The Annealing Behavior of the Subsurface Zone Induced by Friction in Bismuth Detected by Positron Lifetime Technique

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Abstract The annealing behavior of the subsurface zone (SZ) in pure bismuth induced by dry sliding was studied using the positron lifetime measurement. This measurement allows us to detect the SZ and its recovery, and recrystallization processes. The comparative measurements of the sample exposed to compression revealed the thermal stability of the SZ. The compressed sample rebuilt its structure due to the recovery and recrystallization processes at the temperature of 60 °C, whereas the sample exposed to dry sliding does it at higher temperature of 260 °C, which is close to the melting point. The isothermal annealing at the temperature of 100 °C confirmed these results. The defect depth profile induced by dry sliding evolves with the annealing temperature in such a way that the concentration of defects at the worn surface gradually decreases, but at the depth between 50 and 170 μm, the generation of new defects takes place at the temperature of 75, 100 and even at 175 °C. At the temperature of 175 °C, the defects still are extended up to the depth of about 60 μm from the worn surface. The results were qualitatively confirmed by the measurements of the Vickers microhardness depth profile. Similar annealing behavior of the SZ was observed in pure magnesium.

Keywords Subsurface zone · Bismuth · Positron annihilation

1 Introduction

The sliding contact of two ductile bodies induces the hardening of the worn surface and the adjoined subsurface zone (SZ). This is due to the repeating passage of asperities of the counterface, which leads to the accumulation of strains in a loaded surface and below. The accumulation of strains results in plastic deformation, and it is induced by generation of dislocations which can prevent further deformation. Generally, the strain and the hardness decrease with the increasing depth from the worn surface. The interesting review of the topic of wear and material structure is given by Zum Gahr in his book [1]. As it was pointed out by Suh and coworkers in a “delamination” theory of wear, dislocations play also a significant role in voids and crack nucleation [2–4]. Salesky et al. [5] extended this theory. They pointed out that dislocations exhibit tendency to rearrangement themselves to the cell walls. Due to the local heating or mechanical instability, the cell structure can undergo recovery and locally the dislocation density decreases. Due to this, a thin recovered layer embedded by heavily dislocated unrecovered zone occurs below the worn surface. Internal compressive stresses are smaller in the recovered layer than in the unrecovered zone; this causes the interface becomes a preferred location for the generation and propagation of delamination cracks leading to the debris formation and finally wear. Thus, the studies of dislocations and generally defects in the SZ are necessary for better understanding of wear [6].

The motion of dislocations which occurs during plastic deformation is the origin of other point defects, such as interstitial atoms, vacancies, their clusters or jogs on their lines [7]. They create the specific halo accompanying dislocations. Thus, the SZ contains other defects besides

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dislocations which result from the work-hardening. The measurements of hardness seem to be a natural method for the studies of SZ; however, this method is not accurate enough, and it is insensitive to point defects. They are also hidden for the electron microscopic observations. On the contrary, the positron annihilation methods are very sensitive to point defects such as vacancy and their clusters, and jogs at dislocation lines [8]. Additionally, these methods allow studying the worn samples without special preparation, which could change the initial state of the sample as it can happen for instance for transmission electron microscopic (TEM) observation. As it was pointed out in numerous papers by the author of this paper and his coworkers, positron annihilation methods are suitable for the studies of SZ in ductile metals and alloys exposed to dry sliding (see Dryzek et al. [9]). However, these methods were applied also with success to studies of recovery and recrystallization processes in plastically deformed samples [10–13]. The annihilation of defects and formation of defect-free new grain during recrystallization is well reflected in the measured positron annihilation characteristics. This indicates that the positron annihilation is a suitable tool for the studies of the SZ and its restoration process, i.e., recovery and recrystallization [14].

During deformation, the microstructure of polycrystalline metal changes, the grains change their shape and the new grain boundaries occur, but mainly dislocations are generated which create an internal structure within the grains [15]. Increase in the dislocation density is due to the trapping of newly created mobile dislocations by existing dislocations. The deformed metal is in nonequilibrium state, and during storage, deformation energy can be released when temperature of sample rises. At the beginning, the internal structure changes in the recovery process, and the properties are only partially restored to their values before deformation. This process occurs in many cases during the deformation, such as dynamical recovery. During recovery, movement and climbing of dislocations lead to their annihilation and rearrangement lowering the configuration energy. The recovery prepares the deformed metal to the next step of the restoration process, i.e., recrystallization. There occurs nucleation of new grains that grow and consume the small grains, resulting in a new grain structure with a low dislocation density. In some cases, the selective growth of a few grains takes place, which is known as the abnormal grain growth. Generally, these processes are thermally activated and can be easily observed using positron annihilation techniques either in isochronal or in isothermal measurements.

The SZ is the deformed region where deformation exhibits additionally a gradient. The deformation and its gradient are higher close to the worn surface. This should affect the restoration process. Indeed, our former studies

performed for deformed pure copper samples have shown that these processes run with different rates at different depths what can be understood, taking into account that the stored energy deposited during sliding changes with the depth as well [14]. However, the recent studies for pure magnesium indicate that the SZ is completely restored in much higher temperature than it is for a sample exposed to compression [12]. The studies have shown that part of the SZ close to the worn surface is rebuilt at higher temperature than deeper regions. These results seem to be important because they indicate the great thermal stability of the SZ, and we decided to confirm them for another metal, i.e., bismuth. The SZ in pure bismuth was detected already using the positron lifetime measurements [16]. It was shown that the concentration of the vacancy clusters created during sliding exponentially decreases with the depth increase and tends to zero at the depth of about hundreds of micrometers depending on the sliding conditions. The main aim of the paper is to show how the SZ in this metal evolves during annealing.

2 Experimental Details

2.1 Positron Lifetime Measurements

In our studies we used the positron lifetime measurements as the method sensitive to the detection of defects induced by sliding or compression. This method is based on the fact that a positron that is implanted into the crystalline lattice after a certain time of about hundred of picoseconds meets an electron and both particles annihilate, producing two photons. The time is determined mainly by the electron density in the annihilation place, and its value is different for different metals. However, when a crystalline lattice contains defects such as vacancies, the positively charged positrons can be trapped at them. Vacancies, their cluster, or dislocation jogs are places where the electron density is lower in comparison with the interstitial region; then the positron lifetime is longer in comparison with nondamaged lattice, i.e., bulk [17]. For instance, for a vacancy the positron lifetime is longer than in bulk by a factor of 3/2. There are numerous papers devoted to the experimental measurements and theoretical calculations of the positron lifetime for bulk at different materials and defects, because these values are fingerprints that can be used for defect identification [18].

For the positron lifetime measurements, we used the ^{22}Na isotope enveloped into a 7- μm -thick kapton foil as a positron source. Its activity was 32 μCi . One should note that the positrons emitted from the source have sufficient energy ($E_{\text{max}} = 544 \text{ keV}$) to penetrate a certain depth of the sample. For bismuth, the linear absorption coefficient

for positrons is equal to ca. $1/23 \mu\text{m}^{-1}$ [19]. In the top layer of the thickness of $23 \mu\text{m}$, about 64 % of positrons emitted from this source are stopped. For that reason, this technique is not sensitive to surface defects and near-surface inhomogeneities, and mechanically mixed layer and oxide effects in future considerations can be ignored.

For recording the positron lifetime spectra, we used the conventional *fast-fast* spectrometer. The spectrometer was constructed of BaF_2 -based detectors and standard ORTEC electronic units; the time resolution of the system was 260 ps (FWHM). The positron source was located between two identical bismuth samples, and this sandwich was positioned in front of the scintillator detectors of the positron lifetime spectrometer. The positron lifetime spectra contained more than 2×10^6 counts in the spectrum. All obtained spectra were deconvoluted using the LT code, subtracting the background and the source components [20].

2.2 Microhardness Measurements

As a supplement, the measurement of the microhardness profile on the cross section of samples was performed as well. The low-speed diamond saw was used for cutting samples. The Vickers microhardness was measured using Zeiss (Neophot 30) microscope at the load of 10 g at different depths from the worn surface.

2.3 Sample Preparation

In our studies, we used the pure bismuth samples whose surfaces were damaged in the dry sliding or which were compressed. Samples of bismuth of purity 99.8 % had a disk shape of 10 mm in diameter and 3 mm thick. Before treatments, they were annealed in the flow of N_2 gas at a temperature of 220°C for 3 h and then slowly cooled to room temperature. After annealing, the samples were etched in a 5 % solution of acetic acid in distilled water to reduce their thickness by $100 \mu\text{m}$ and clean their surface. This procedure allows us to remove defects that occurred during manufacturing. In fact, in the positron lifetime spectrum measured for virgin samples, only one lifetime component equal to 241 ± 1 ps was resolved. This corresponds well with the data reported in the literature as the bulk lifetime for bismuth (see, e.g., the paper of Campillo et al. [18]).

2.4 Sample Treatment

After annealing, a sample was located in a tribotester, and the base surface of the sample was slid against the rotating disk with the load of 15 N. This disk of diameter of 50 mm was made from the martensitic steel (steel SW18 hardness

about 670 HV0.1). The speed of the disk relative to the surface of the sample was equal to 5 cm/s. The treatment was performed in air for 1 min, and no oxidation was observed. The average value of the friction coefficient determined during the tribotest equals to 0.30, and the specific wear rate defined as worn volume per unit sliding distance per unit load equals to $(2.41 \pm 0.08) \times 10^{-18} \text{ m}^3 \text{ N}^{-1} \text{ m}^{-1}$.

Other annealed samples were deformed by compression at room temperature to reduce their initial thicknesses. For compression, the uniaxial hydraulic press was used, and after 15 s, the pressure was released.

3 Results

3.1 The Sample Exposed to Compression, the Calibration Test

As mentioned above, the accumulation of the strain is accompanied by the increase in dislocation density with the point defects halo. This should be reflected as the increase in the mean positron lifetime extracted from the measured positron lifetime spectra. The mean positron lifetime is the robust parameter defined as the sum of the lifetimes of positrons annihilating from different states in the samples weighted by probabilities of annihilation from these states, i.e., intensities. This parameter is commonly accepted, and its value depends on the positron lifetime in separated states and also the defect concentration [16, 17]. In our considerations, we will focus on the mean positron lifetime only. To convince the reader that the mean positron lifetime sensitive to the defects in the crystalline lattice is sensitive also to a macroscopic parameter, i.e., the strain, Fig. 1 presents its dependency on the thickness reduction of the compressed bismuth samples. The mean positron lifetime increases starting from the bulk value, 241 ps, and it saturates at the value of 263 ps for the thickness reduction of about 73 %. This dependency is well understood; when the strain is low and the defect concentration is low as well, the positrons can annihilate being trapped in defect but also in the free state in the nondamaged regions, i.e., bulk. However, when the strain increases and the average distance between defects decreases, each randomly walking positron is always trapped in a defect. We can estimate that the average walking distance of a positron is about $0.1 \mu\text{m}$, and at the defects concentration of 10^{-3} , all positrons are trapped and the saturation is observed [17]. Similar saturation effect is observed for instance in deformed steel samples [21]. The dependency shown in Fig. 1 links the measured microscopic parameter, i.e., the mean positron lifetime with the macroscopic one, i.e., the sample thickness reduction that can be treated as the strain.

Fig. 1 The dependency linking the mean positron lifetime extracted from the positron lifetime spectra and the macroscopic parameter, i.e., the thickness reduction achieved in the compression using the hydraulic press

3.2 The Isochronal and Isothermal Annealing

In this experiment, samples after compression or sliding were annealed during 1 h at increasing temperatures and then cooled with the furnace, and the positron lifetime spectra were measured at room temperature. The obtained dependencies of the mean positron lifetime versus the annealing temperature are depicted in Fig. 2.

For the samples after compression (73 % thickness reduction), the mean positron lifetime decreases rapidly with the increase in the annealing temperature, and the bulk value is reached at the temperature of 60 °C. This is a characteristic dependency observed for different metals exposed to plastic deformation, which can be explained by the recovery and recrystallization processes [10]. The presence of new grains free of defects, which size is large enough that the annihilation at grain boundaries can be neglected, causes that the bulk value of the positron lifetime is obtained. It is worth noticing that similar dependency was obtained also for the samples with lower thickness reduction, i.e., 23 and 34 %. Dryzek [11, 12] proposed a theoretical model that allows describing this temperature dependency. It takes into account two processes: the positron diffusion inside the new spherical grains and increase in the grain radius with the temperature and the time of annealing. The model allows us to obtain the activation energy of the grain boundary migration which is equal to $Q = 0.92 \pm 0.40$ eV in this case. The solid line in Fig. 2 represents the best fit of the equations

Fig. 2 The mean positron lifetime as a function of the temperature in the isochronal annealing measurements for pure bismuth sample after compression (a) (closed circles) (73 % of the thickness reduction) and sample exposed to sliding (b) (open circles). The arrows indicate temperatures for which the depth profiles of the samples exposed to dry sliding were measured in sequenced etching procedure, and the results are presented in Fig. 4. The hatched region represents the bulk value of the positron lifetime in the well-annealed sample with only residual defects. The solid curve (c) represents the best fit of equation (12 b) and (14) (see Dryzek [12]) to the experimental points obtained for compressed sample

(12 b) and (14) (see Dryzek [12]) to the experimental points.

Whereas the compressed sample rebuilt its structure to the initial one after annealing at the temperature of 60 °C, the sample exposed to sliding exhibits a different type of dependency. The mean positron lifetime gradually decreases to the value of 246 ps at the temperature of 120 °C, and then it remains almost constant, and at the temperature of 260 °C, i.e., 11 °C below the melting point, it drops to the bulk value (Fig. 2). Thus, the process of the SZ restoration needs higher temperature, than that of the compressed sample. Almost identical type of dependencies was observed by Dryzek for the pure magnesium sample exposed to sliding (see Fig. 2 in Ref. [12]). The structure restoration of magnesium sample exposed to sliding was observed at the temperature of 500 °C, whereas for the compressed sample, it was about 300 °C. The melting point of this metal is 649 °C.

The resistance of the SZ to annealing may be demonstrated in the isothermal experiment as well. The samples were annealed at the temperature of 100 °C during a certain time and then cooled, and the measurements of the positron lifetime spectra were taken at room temperature. The results are depicted in Fig. 3. After 80-min annealing, the compressed sample rebuilt its structure and the positron lifetime reaches the bulk value. However, the sample exposed to sliding needs much longer time, i.e., almost 1,000 min is necessary for the complete structure restoration. This unambiguously proves high thermal stability of

Fig. 3 The mean positron lifetime as a function of the time in the isothermal annealing measurements for pure bismuth sample after compression (closed circles) (73 % of the thickness reduction) and the sample exposed to sliding (open circles). The annealing temperature was equal to 100 °C. The hatched region represents the bulk value of the positron lifetime in the well-annealed sample with only residual defects

the SZ. One can notice the large scatter of the points observed for the sliding sample, which can reflect some structural processes. It can suggest the significant change in the microstructure of the SZ during long annealing; the defects that trap positrons can annihilate but also can be generated. This is a new phenomenon observed for the first time in the SZ, and it needs future studies, because it could deliver new information about this zone.

3.3 The Depth Profiles

The results and conclusions obtained above are related to processes in the layer adjoined to the worn surface. The thickness of the layer is about 23 μm where about 64 % of positrons emitted from this source are stopped. It is well known that the SZ is extended deeper even at the depth of a few hundreds of micrometers. For the detection of this zone, we proposed the sequenced etching method. The measurement of the positron lifetime spectrum or other positron characteristics is performed after removing a layer of a certain thickness from the worn sample by etching. Etching itself does not introduce new defects, and we assume it is neutral to the plastic deformed regions in the samples; no additional deformation of etched samples was observed. The obtained dependency reflects the depth profile of the mean positron lifetime; it means the defect depth distribution below the worn surface. In our method the samples were etched in the 25 % solution of nitric acid in distilled water to remove a layer of about 15 μm thick. In Fig. 4a the dependence of the mean positron lifetime on the depth from the worn surface, i.e., the thickness of the

etched layer, is depicted. As it can be seen, the exponential decay of the mean positron lifetime with the depth increase was obtained. This result seems to be a common feature of the SZ created in metals and alloys during the sliding-wear process. Note the total depth of the SZ that occurs during dry sliding is about 200 μm , and it corresponds to our previous results [16]. In the next experiment, the samples with such SZ were annealed at the temperature of 75 °C during 1 h and then cooled with the furnace to the room temperature. Then the depth profile using the sequenced etching method was measured. Note that the annealing temperature is above the recovery temperature of the compressed sample. The results are depicted in Fig. 4b. The significant modification of the profile can be noticed. The decrease in mean positron lifetime up to the depth of 90 μm remains, but for higher depths, the sudden increase is observed. After reaching the maximum at the depth of 110 μm , the mean positron lifetime decreases, and at the depth of 230 μm , the bulk value is reached. This effect is even more pronounced for the sample with the SZ annealed at the temperature of 100 °C. The increase in the mean positron lifetime at the depth between 50 and 170 μm is well visible (Fig. 4b). The maximum in this range is clear also after annealing at the temperature of 175 °C. However, below the worn surface, the mean positron lifetime still decreases, indicating that the material is not restored in the layer adjoined to the worn surface. The resistance for the annealing of this layer is responsible for the isochronal dependency presented in Fig. 2.

In our former paper devoted to the SZ in pure magnesium, it was a suggestion to recalculate the depth profiles as in Fig. 3 because in fact the positron always penetrate certain depth due to the implantation profile. However, when the average implantation depth is low, as it is in bismuth, it is not necessary, because the implantation profile only slightly affects the mean positron lifetime [12].

Almost identical annealing behavior of the SZ created during sliding was observed in pure magnesium, as it was reported by Dryzek [12]. The decay of the mean positron lifetime at the worn surface with the increasing annealing temperature and the characteristic maximum at the depth of about 80 μm were observed in this metal as well. The existence of the SZ after annealing at the temperature of 300 °C was also noticed. Thus, all the features of the SZ observed in pure magnesium are recognized in pure bismuth.

3.4 Microhardness Depth Profile

The corresponding depth profiles of the HV microhardness for the samples exposed to dry sliding and then annealed at the selected temperature are depicted in Fig. 5. The increase in the microhardness in the layer adjoined to the

Fig. 4 The depth profile of the mean positron lifetime obtained using the sequenced etching procedure described in the text. In **a**, the profile obtained for the sample exposed to dry sliding, no annealing was performed. The *solid line* represents the best fit of the exponential function. In **b**, the depth profile, obtained in a similar way, but before taking measurements, the samples were annealed at the temperatures of 75, 100 and 175 °C. The *hatched region* represents the bulk value of the positron lifetime in the well-annealed sample with only residual defects

worn surface is well visible for all samples. However, the total depth profile is shallower than those detected by positrons. The microhardness profile range for the non-annealed sample is about 150 μm (Fig. 5a), whereas the range detected by positrons (Fig. 4a) is about 250 μm . This discrepancy can result from the fact that the indenter of the microhardness records large regions of the sample and is more sensitive to the hardening of the region than the presence of point defects. The shorten range of the SZ detected by microhardness in comparison with the positron measurements has been observed already in our studies of the SZ [22]. The microhardness profiles for the SZ annealed at different temperatures (Fig. 5b) do not reveal the features observed in Fig. 4b. Only one coincidence can be noticed: The SZ annealed at the temperature of 175 °C still exhibits the increase in the microhardness at the layer

Fig. 5 The depth profile of the Vickers microhardness measured on the cross section of the bismuth sample exposed to dry sliding (**a**). In **b**, the same depth profiles but before cutting and taking measurements, the samples were annealed at the temperatures of 75, 100 and 175 °C during 1 h after sliding. The *error bar* for all the measured points is presented in **a**

adjoined to the worn surface. Thus, this measurement confirmed the thermal stability of the SZ close to the worn surface. However, one can notice the large scatter of the points, which shows that this is a crude method for the detection of the SZ.

4 Discussion

The SZ is the damaged region below the worn surface induced by sliding. The main feature of the SZ is the gradient of the strain and defect concentration, which leads to the work-hardening of this zone. The highest defect concentration and strain is at the worn surface and then decreases with the depth increase. The total depth of the SZ is large, it can reach the depth of a few hundreds of micrometers, and it seems independent of the sample hardness. Such a large expansion of the SZ was observed for ductile metals such as aluminum [23] and much harder

stainless steel [24]. We argue that the stream of dislocations generated directly at the surface in the asperities moving in the interior of the sample is responsible for the constitution of the SZ. The dislocations cannot move freely; they can stop at other dislocations that arrived earlier or other defects or precipitation. Around the dislocations, the point defects such as vacancies and jogs on the dislocation lines are present. It is well known that vacancies and interstitial atoms migrate at low temperature; however, due to the dislocation net, they are fixed in the lattice even at a higher temperature. Their depth profile at room temperature decreases exponentially with the depth increase. Nevertheless, when such a SZ is annealed, the recovery and recrystallization occur because the energy deposited during deformation is released. Assuming that this energy is distributed similarly to the defect concentration, i.e., it decreases with the depth increase, one should expect that the recovery and recrystallization should be faster close to the worn surface and slower deeper. Unfortunately, the studies of the annealing behavior of the SZ in pure bismuth and magnesium [12] have shown other types of behavior. The layer adjoined to the worn surface is not fully recrystallized even at the temperature close to the melting point. At deeper regions, we observed generation of new defects instead of their annihilation. The positron studies in pure copper [14] using another positron technique also revealed similar annealing, but the defects in the SZ were annealed at the temperature of 600 °C, i.e., much lower related to the melting point unlike for bismuth and magnesium. Nevertheless, the characteristic maximum induced due to the defect generation at the depth of about 80 μm was also observed.

At this stage, this surprising result can be explained as follows. In the deeper regions, the concentration of dislocations is lower; then after increase in the temperature, they can move freely. During their motion, they can generate point defects such as interstitial atoms or vacancies, and this causes the characteristic increase in the mean lifetime at the depth between 50 and 170 μm . The dislocations close to the worn surface, where their concentration is much higher, are more fixed, and they are not mobile like dislocations in the deeper regions. However, still there is not clear why in bismuth and magnesium much higher temperature is needed for the restoration of the SZ created by sliding than for the samples exposed to compression. This shows the unique properties of the SZ created during sliding in these metals.

Another explanation should be taken into account. Vacancies generated during sliding with the temperature increase become mobile and join together, creating voids. They also are traps for positrons, and their presence can also cause the increase in the mean positron lifetime. Such effect is observed for samples which surface was implanted

by electrons or ions at low temperature. In such conditions, a large number of point defects are generated. However, the coalescence of vacancy and void formation, for instance in Fe, takes place at low temperature [25]. When vacancy clusters are decorated by carbon or hydrogen atoms, they can be stable at a higher temperature, as it was observed by Moutanabbir et al. [26] in silicon. Nevertheless, one should point that the highest defect concentration in SZ is close to the surface; thus, one can expect that in the region close to the surface, voids concentration induced by the temperature should be higher than in deeper regions. Thus, the mean lifetime should also significantly increase close to the surface in comparison with deeper region. We did not observe such an effect in our experiments. However, it cannot be excluded that in the deeper regions the vacancy cluster formation has taken place, and they survive up to higher temperature.

The results can shed light on the dynamic recrystallization. Generally, this process occurs during hot deformation of metals; however, several authors discussed it also in the SZ during sliding wear. Bill and Wisander [27] and Dautzenberg [28] reported on this phenomenon in copper, and Kuo and Rigney in aluminum [29]. They observed the grains free of dislocations in microstructure of their samples using TEM. It is well known that sliding contact of two bodies is accompanied by increase in temperature in this region, which induces processes affecting the SZ constitution. Locally at the asperities, the so-called flash temperature can arise up to hundreds of degrees centigrade [14]. However, the time when such a temperature is hold on is extremely short, i.e., few of microseconds. Up to now, our positron annihilation results have not revealed the significant reduction in the point defect concentration in the layer adjoined to the worn surface, which could indicate the process of recrystallization. Even application of the slow positron beam technique, which allows locating of positrons at the depth below 1 μm from the worn surface, supports this [30]. There are two explanations for this fact. The positron method in opposition to the TEM observations allows us to scan average information from the regions of micrometer size for slow positron beam or dozen of micrometers in the conventional experiment using a positron source. Additionally, positron current is negligible and cannot affect the sample structure as it can happen in TEM observations where the electron current is higher by several orders of magnitude. It is not excluded that the sliding conditions can be important to initiate the dynamic recrystallization process as it was reported by Dautzenberg [28]. The sliding velocity used for the generation of SZ in copper by this author was twenty times higher than in our experiment. Nevertheless, the experiment with annealing of the SZ indicates rather the high thermal stability of the SZ just close to the worn surface.

5 Conclusions

The annealing behavior of the SZ in pure bismuth exposed to dry sliding detected by positron annihilation reveals its high thermal stability in comparison with the compressed sample. For the samples after compression the restoration of their structure is completed at the temperature of about 60 °C. However, after dry sliding, this is observed at 260 °C, i.e., 11 °C below the melting point. The annealing at the temperatures of 75, 100 and 175 °C shows the change of the profile shape, indicating generation of defects instead of expected defect annealing at the depth between 50 and 170 µm. Defects are still present in the layer adjoining to the worn surface. It is interesting that isothermal annealing at the temperature of 100 °C performed for the compressed and the worn samples shows also the significant differences. The compressed sample rebuilt its structure to the initial one after 80-min annealing, whereas the sample exposed to sliding needs much higher time, i.e., of 1,000 min. The results presented in this paper fully confirm the results obtained for pure magnesium samples exposed to sliding or compression. They are also in agreement with the results obtained for pure copper.

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References

1. Zum Gahr, K.-H.: *Microstructure and Wear of Materials*. Elsevier, Amsterdam (1987)
2. Suh, N.P.: An overview of the delamination theory of wear. *Wear* **44**, 1–16 (1977)
3. Jahanmir, S., Suh, N.P.: Mechanics of subsurface void nucleation in delamination wear. *Wear* **44**, 17–38 (1977)
4. Jahanmir, S., Suh, N.P., Abrahamson, E.P.: Microscopic observations of the wear sheet formation by delamination. *Wear* **28**, 235–249 (1974)
5. Salesky, E.J., Fisher, R.M., Ritchie, R.O., Thomas, G.: The nature and origin of sliding wear debris from steels. In: Ludema, K.C. (ed.) *Wear of Materials*, pp. 434–445. ASME, New York (1983)
6. Marcinkowski, M.J.: A surface dislocation model of wear. *J. Mat. Sci.* **1**(9), 1296–1306 (1984)
7. Hull, D.: *Introduction to Dislocations*. Pergamon Press, Oxford (1975)
8. Byrne, J.G.: Dislocation studies with positrons. In: Nabarro, F.R.N. (ed.) *Dislocations in Solids*, vol. 6, pp. 264–318. North-Holland, Amsterdam (1983)
9. Dryzek, J., Dryzek, E., Stegemann, T., Cleff, B.: Positron annihilation studies of subsurface zones in copper. *Tribol. Lett.* **3**, 269–275 (1997)
10. Tanigawa, S., Shinta, I., Iriyama, H.: Migration of vacancies in deformed metals studied by positron lifetimes. In: Coleman, P.G., Sharma, S.C., Diana, L.M. (eds.) *Positron Annihilation*, pp. 401–403. North-Holland, Amsterdam (1982)
11. Dryzek, J.: Positron trapping model in fine grained sample. *Acta Phys. Polon. A* **95**, 539–545 (1999)
12. Dryzek, J.: Positron annihilation studies of recrystallization in the subsurface zone induced by friction in magnesium—effect of inhomogeneity on measured positron annihilation characteristics. *Appl. Phys. A* (2013). doi:10.1007/s00339-013-7667-6
13. Dryzek, E., Sarnek, M., Siemek, K.: Annealing behaviour of plastically deformed stainless steel. *Nukleonika* **58**, 215–220 (2013)
14. Dryzek, J., Kozłowska, A.: Study of recrystallization process in subsurface zone induced by sliding using positron annihilation techniques. *Tribol. Int.* **43**, 447–454 (2010)
15. Humphreys, F.J., Hatherly, M.: *Recrystallization and Related Annealing Phenomena*. Elsevier, Amsterdam (2004)
16. Dryzek, J.: Positron studies of subsurface zone created in sliding wear in bismuth. *Tribol. Lett.* **40**, 175–180 (2010)
17. Dryzek, J.: *Charakterystyki Procesu Anihilacji Pozytonów w Fazie Skondensowanej*. Wydawnictwo Uniwersytetu Jagiellońskiego, Kraków (2005)
18. Campillo Robles, J.M., Ogando, E., Plazaola, F.J.: Positron lifetime calculation for the elements of the periodic table. *J. Phys.* **19**, 176222 (20 pp) (2007)
19. Dryzek, J., Singleton, D.: Implantation profile and linear absorption coefficients for positrons injected in solids from radioactive sources ^{22}Na and $^{68}\text{Ge}/^{68}\text{Ga}$. *Nucl. Instr. Methods Phys. Res. B* **252**, 197–204 (2006)
20. Kansy, J.: Microcomputer program for analysis of positron annihilation lifetime spectra. *Nucl. Instr. Methods Phys. Res. A* **374**, 235–244 (1996)
21. Somieski, B., Krause-Rehberg, R.: Application of the positron lifetime spectroscopy as a method of non-destructive testing. *Mater. Sci. Forum* **175–178**, 989–992 (1995)
22. Dryzek, J., Dryzek, E.: Subsurface zone studies in the AK 12 alloy and metal matrix composite AK 12 with Al_2O_3 using positron annihilation spectroscopy. *Wear* **261**, 549–555 (2006)
23. Dryzek, J., Dryzek, E.: Subsurface zone in aluminum by positron lifetime spectroscopy. *Tribol. Lett.* **17**, 147–153 (2004)
24. Dryzek, J., Horodek, P., Wróbel, M.: Use of positron annihilation measurements to detect the defect beneath worn surface of stainless steel 1.4301 (EN) under dry sliding condition. *Wear* **294–295**, 264–269 (2012)
25. Hautojärvi, P., Johansson, J., Vehanen, A., Yli-Kauppila, J.: Vacancy-carbon interaction in iron. *Phys. Rev. Lett.* **44**, 1326 (1990)
26. Moutanabbir, O., Terrault, B., Chicoine, M., Shiettekatte, F.J., Simpson, P.: Influence of isotopic substitution and He co-implantation on defect complexes and voids induced by H ions in silicon. *Phys. Rev. B* **75**, 075201–0752011 (2007)
27. Bill, R.C., Wisander, D.: Recrystallization as a controlling process in the wear of some fcc metals. *Wear* **41**, 351–363 (1977)
28. Dautzenberg, J.H.: The role of dynamic recrystallization in dry sliding wear. *Wear* **60**, 401–411 (1980)
29. Kuo, S.M., Rigney, D.A.: Sliding behavior of aluminum. *Mater. Sci. Eng. A* **157**, 131–143 (1992)
30. Dryzek, J., Dryzek, E., Cleff, B.: Study of subsurface zones induced by friction and wear using positron annihilation method. *Appl. Surf. Sci.* **116**, 236–238 (1997)