1. Introduction

Stainless steels are notable for their corrosion resistance. The machinability of stainless steels is substantially different from that of carbon or alloy steels and other metals and they are commonly known as difficult-to-cut materials. The use of cutting fluids is generally advised in machining of stainless steels in order to overcome their work-hardening tendency as well as low thermal conductivity that restricts the heat flow away from the machined surfaces. Overheating of stainless steel surface during machining, characterised by the formation of heat tinting colours, must be avoided since the corrosion resistance can be deteriorated. At issue, pickling the surface can be used to restore corrosion resistance on the finished workpiece. Another reason that cutting fluids are usually necessary for cutting stainless steels is their tendency of forming the long chips, which adhere to the tool rake face and frequently form built-up edge leading to a poor surface finish. Flood supplied oil-in-water emulsions are normally used for machining at higher cutting speeds with carbide tooling. To allow self-passivation of the stainless steel surfaces, all traces of the cutting fluid should be removed from the workpiece after machining [1].

The growing challenge in industry is to do machining in a green environment without sacrificing the machining performance. Conventional liquid cutting fluids in so-called wet machining

create several health and environmental problems. Especially, their degradation and ultimate disposal are the main difficulties. Therefore, using the gas as a coolant may work as an alternative to conventional liquid coolants in wet machining. Nowadays, the most exploited gases in gas-cooled machining are air, carbon dioxide and nitrogen. The air is a free natural resource readily available everywhere and without any chemical exposure risks to humans or the environment. In addition, there are no coolant disposal problems and associated costs since the air is merged into the atmosphere. Amongst available methods of cooling in machining, application of air is recognized to be the cleanest and most environmentally friendly one [2].

Numerous firms have implemented chilled air-cooling as an alternative cooling method, achieving different benefits in substituting conventional liquid cutting fluids supplied by flooding. An environmentally chilled air supply can be performed by vortex tube for cooling and jetting the compressed air to the cutting zone, by thermoelectric air cooler or by cryogenic compressed air cooler [3].

Ranque-Hilsch vortex tube, or simply vortex tube, is a mechanical device that is used for simultaneous generation of cold and hot air streams out of a single source of compressed air. Furthermore, the cost of a vortex tube with accessories is between 500-1000 €, so it is reasonably priced for small manufacturing firms [4]. Generally, it can be claimed that such a system is able to deliver thermal cooling performance very much comparable to conventional liquid coolants and produces better machining performance compared to dry machining without any cutting fluid [5]. In turning hypereutectic Al-Si alloys chilled air in comparison to dry machining reduces the flank wear depending upon cutting conditions (up to 20 %), the temperature in the tool-chip interface (up to 7 %) and cutting forces mostly owing to lessening of adhesion and built-up edge [6]. In hard turning of Ti6Al4V titanium alloy, chilled air-cooling in comparison to dry machining simply generates the wrinkled and breaking chips, provides significantly lower cutting temperature (up to 57.1 %), diminishes the tool wear and decreases the average value of surface roughness (up to 27.6 %) [7]. In soft materials end milling, the values of surface roughness for chilled air-cooling are lesser than those in dry machining and are greater than those in conventional wet machining (flood cooling) while the values of flank wear for chilled air-cooling are near to those in conventional wet machining [8]. Similar results of the conducted investigations in milling and hard milling of 42CrMo4 steel also confirmed high efficiency of the chilled air-cooling not only in comparison with dry machining, but also in comparison with conventional flood cooling using liquid cutting fluids [9, 10]. In milling of carbon fibre reinforced plastic (CFRP), the tool life prolongation when utilizing chilled air as a replacement for dry machining is from 12.1 % at lowest cutting speed and feed to 45.6 % at highest cutting speed and feed with the improvement of delamination factor too [11]. In cylindrical grinding of spindle shaft materials SCM4 and SCM21, chilled air-cooling can reduced both the resulting compressive residual stresses at the workpiece surface and the surface roughness [12]. Hence, apart from its environment friendliness option, vortex tube based chilled air-cooling systems find application in machining difficult-to-cut materials.

Heat removal, i.e. cooling is one of the most significant roles of a cutting fluid. More efficient removal of heat leads to better tool life and dimensional accuracy of workpiece. In comparison to oil, water possesses greater capacity for removing the heat. Yet, water causes corrosion on the freshly machined metal, which is a nuisance for both user and manufacturer of water miscible cutting fluids. Corrosion inhibitors are an integral part of their formulations with purpose to prevent corrosion on workpieces, machine tool parts and tools made of metals. However, corrosion can also appear in dry machining since it occurs not only due to use of water miscible cutting fluids [13]. Consequently, it is worth to study the influence of chilled air-cooling during the cutting process on the corrosion resistance of a machined surface. It should be noted that, according to the data available to the authors of this study, there are no professional or scientific papers on this topic so far.

Therefore, the objective of this paper was to compare alternative chilled air-cooling vs. conventional flood cooling considering the corrosion resistance when turning martensitic stainless steel X20Cr13. Flood cooling was carried out by the commercial oil-in-water emulsion and chilled air was generated by Ranque-Hilsch counter-flow vortex tube. Selection of the test mate-

rial was done bearing in mind that the martensitic stainless steels have the highest strength but also the lowest corrosion resistance in comparison with the austenitic and ferritic grades of stainless steels [14]. The presented results show that environmentally friendly turning of the martensitic stainless steel can be performed and ecological burden of conventional flood cooling can be eliminated.

2. Electrochemical testing of corrosion resistance

In standard EN ISO 8044:1999 [15], corrosion is defined as "physicochemical interaction between a metal and its environment, which results in changes in the properties of the metal, and which may lead to significant impairment of the function of the metal, the environment, or the technical system of which these form a part". Corrosion resistance is a property of the material resistance to the action of the surrounding medium, which means that the corrosion more stable material is the one in which, in the same external conditions, there is less intensive destruction on the surface, or less undesirable changes in microstructure [16].

Corrosion resistance of material can be determined by using different methods. Responsiveness to low corrosion rates, short experimentation and well-founded theory are the main advantages of electrochemical techniques. Measurements of an electrochemical potential is one of the more basic measurements in electrochemistry. In testing practice, a basic polarization cell is used consisting of an electrolyte solution, a working electrode (metal specimen whose corrosion rate should be defined), a reference electrode (saturated calomel electrode) and an auxiliary electrode (made of platinum or graphite). The electrodes are connected to a potentiostat, which enables both the controlled changes of the metal specimen potential (voltage) and the current flows measurements as a function of potential.

As a rule, corrosion potentials pertain to open circuit (no current flow) measurements. In corrosion literature, the open circuit potential and the corrosion potential are used interchangeably. It takes a certain amount of time for a specimen in a given electrolyte to reach a stable corrosion potential at which the cathodic reduction rate is equal to the anodic dissolution rate (metal corrosion). Corrosion measurements should be made only after the stable corrosion potential has been reached [17].

Corrosion potential is used as a criterion for the corrosion behaviour. During the open circuit measurements, potential vs. time of exposure plot can be obtained. Positive values of corrosion potential indicate the specimen stability in the test electrolyte, negative values indicate dissolution (corrosion), and if the values change from negative towards positive ones, then a spontaneous passivation of specimen occurs. In addition, the specimen with lower corrosion potential will dissolve faster in the test electrolyte.

Tafel extrapolation method [18] is probably the most commonly used polarization-testing method for measuring corrosion rate and a wide variety of functions. It relies greatly on the determination of so-called Tafel lines from cathodic and anodic polarization branches represented in E-log j plot where E is the applied potential and j is the applied current density. The intersection of both extrapolated Tafel lines determines the value of corrosion potential E_{corr} and the corrosion current density j_{corr}, Fig. 1. Once j_{corr} is known, it is possible to define the corrosion rate.

The base of Tafel extrapolation method is Butler-Volmer equation, which designates the dependence of the current density at an electrode on its potential, assuming that both reactions (a cathodic and an anodic) take place on the same electrode:

$$j = j_a + j_c = j_{corr}\left[e^{\frac{(1-\alpha)zF\eta}{RT}} - e^{\frac{-\alpha zF\eta}{RT}}\right] \tag{1}$$

where j_a and j_c are the individual anode and cathode current densities respectively, α is the transfer coefficient, z is the number of electrons included in the electrode reaction, F is the Faraday constant, R is the universal gas constant, T is the absolute temperature and $\eta = E - E_{corr}$ is the

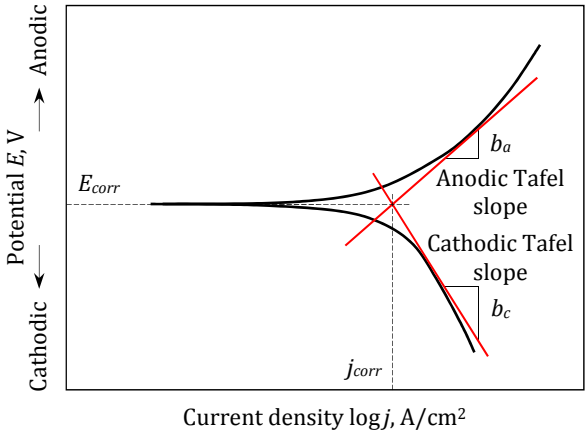

Fig. 1 A schematic illustration of the Tafel extrapolation method

activation overpotential. For $E >> E_{corr}$ the Butler-Volmer equation simplifies to the Tafel equation for the anodic reaction:

$$\eta = a_a + b_a \log i \tag{2}$$

Analogously, for $E << E_{corr}$ the Tafel equation for the cathodic reaction is:

$$\eta = a_c - b_c \log i \tag{3}$$

Constants (a_a, a_c) and slopes (b_a, b_c) of anodic and cathodic Tafel lines are given as follows:

$$a_a = -\frac{2{,}303RT}{(1-\alpha)zF}\log i_{corr}\,;\; b_a = \frac{2{,}303RT}{(1-\alpha)zF};\; a_c = \frac{2{,}303RT}{\alpha zF}\log i_{corr}\,;\; b_c = \frac{2{,}303RT}{\alpha zF} \tag{4}$$

3. Vortex tube cooling

Georges J. Ranque, a French physics student, invented the vortex tube by accident in 1928. He made a number of efforts to commercialise the technology including a patent in 1934. However, the technology only became widely known after a German physicist, Rudolph Hilsch published a scientific paper in 1945 entitled Wirbelröhre (literally, vortex tube). Hence the name Ranque-Hilsch vortex tube.

Vortex tube is a mechanical device that splits a compressed air into cold and hot streams. In the vortex tube, supplied compressed air flows throughout tangentially arranged nozzles to an internal counter bore. The nozzles cause a vortex motion of the air. This spinning stream of air turns 90° and flows down the tube like a spinning shell, similar to a tornado. An amount of the heated air escapes through a valve at hot end of the tube. The remained air moves back in the form of a second vortex located within the low-pressure area of the larger vortex. The internal vortex cools down and releases at cold end of the tube. The hot stream of air can attain temperature of 100 °C while the cold stream of air can reach even −50 °C. Fig. 2 shows a schematic view of such counter-flow Ranque-Hilsch vortex tube. A parallel vortex tube (due to airflow) is also available, but the efficiency is lower.

Since it is very simple, compact, light and quiet, the vortex tube can be used as cooling equipment of CNC machine tools. Furthermore, there are no moving parts to be broken or worn out and hence the vortex tube needs slight servicing [19]. The vortex tube fits well the cooling requirements of cutting tools. A fast cold stream of air ensures cooling as well as removal of the "chip" that is produced by the tool. Besides, compressed air can be found in every machine shop.

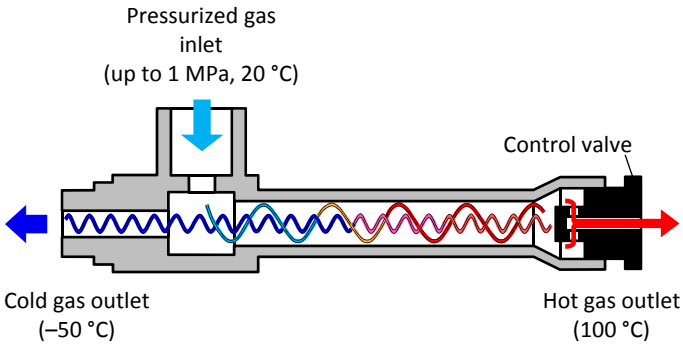

Fig. 2 Ranque-Hilsch counter-flow vortex tube – scheme of working principle

The major disadvantage is the lack of lubrication, which can be replaced by choosing appropriate tools coated with self-lubricating coatings that enable machining in these conditions [9, 20]. In addition, it requires a high airflow rate and a compressor of large capacity to back up the cooling action of the vortex tube [3].

4. Experimental work

Experimental research included both the corrosion testing and the surface analysis of the material prior and after machining.

For the electrochemical corrosion testing, three specimens from the martensitic stainless steel X20Cr13 with hardness of 272 HB were prepared. The chemical composition of test material is specified in Table 1. First specimen was in the basic (un-machined) condition and marked OS. The second one was machined using the flood cooling with oil-in-water emulsion INA BU 7 and marked EM. The third one was machined using the chilled air-cooling by means of the Ranque-Hilsch counter-flow vortex tube Nex Flow™ Frigid-X Cooler System c/w 57025AD with an inlet air pressure of 0.69 MPa and marked VO. The experiments were performed on the CNC lathe Prvomajska TU 360 in the Laboratory for Machining Processes at the University of Rijeka, Faculty of Engineering. The selected cutting parameters were: cutting speed v_c = 220 m/min, feed rate f = 0.3 mm/rev and depth of cut a_p = 0.4 mm. The workpiece diameter for turning with cutting inserts SECO DNMG 150608-MF-4 TP 2501 was Ø80 mm × 463 mm.

Table 1 Chemical composition of martensitic stainless steel X20Cr13

Chemical element	Fe	C	Si	Mn	P	S	Cr	Mo	Ni	V	Nb	Cu
%	85.85	0.236	0.352	0.683	0.044	0.023	11.97	0.125	0.299	0.053	0.07	0.195

Electrochemical testing of corrosion rate was carried out in the Laboratory for Chemical Testing at the University of Rijeka, Faculty of Engineering. Two methods were applied: open circuit potential vs. time of exposure measurements and Tafel extrapolation. The PARSTAT 2263 potentiostat and the PowerSuite software were used. Electrolyte was 3.5 % aqueous solution of NaCl.

The corrosion potential (open circuit potential) was determined for the first specimen (OS) and then the corrosion current density required for defining the corrosion rate was obtained by the Tafel extrapolation method. The same procedure was repeated for the second specimen (EM) and the third specimen (VO).

To gain insight into the surface condition of the specimens after corrosion testing, two analytical techniques were applied: Scanning Electron Microscopy (SEM) using VEGA TS 5136 MM microscope and Energy Dispersive X-ray Spectroscopy (EDS) using Oxford Instruments Si(Li) INCA X-sight device. Surface analysis of specimens was performed in the Laboratory for Materialography at the University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture. In addition, the achieved surface roughness was measured using Hommel Tester T1000 measuring device.

5. Results and discussion

5.1 Corrosion testing

Open circuit potential vs. time of exposure summary plot as well as polarization behaviour summary plot for all three specimens (OS, EM and VO) in electrolyte are given in Fig. 3 and Fig. 4 respectively. Table 2 demonstrates the results of the Tafel extrapolation method.

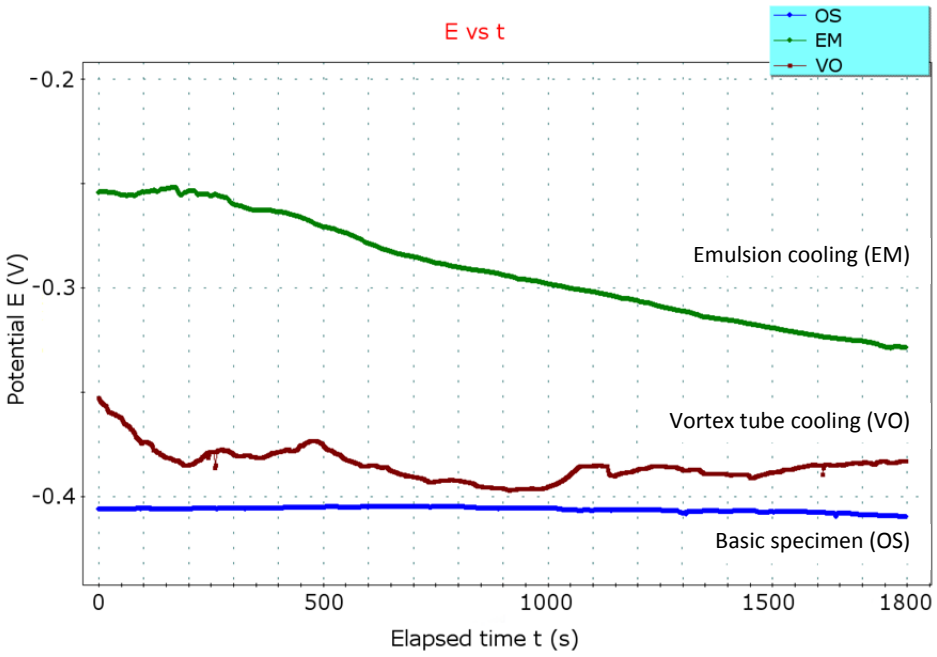

Fig. 3 Open circuit potential vs. time of exposure for specimens in 3.5 % aqueous solution of NaCl

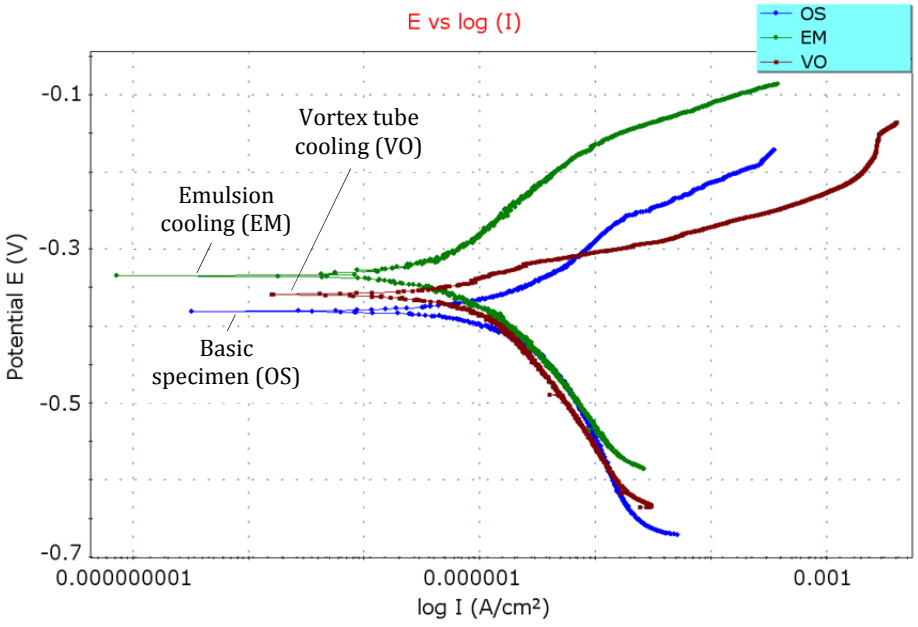

Fig. 4 Polarization behaviour for specimens in 3.5 % aqueous solution of NaCl

Table 2 Results of corrosion testing obtained by the Tafel extrapolation method

Specimen	E_{corr} [mV]	j_{corr} [mA/cm²]	b_a [mV]	b_c [mV]	Corrosion rate [mm/year]
OS	-380.736	1.94	106.705	241.747	0.0218
EM	-332.724	0.555	131.619	153.754	0.00625
VO	-359.706	3.56	208.859	458.957	0.04

Test results show that the corrosion potential of the basic specimen (OS) is stable and there are no major deviations. In addition, the value of the corrosion potential of this specimen is the most negative of all three observed specimens, which indicates the lowest corrosion resistance. The emulsion-cooled specimen (EM) during the turning operation demonstrates in the beginning the value of the corrosion potential nearest to zero and consequently better corrosion properties in comparison with other specimens. This can be explained by the presence of the oil film, which after a while "break down" and then the corrosion resistance of the specimen decreases (curve *E-t* tends to fall). The vortex tube cooled specimen (VO) during the turning operation indicates slight decline of *E-t* curve at the beginning of measurement and then, after a time, the creating of protective layer increases the corrosion resistance (curve *E-t* on an uptrend). To end with, the Tafel extrapolation method obtained slightly higher corrosion rate of the vortex tube cooled specimen in comparison to the emulsion-cooled specimen.

5.2 Surface analysis

The images of surfaces for the specimens without and after exposure to the electrolyte taken by the scanning electron microscope are presented in Fig. 5 and Fig. 6 respectively. The results of EDS analysis for identification of specific chemical elements and their proportions within observed surfaces on specimens are presented in Fig. 7, Fig. 8 and Fig. 9.

With respect to the basic specimen (i.e. un-machined), the analysis results show the difference in surface condition considering the presence of chemical elements. The surface of the specimen that was not exposed to the electrolyte (Fig. 7a) contains chemical elements that are in

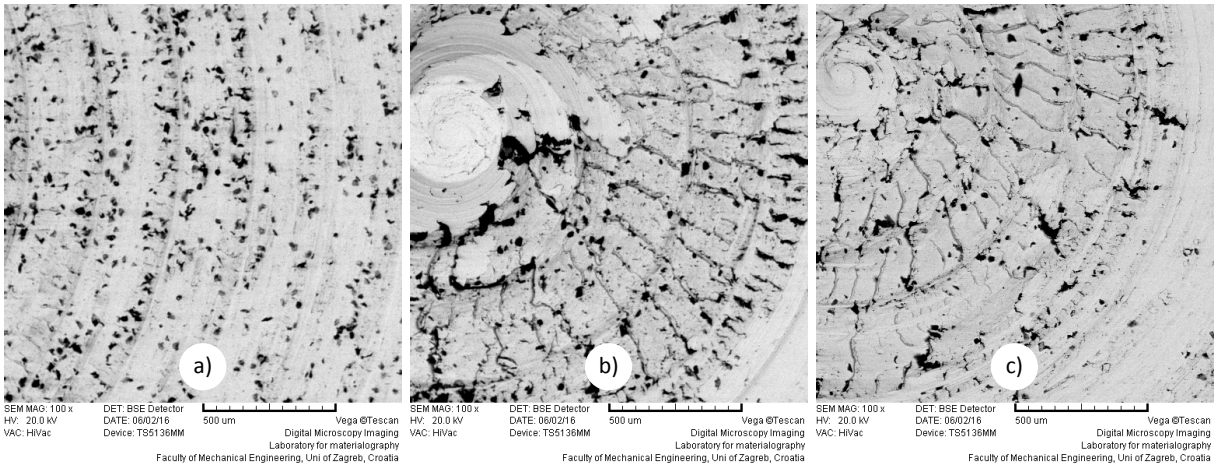

Fig. 5 Images of surfaces for the specimens without exposure to the electrolyte: a) basic specimen, b) emulsion-cooled specimen, c) vortex tube cooled specimen

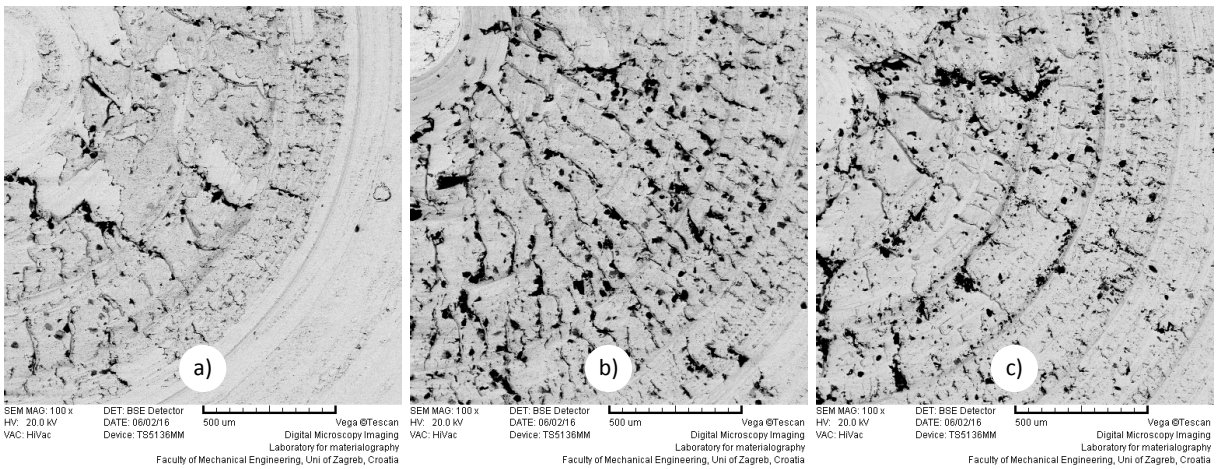

Fig. 6 Images of surfaces for the specimens after exposure to the electrolyte: a) basic specimen, b) emulsion-cooled specimen, c) vortex tube cooled specimen

the chemical composition of the test material X20Cr13. However, the surface of the specimen that was in the electrolyte (Fig. 7b) shows the presence of other chemical elements, such as oxygen (O) and sodium (Na), because of the electrolyte composition.

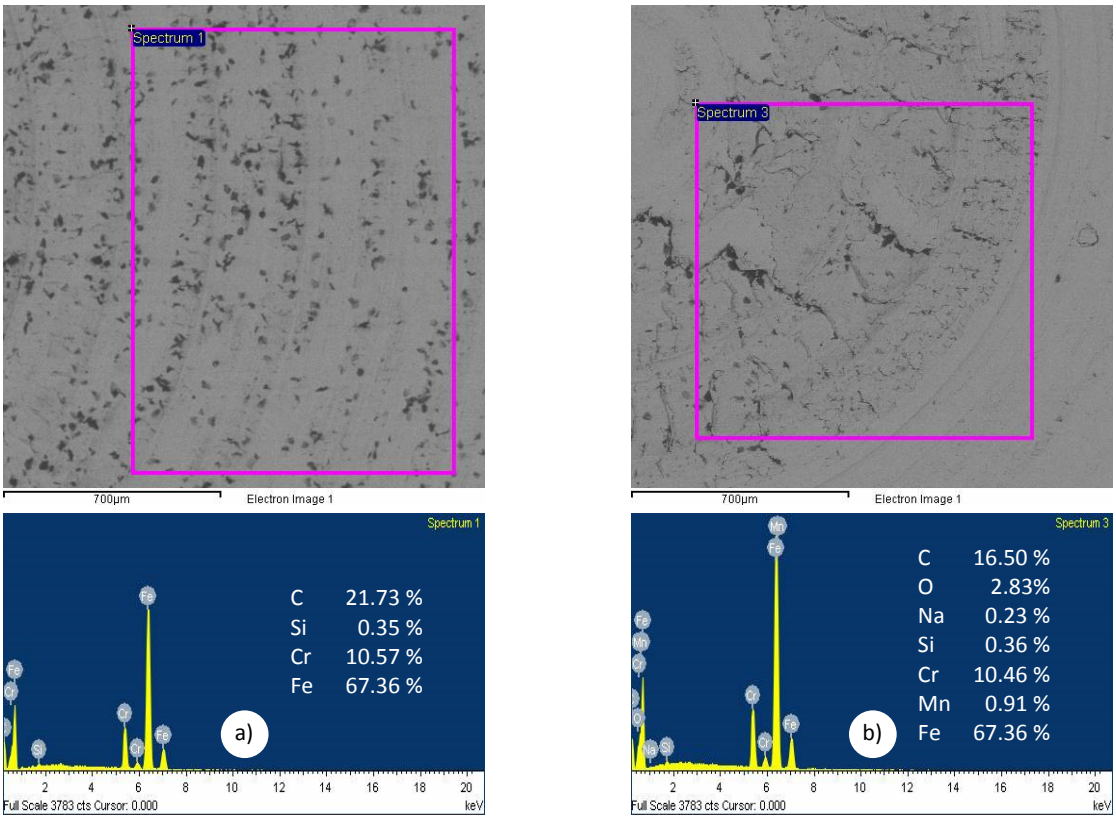

Fig. 7 EDS analysis of basic specimen: a) without and b) after exposure to the electrolyte

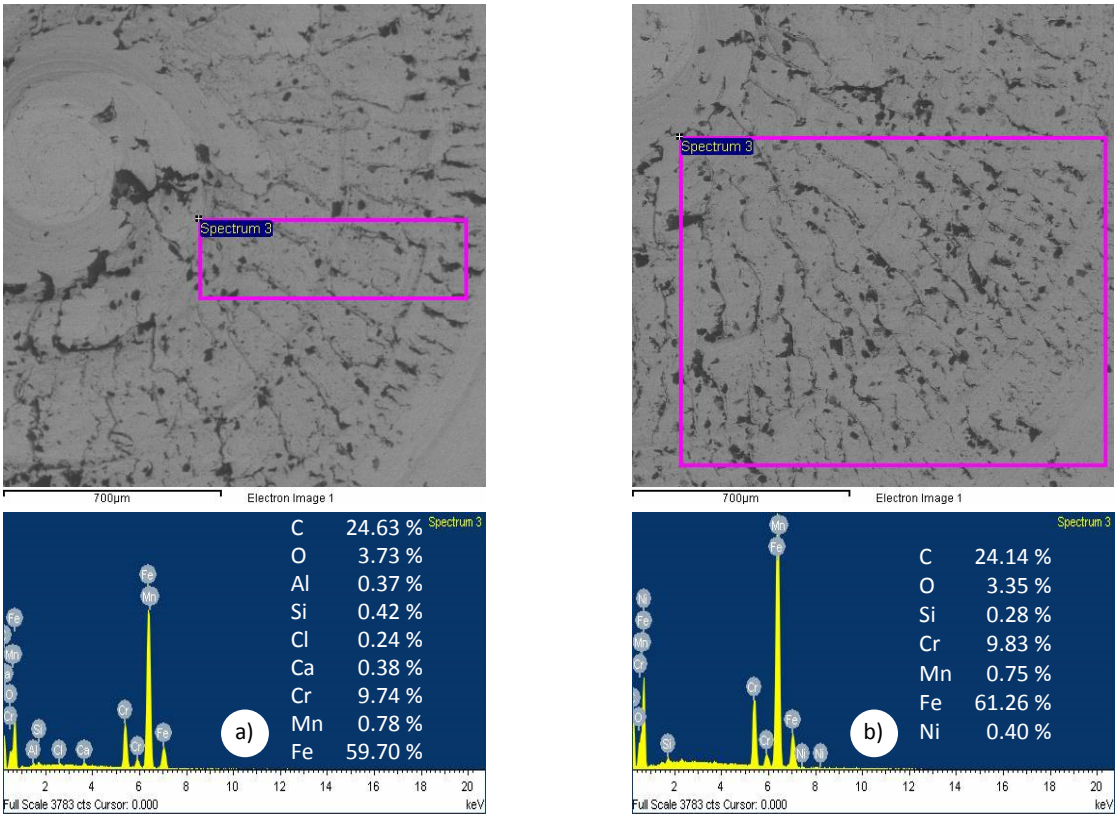

Fig. 8 EDS analysis of emulsion-cooled specimen: a) without and b) after exposure to the electrolyte

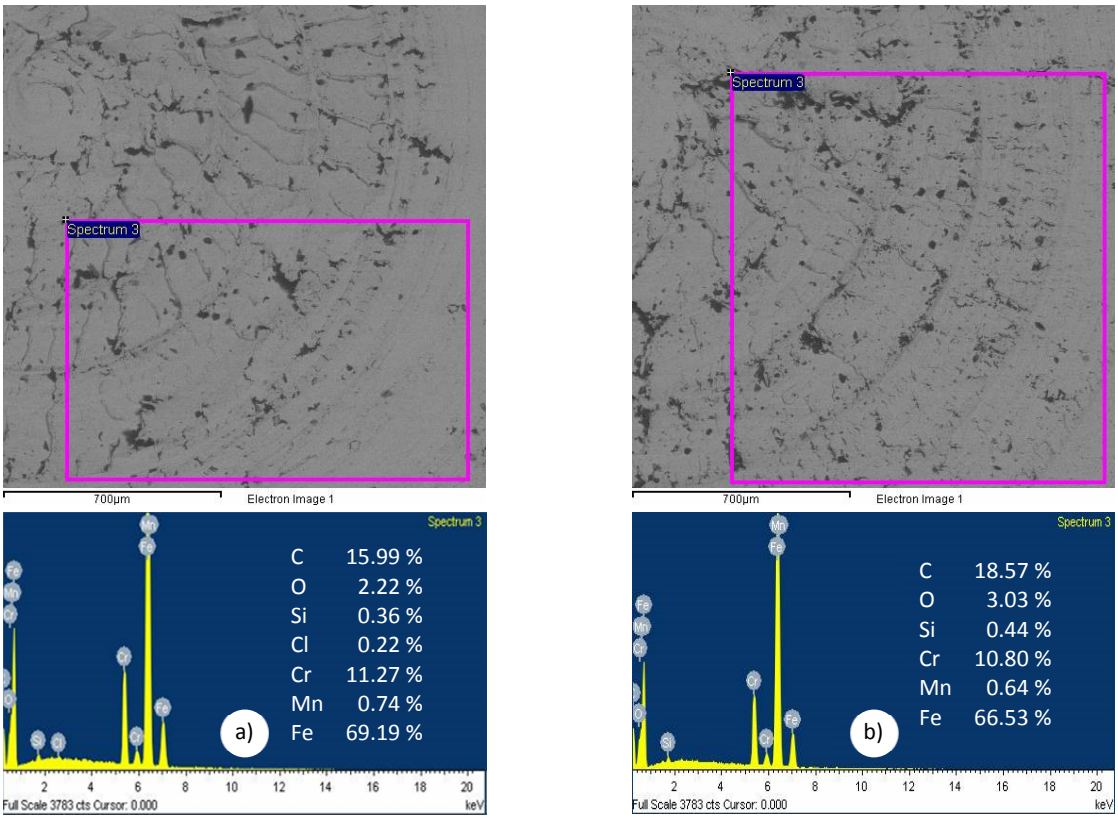

Fig. 9 EDS analysis of vortex tube cooled specimen: a) without and b) after exposure to the electrolyte

The surface of the emulsion-cooled specimen during turning operation that was not exposed to the electrolyte (Fig. 8a) contains other chemical elements in addition to the ones that are part of the test material. Here it should be highlighted the presence of calcium (Ca), probably from the emulsion composition. Surface analysis of the specimen that was in the electrolyte (Fig. 8b) also shows the presence of oxygen (O) and nickel (Ni).

The surface of the vortex tube cooled specimen during turning operation that was not exposed to the electrolyte (Fig. 9a) comprises basic chemical elements with the addition of oxygen (O), due to type of cooling. Specimen that was in the electrolyte (Fig. 9b) contains a slightly higher percentage of oxygen (O).

Finally, the vortex tube cooled specimen surface has lower mean roughness in comparison to the surface of emulsion-cooled specimen ($Ra_{(VO)}$ = 1.576 µm vs. $Ra_{(EM)}$ = 1.645 µm), which has a positive effect on the corrosion resistance. The corrosion resistance is better for lesser value of surface roughness.

6. Conclusion

The conducted study provides valuable insights on the possibility of applying Ranque-Hilsch counter-flow vortex tube based chilled air-cooling instead of the conventional flood cooling with oil-in-water emulsion considering the corrosion resistance when turning martensitic stainless steel X20Cr13. The most interesting finding stands out: the specimen cooled with chilled air has better resistance to corrosion activity after a certain longer time in relation to the specimen cooled with emulsion, probably due to creation of a protective layer. This phenomenon requires more research effort. It should be pointed out that the use of chilled air-cooling can be recommended when turning given material, especially in view of lower achievable surface roughness values in comparison to the conventional flood cooling. This recommendation should be taken into account regarding the environmental aspects of machining. Since the cooling medium is air, there are no chemical exposure risks to humans or the environment.

In further research, it is suggested to establish the mathematical model between the corrosion resistance and the surface roughness of the tested material considering different cooling techniques. In addition, their impact on the tool life needs to be examined as well as the economic viability of introducing the chilled air-cooling. Finally, the optimization of cutting parameters, namely cutting speed, feed rate and depth of cut, would also be welcomed.

Acknowledgement

This work was financially supported by the University of Rijeka, Croatia, No. 13.09.1.2.10.

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