“The effect of surface preparation on high temperature oxidation of Ni, Cu and Ni-Cu alloy”

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Abstract

In the present paper, the analysis of polishing, grinding and sand-blasting processes on oxidation behavior of nickel, copper and nickel-copper alloy has been investigated. Surface roughness has been measured using two methods: by contact profilometer and by fractal analysis. It has been proved that sand-blasting process influences the surface roughness the most but also contaminates the surface with alumina particles. The oxidation tests were performed in thermogravimetric furnace. The obtained mass gain plots, SEM microphotographs of cross-sections and SEM/EDS analysis of the samples prove that surface preparation changes oxidation kinetics - morphology of the polished and ground samples does not vary significantly after oxidation at investigated temperatures, but differences in oxide layer thicknesses and mass gains were observed. Oxidized sand-blasted samples reveal that increased surface roughness and alumina intrusions change the oxidation process – mixed Al/(Ni, Cu or Ni-Cu) oxide is formed and separate Al₂O₃ particles are visible. The results prove that surface preparation influence high-temperature oxidation of the samples by promoting new diffusion mechanism.

Keywords: oxidation kinetics, surface roughness, fractal analysis, sand-blasting
1. Introduction

Oxidation of pure metals has been studied over the years by many authors [1,2]. Copper and nickel make no exception. The oxidation of the former was performed in wide temperature range by Mrowec and Stoklosa [3] and Zhu et. al [4,5] because copper and its alloys are commonly used as an engineering materials due to their high ductility, electrical and thermal conductivity and quite good strength [6]. Also oxidation of nickel has been investigated, mainly because it forms only NiO during exposure at high temperature, what made it relatively easier to use it as a basis of theoretical calculations, which improved understanding of oxidation processes [1,2]. Nickel is characterized by very strong corrosion resistant properties and is distinguished for its high strength at elevated temperature. Moreover nickel provides stabilization of austenitic phase and precipitation of γ’ and is also responsible for increasing the thermal stability of alloys [7]. All of that makes this element a base or a major component of great number of alloys used for high temperature applications [8]. Nickel forms solid solution with copper at a whole range of concentration. Addition of copper dramatically improves alloy’s thermal conductivity and its resistance to seawater at low temperature [7]. From the other side nickel is alloyed with copper to increase its strength and corrosion resistance, mainly to stress corrosion cracking [6]. Due to this properties, nickel-copper alloys with addition of iron (Ni-31Cu-2Fe) titanium and aluminum (Ni-30Cu-2Fe-0,6Ti-2,7Al) are used in boiler feed water heat exchanger tubes, in pump shafts and impellers in seawater pump, respectively [6,7].

Even though these materials have been extensively studied, there is still a place for further investigations. Mentioned researchers investigated samples that were prepared in slightly different processes like sand-blasting, shot-peening or grinding and polishing ended on non-identical levels – the question arises if there is a relationship between the surface roughness and number of microstructural defects that were induced into subsurface area in preparation
process. It was already proved by Yuan et al [9] that increasing the time of sandblasting for copper samples improves samples’ roughness and also their corrosion resistance. Sandblasting process enhances also corrosion resistance of pure titanium samples [10]. For nickel samples however it was concluded that after polishing performed in different conditions, the greater nickel roughness initially was, the greater values also the oxidation rate reached [8]. Despite that, relationship between surface roughness preparation was much wider studied for alloys – beginning by Giggins and Pettit [11] in 1969 for Ni-Cr alloys. Over the years it was concluded that surface treatment processes may cause grain refinement and therefore increase the number of grain boundaries, what changes the alloy’s mass gain during oxidation [12]. Also the number of defects in the surface region changes as energy is stored in the form of dislocations as a result of surface treatment [13]. All of that has an influence on oxidation of metals.

The aim of this paper is to determine the influence of different surface preparation on the oxidation kinetics and its mechanism at different temperatures in an ambient air for samples of high purity copper (99,99% Cu), nickel (99,99% Ni) and nickel-copper alloy (Ni30Cu70).

2. Material and methods

2.1. Surface preparation

From metal sheets rectangular samples with 17 x 11 x 2,5 mm dimensions were cut. For each material 3 different surface preparation processes were chosen – initially each sample was ground using 220 grit SiC paper. First sample was left on this level of preparation (ground sample), second one, after grinding, was subsequently sand-blasted with alumina particles (sand-blasted sample) and the third one was further ground using SiC paper with increasing gradation (till 2400 grit) and then polished, finishing on 1 μm polishing SiO₂ suspension
Such prepared samples were ultrasonically cleaned with ethanol prior exposure.

2.2. Roughness evaluation

After surface preparation processes, surface roughness was measured with two different methods – conventional contact profilometer and using fractal analysis evaluation.

2.2.1. Conventional contact profilometer

Surface roughness is usually described by amplitude parameters, which enable to characterize the surface topography by measuring vertical characteristics difference. The most important parameters are: arithmetic average height ($R_a$) and maximum height of the profile called also as ten-point height ($R_z$). Calculation procedure is described in [14]. Measurements were perform using Hommel Werke T8000 profilometer: traverse length was set as 4 mm and linear speed – 0.5 mm/s. For each sample, 5 measurements of surface roughness were performed. Based on obtained data, the average value and standard deviation of measurements were calculated.

2.2.2. Fractal analysis

Surface roughness may be also described by fractal analysis. This is a mathematical method, which enable to describe self-similar objects. Surface roughness evaluation by fractal analysis starts with metallographic images of cross-sections of the samples prepared in different manners. Then image must be adjusted to meet the requirements of Sfrax 1.0 software [15] – description of the full procedure has been already published [16].

The outcome of data processing by this software contains information of the measured surface roughness profiles like following parameters: D – Fractal Dimension, LSFC – Length – Scale
Fractal Complexity and $L_R$ – Relative length at given scale [17]. The more complex surfaces are, the higher values this parameters achieve [16].

2.3. Oxidation

Prior to oxidation process, the exposure temperature was established – pure copper samples were oxidized at the temperature range 650–750°C, pure nickel was oxidized at 950–1050°C, binary alloy samples – at 650–750°C range. The ratio of chosen temperature to the melting point of particular sample was similar for different materials. Samples were then oxidized in a thermogravimetric furnace Xerion for 2 hours each in the ambient air.

2.4. Analysis and observations

After exposure chosen samples were examined by using glow discharge optical emission spectrometry (GD-OES). Depth profiles were obtained by quantification described already by other authors [18–20]. Samples were then sputtered with very thin gold coating, so that electrolytically deposited layer of nickel had better adherence to the surface of the samples. The aim of nickel layer is to increase the contrast between the oxide layer and the resin during microscopic observations. After electrolytical deposition, samples were cleaned and then mounted in epoxy resin. Microstructure of the samples was revealed thanks to grinding and polishing processes, that were finished on woven cloth with SiO$_2$ suspension characterized by 0.25 μm grain size. Microstructure of the samples was then observed using scanning electron microscope Hitachi S3400N (SEM).
3. Results

3.1. Surface roughness

Roughness profiles of pure copper samples prepared in three different manners: by polishing, grinding and sand-blasting processes are presented in figure 1. The differences in profiles were so high, that the y-scale had to be adjusted – it proves that surface preparation influences greatly the surface roughness. The roughness profile was the highest for sand-blasted sample and definitively the lowest for polished sample. Similar observations were made for nickel and Ni30-Cu70 samples. Conclusions based on roughness profiles are proved by roughness parameters (Table 1).

![Figure 1. Roughness profile as a function of measurement distance obtained for copper samples: a) polished, b) ground, c) sand-blasted](image)

Table 1. Results of roughness parameters obtained by conventional profilometer (P – polished sample, G – ground sample, SB – sand-blasted sample)

| Parameter | Copper | Ni30-Cu70 | Nickel |
|-----------|--------|-----------|--------|
|           | P      | G         | SB     | P      | G         | SB     | P      | G         | SB     |
| $R_a$, μm | 0,089  | 1,371     | 4,303  | 0,092  | 1,173     | 3,285  | 0,072  | 0,331     | 3,496  |
| SD        | 0,006  | 0,062     | 0,425  | 0,001  | 0,068     | 0,356  | 0,001  | 0,021     | 0,296  |
| $R_z$, μm | 0,532  | 10,261    | 23,713 | 0,466  | 9,342     | 19,963 | 0,291  | 3,026     | 21,803 |
| SD        | 0,072  | 0,732     | 3,341  | 0,052  | 0,865     | 1,300  | 0,144  | 0,367     | 1,288  |

To perform surface roughness evaluation by fractal analysis, binary scale images of metallographic cross-sections after preparation processes had to be make out. Examples of binary scale images of surface profile for copper samples are presented in figure 2. It is clearly seen, that for sand-blasted sample the surface is much more complex in comparison to
polished and ground samples. Figure 3 proves this observation and depicts plots of relative length vs. scale. For all of the materials sand-blasted sample was characterized by the highest roughness and the polished one – by the lowest, although for Ni30Cu70, the difference between ground and polished sample was slightly visible. More information may be obtained by analyzing roughness parameters that were calculated by Sfrax 1.0 software (Table 2). For pure materials all the parameters increased in value in the following order: polished – the lowest values, sand-blasted – the highest. For nickel-copper alloy the roughness parameters obtained using fractal analysis are very similar, while, as observed for pure metals, sand-blasted sample exhibited the highest roughness values.

Figure 2. Binary scale images of surface profile for Sfrax 1.0 software of copper samples: a) polished, b) ground, c) sand-blasted

Table 2. Results of roughness parameters obtained by fractal analysis (P – polished sample, G – ground sample, SB – sand-blasted sample)

| Parameter | Copper | Ni30-Cu70 | Nickel |
|-----------|--------|-----------|--------|
|           | P      | G         | SB     | P      | G         | SB     | P      | G         | SB     |
| D         | 1,016  | 1,084     | 1,105  | 1,016  | 1,015     | 1,100  | 1,004  | 1,036     | 1,11   |
| LSFC      | 15,787 | 83,742    | 105,351| 16,231 | 14,603    | 99,934 | 4,094  | 35,899    | 110,066|
| L<sub>R</sub> 5 µm | 1,028  | 1,182     | 1,312  | 1,030  | 1,029     | 1,267  | 1,005  | 1,072     | 1,216  |
Nevertheless, surface roughness parameters obtained via profilometer and fractal analysis enabled to formulate similar conclusions – surface preparation process greatly affects surface roughness. Standard methods for quantification of material roughness, like $R_a$ and $R_z$, are useful for characterization of profile depth while fractal analysis gives more information about surface complexity and deformation. Combination of both methods are more and more widely used while describing oxidation processes [16,21].

### 3.2. Oxidation of pure copper

Normalized mass change as a function of oxidation time for copper samples is shown in figure 4. It is clearly seen that at 650°C (figure 4a) and 700°C (figure 4b), the mass gain of the particular samples was ordered in the same manner – the highest mass gain was obtained for polished samples, the lowest – for sand blasted ones. This order changed after exposure at 750°C (figure 4c) – the highest mass gain was observed for sand-blasted sample – the mass gain increased almost three times in comparison to sand-blasted sample oxidized at 700°C. The lowest mass gain was observed for polished sample – the value obtained was lower than that recorded for polished sample oxidized at 700°C.
Different surface preparation of the samples changes not only oxidation kinetics but also microstructure of the growing oxide layers. Observations of SEM images of cross-sections of the samples after oxidation (figure 5) present these differences. For polished (figure 5, a, d, g) and ground (figure 5, b, e, h) samples everything looks quite similar and relatively simple – thick layer of Cu$_2$O is formed, which is covered by very thin layer of CuO oxide. Clear boundary between copper substrate and different oxides may be also proved by GD-OES depth profile (figure 6). This observation is in good agreement with literature – at 600 – 900°C copper forms two oxide layers, but growth of Cu$_2$O dominates [4].
|       | Polished | Ground | Sand-blasted |
|-------|----------|--------|--------------|
| **650°C** | ![Image](a) | ![Image](b) | ![Image](c) |
| ![Image](d) | ![Image](e) | ![Image](f) |
| ![Image](g) | ![Image](h) | ![Image](i) |
| **700°C** | ![Image](d) | ![Image](e) | ![Image](f) |
| ![Image](g) | ![Image](h) | ![Image](i) |
| **750°C** | ![Image](g) | ![Image](h) | ![Image](i) |

Figure 5. SEM images of cross sections of copper samples oxidized at 650°C (a, b, c), 700°C (d, e, f), 750°C (g, h, i) and of samples characterized by different surface preparation: polished (a, d, g), ground (b, e, h) and sand-blasted (c, f, i).

![Graph](a)  ![Graph](b)

Figure 6. The GD-OES depth profiles for a) polished and b) ground copper samples after exposure for 2 hours at 650°C.
Situation is much more complicated for sand-blasted samples (figure 5, c, f, i). Due to differences in coefficients of thermal conductivity of pure copper and its oxides, it was impossible to observe the microstructure of copper oxidized at 650°C (figure 5c) – only small traces of copper oxide were noticed. However, they look similar to the mixed Cu/Al oxide that was formed after exposure for 2 hours at 700°C (figure 5f). It may be assumed that mechanism of oxidation of these samples is similar – due to outward diffusion of copper, copper oxide is formed, but because of relatively slow rate of diffusion, copper oxide reacts with alumina that was induced by sand-blasting process and forms Cu/Al- mixed oxide (figure 7a). It is worth noticing, that oxide layer on these samples was possible to observe only in small areas of the samples, in comparison with rather even and compact oxide layers that were formed on polished and ground samples at these temperatures. It is a proof, that sand-blasting process results in decreasing oxide adhesion to the metallic substrate at lower temperatures.

It is clearly visible in the microphotograph of sand-blasted sample at the highest temperature –750°C (figure 5i) that the oxidation mechanism changed – alumina particle does not form Al/Cu-mixed oxide, but is surrounded by columnar grains of Cu$_2$O. Moreover its position inside the oxide layer is a proof of outward diffusion of copper. However, remembering how the surface roughness looked like before oxidation (figure 2c) it is interesting to observe, how smooth the boundary between oxide and substrate looks like – in this case probably the diffusion rate increased by including not only outward diffusion of copper but also inward diffusion of oxygen in the initial point of oxidation. It also prevented creation of mixed Al/Cu oxide (figure 7b).
Above formulated theory about the influence of diffusion on kinetics of oxidation can be further justified by calculating the ratio of \( \text{Cu}_2\text{O} \) to CuO oxides thicknesses (table 3). It is already known, that in case of oxidation under the same conditions (temperature and oxygen partial pressure), ratio of particular phases thickness of multilayer scale depends on diffusion of reagents in the growing oxide so that the oxidation kinetics is also determined by the diffusion rate and in consequence – by concentration of lattice defects [22]. Analyzing table 3 one can observe that at 650°C ratio of thickness of \( \text{Cu}_2\text{O} \) to CuO is almost similar for samples prepared in polishing and grinding processes. Situation changes at 700°C – for polished sample ratio of \( \text{Cu}_2\text{O} \) to CuO equals 17.18. This value increases further for ground sample to 20.20. Unexpectedly mentioned ratio decreased for sand-blasted sample to 14.76, but microphotograph of this sample (figure 5f) has already revealed that Al/Cu-mixed oxide formed which considerably slowed the oxidation process. Such effect is not observed after exposure at 750°C. For this samples, the lowest value of \( \text{Cu}_2\text{O} \) to CuO thicknesses ratio was observed for polished sample (26.20) and slightly greater for ground sample (29.64). For sand-blasted sample however, the value of measured ratio was almost two times higher than for polished sample. It proves, that the diffusion process is connected with increased number of defects occurred for this sample and increased the oxidation kinetics.
Table 3. Measured thicknesses of two formed copper oxides and the relationship between them

| Temp . | Sample preparation | CuO | Cu₂O | Cu₂O to CuO thickness ratio |
|--------|-------------------|-----|------|---------------------------|
|        |                   | Avearege thickness, µm | Standard deviation | Average thickness, µm | Standard deviation |                           |
| 650°C  | Polished          | 2.48 | 0.81 | 39.34 | 0.55 | 15.87 |
|        | Ground            | 2.95 | 0.54 | 45.48 | 0.85 | 15.40 |
|        | Sand-blasted      | -    | -    | -     | -    | -    |
| 700°C  | Polished          | 3.10 | 0.76 | 53.29 | 0.96 | 17.18 |
|        | Ground            | 3.11 | 0.51 | 62.85 | 1.23 | 20.20 |
|        | Sand-blasted      | 3.66 | 0.40 | 54.03 | 4.21 | 14.76 |
| 750°C  | Polished          | 2.35 | 0.75 | 61.52 | 0.87 | 26.20 |
|        | Ground            | 2.29 | 0.46 | 67.83 | 0.75 | 29.64 |
|        | Sand-blasted      | 2.89 | 0.80 | 125.53| 0.78 | 43.45 |

3.3. Oxidation of pure nickel

Normalized mass change for pure nickel samples oxidized at 3 different temperature values is shown in figure 8. Also in this case it is seen, that the mass gain is influenced by surface preparation, but it is worth noticing, that the mass gain obtained for these samples does not vary significantly – even though at 950 and 1000°C (figure 8, a and b) the order of the samples characterized by particular surface preparation process is different during the exposure time – the final mass gain for these samples is almost equal. The change is observed for last samples, oxidized at 1050°C – the sand blasted sample was characterized by the highest mass gain, and ground sample – the lowest, even though its oxidation rate at the first 0,5h was the fastest.

Figure 8. Normalized mass change volume for pure nickel oxidized for 2 hours at a) 950°C, b) 1000°C, c) 1050°C
Similarly to the copper samples prepared before oxidation in grinding and polishing processes, the oxide layer that forms on its surface does not differ significantly – the NiO layers on polished (figure 9, a, d, g) and ground (figure 9, b, e, h) samples is compact and demonstrates good adherence to the nickel substrate. Again the situation changes for sand-blasted samples, because their surfaces are rougher and also contaminated by alumina particles that were induced into the surface in preparation process. Microphotographs of these samples (figure 9, c, f, i) show that alumina particles inhibits the formation on nickel oxide – in figure 9c, thickness of NiO that grows on Al₂O₃ is lower than the same oxide growing directly on nickel substrate. The explanation is simple - NiO is formed by inward diffusion of oxygen anions, so in case of alumina particles, the diffusing anions have to overcome longer way. In figure 9i, alumina particle is so high, that the growing NiO does not overgrow its surface as in figure 9c and the discontinuity in NiO-layer is observed. Taking that into account one can conclude that sand-blasting process influences the adhesion between nickel surface and growing oxide.
| Temperature | Polished | Ground | Sand-blasted |
|-------------|----------|--------|-------------|
| 950°C       | ![Image](image1.jpg) | ![Image](image2.jpg) | ![Image](image3.jpg) |
| 1000°C      | ![Image](image4.jpg) | ![Image](image5.jpg) | ![Image](image6.jpg) |
| 1050°C      | ![Image](image7.jpg) | ![Image](image8.jpg) | ![Image](image9.jpg) |

Figure 9. SEM images of cross sections of nickel samples oxidized at 650°C (a, b, c), 700°C (d, e, f), 750°C (g, h, i) and of samples characterized by different surface preparation: polished (a, d, g), ground (b, e, h) and sand-blasted (c, f, i).

How the induced alumina particles change the chemical composition of oxide layer is clearly visible on GD-OES depth profiles (figure 10). For polished and ground samples (figure 10, a, b) only NiO is formed – there are only small, irrelevant amounts of aluminum. In figure 10c however great enrichment of aluminum can be observed. Outer layer contains lower amount of this element – it proves, that due to the diffusion of oxygen anions, the alumina particles are eventually covered by growing NiO. Aluminum is visible not only in the oxide but also in the substrate. It means that during sand-blasting process alumina particles gain great kinetic energy so that it is possible for them to be inserted in relatively deep regions of the substrate.
Figure 10. The GD-OES depth profiles for a) polished, b) ground and c) sand-blasted nickel samples after exposure for 2 hours at 950°C

3.4. Nickel-copper alloy oxidation

Plots of mass change per unit area observed for Ni30Cu70 samples oxidized for 2 hours at different temperature are depicted in figure 11. It is clearly seen that oxidation kinetics changes as a result of surface preparation – regardless the temperature changes, the lowest mass gain was revealed sand-blasted samples. At lower temperatures (figure 11, a and b) ground samples obtained the greatest mass change, whereas at 750°C, the polished sample started to prevail. The highest mass gain for all the samples was obtained after exposure at 700°C (figure 11b), but the values were significantly lower than that observed for oxidation of pure copper at the same temperature (figure 4b).

Figure 11. Normalized mass change for nickel-copper alloy (Ni30Cu70) oxidized for 2 hours at a) 650°C, b) 700°C, c) 750°C

SEM images of cross sections of samples after exposure at different temperatures help to explain the effect observed on kinetics plots. For polished samples (figure 12, a, d, g) the oxide layer that grows on Ni30-Cu70 substrate looks similar: CuO forms the outer layer
beneath which mixed nickel/copper oxide is situated. Difference is observed in their thickness – the higher the temperature is, the thicker both of these layers are. As a result of outward diffusion of copper, outer surface of Ni30-Cu70 substrate is depleted in this element. GD-OES depth profile after exposure at 750°C (figure 13a) outer layer is created almost completely by CuO – small peak of nickel indicates electrodeposited layer of this element on the sample after oxidation exposure. Below CuO enrichment in nickel and depletion in copper are observed – this part of the plot presents formation of Ni/Cu mixed oxide.

|     | Polished | Ground | Sand-blasted |
|-----|----------|--------|--------------|
| 650°C | ![Image](a) | ![Image](b) | ![Image](c) |
| ![Image](d) | ![Image](e) | ![Image](f) |
| 700°C | ![Image](g) | ![Image](h) | ![Image](i) |

Figure 12. SEM images of cross sections of Ni30-Cu70 samples oxidized at 650°C (a, b, c), 700°C (d, e, f), 750°C (g, h, i) and of samples characterized by different surface preparation: polished (a, d, g), ground (b, e, h) and sand-blasted (c, f, i). In situations when mixed oxide is formed, the former element indicates the element with highest content in the oxide while the latter – the lowest.
Figure 13. The GD-OES depth profiles for a) polished, b) ground and c) sand-blasted Ni30-Cu70 samples after exposure for 2 hours at 750°C

Quite similar observations can be made for ground samples (figure 12, b, e, h, figure 13b). Outer layer is also formed by CuO and inner – by mixed Cu/Ni oxide. It is impossible to observe the oxide layer that grew on ground sample that was oxidized at 700°C – oxidation products spalled off during cooling to the room temperature. Because this sample exhibited the highest mass gain of all the samples (figure 11b) it may be assumed that the oxide layer on this sample reached its critical thickness what caused the effect of flaking off.

It is once again visible that sand-blasting process changes the oxidation mechanism the most. For the samples prepared in this way (figure 12, c, f, i) alumina particles were observed in two forms – as a separate particles that were stuck in the substrate and were then surrounded by growing oxide and as a component of mixed oxides that also appeared during oxidation.

5. Discussion

In this paper three different materials: high purity copper, high purity nickel and high purity binary nickel-copper (Ni30-Cu70) alloy were treated in three different preparation processes: grinding, polishing and sand-blasting and then oxidized at three different temperature values.

Two methods of evaluation of surface roughness have been applied – they both confirmed that surface preparation process influences greatly the surface roughness. As it was predicted, the roughest surface was obtained for sand-blasted samples and the smoothest – for polished
ones. The parameters of roughness obtained by conventional contact profilometer the values changed almost of one order of magnitude (table 1). It was also noticed, that even though samples of different materials in particular processes were prepared in exactly the same way, roughness parameters varied for each material – for example ground sample of nickel had almost 4 times lower value of $R_a$ than copper and Ni30-Cu70 samples (table 1). The relationship between grinding conditions and surface roughness was already studied elsewhere [23,24].

Surface preparation processes do not only influence surface roughness – they may also induce an increase in residual stresses and number of defects in the subsurface area and therefore – to change the oxidation mechanism by promoting fast diffusion paths [25,26]. Putting together increased area exposed to oxidant and faster diffusion of components, one can assume that the more convoluted the surface is due to preparation process, the faster the oxidation proceeds. Such theory has been already proposed by Nowak et al. [27] for Ni-based superalloy IN 713C samples prepared in grinding and polishing processes. The mentioned theory seems to be valid also for oxidation of pure copper at 750°C (figure 4c) and nickel at 950 and 1050°C (figure 8) but fails in other cases – for example for Ni30Cu70 sand-blasted samples obtained the lowest mass gain at each temperature (figure 11). It is known however that oxidation mechanisms for pure metals and commercially available alloys vary significantly, so that further investigations about the induction of defects in the subsurface area in preparation processes should be performed. Moreover SEM analyses and GD-OES depth profiles revealed that intrusions of aluminum may be responsible for changes in oxidation kinetics – it is widely know that any impurities have great influence on oxidation process [2]. Considering the results obtained in this research it is impossible to distinguish the influence of surface roughness, number of defects and addition of $\text{Al}_2\text{O}_3$ particles on oxidation kinetics.

From the other side comparison of ground and polished samples, which theoretically did not contain any contaminations before oxidation process, also does not give a straight
confirmation of the theory. For oxidation of pure copper polished sample presented the highest mass gain at 650 and 700°C, but the lowest at 750°C (figure 4). In the contrary during oxidation of nickel-copper alloy, ground samples had the highest mass gain at lower temperatures (figure 11) but polished sample won the competition at 750°C. In case of pure copper the explanation may be as followed: copper oxide grows due to the outward diffusion of metal cations, so in case of smooth surface all of copper ions may connect with oxide anions. The more convoluted surface however, for example, in concave areas, the number of oxide anions may be to scarce to connect all of copper cations, and thus for flat, polished samples, the oxidation rate was higher. In case of oxidation of nickel-copper alloy, formation of mixed oxide may play a key role which changes the oxidation mechanism observed for pure nickel and copper separately. The exact explanation is not yet known.

It is visible that there is a relationship between surface treatment and oxidation rate and mechanism for pure metals and binary alloy, but to confirm the mentioned theory and form more specific conclusions another testing must be performed, like measurement of residual stresses of samples before oxidation and oxidation tests with application of markers. Both investigation techniques will be used in further research.

6. Conclusions:

In the present work, the effect of surface deformation on high temperature oxidation of Ni, Cu and Ni-Cu alloy has been investigated. Based on obtained results of research following conclusions are formulated:

1. Sand-blasting causes the greatest surface deformation in comparison to polishing and grinding processes. Such preparation results in the highest surface roughness and introduction of alumina particles in subsurface area.

2. Alumina particles sticking in subsurface area cause formation of Cu/Al-mixed oxide for copper sample oxidized at 700°C and for all sand-blasted samples of Ni-Cu alloy.
Al$_2$O$_3$ is also observed as a separate particles surrounded by the growing oxide as in oxidation of pure nickel, which may lead to discontinuity in NiO layer and lower the oxide adhesion to the metal surface.

3. Morphology of the polished and ground samples does not vary significantly for pure Cu, Ni and binary Ni-Cu alloy after oxidation at investigated temperatures, although differences in oxide layer thicknesses and mass gains were observed.

4. Observation of pure copper sample revealed that initially rough surface after sand-blasting process smoothed after exposure at 750°C. In connection with great increase in oxidation kinetics it proves that additional diffusion mechanism has occurred for this sample at high-temperature due to increased number of defects introduced in sand-blasting process.

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