Effect of ultrasonic-electric surface modification on metal material

D Liu, J Z Zhao, Y Gao, J B Liu, Y L Shen and C Meng
Northwest Institute of Mechanical and Electrical Engineering, Xianyang 712099, PR China

E-mail: liudan0501happy@163.com

Abstract. With the demand for the materials are increasing in the field of military and civilian application with each passing day, an ultrasonic-electric surface modification treatment was employed to improve the surface properties of metal material with different heat-treated conditions. The surface properties of the specimens after conventional cutting and ultrasonic-electric surface modification treatment were characterized, respectively. A grain refinement layer was formed on the surface of different heat-treated specimens after ultrasonic-electric surface modification treatments. The average grain size on the top surface was refined into the submicrometer or nanometers scale. This is caused mainly by two aspects: one is the accumulation of initial tiny particles during deformation; the other is that the ferrite is smashed into pieces due to micro-fatigue damage. Moreover, it was found out the specimens after ultrasonic-electric surface modification treatment had shown the optimal surface properties and friction-wear properties.

1. Introduction

With the demand for the materials are increasing in the field of military and civilian application with each passing day, and applications to different heat-treated conditions of 40Cr17Mo steels are of a special interest. The sustainable growth in military-civilian technology and consumption of metal material has also influenced the tool steel market with its demand for increasing amounts and good availability, machinability of tool steels. On one hand, due to the diversities of equipment and process technologies limitation, workpieces after machining probably caused the degradation of properties. On the other hand, there existed obvious shortages, such as low processing efficiency, seriously cutting tool wear and high cutting force during the processing. Therefore, in order to obtain outstanding comprehensive properties in a single material, novel techniques should be used in priority for this materials processing.

High-efficiency processing method, known as ultrasonic striking treatment, has attracted more and more attention on materials surface modification especially for improving the surface mechanical properties. Many surface severe plastic deformation (SSPD) processes have been invented taking efficiency and production cost factors into account. The key feature of these processes, surface mechanical attrition treatment (SMAT) [1], surface rolling [2], ultrasonic shot peening (USSP) [3] and surface nanocrystallization (SNC) [4], is severe plastic deformation (SPD) at the surface region to induce nanocrystallization at the surface while maintaining a coarse-grained interior. Lu and Lu [5] summarized the behavior of the engineering materials by means of the SNC techniques, and analyzed...
the industrial application possibility. Thus, the nanocrystalline surface generated through SSPD has been shown huge potential for improvement of the tensile strength, wear resistance and fatigue strength in various materials.

Another high-energy electropulsing treatment (EPT), as a novel style of energy input assisted processing technology aiming to improve the mechanical properties and formability of materials has emerged. Conrad [6] and Okazaki et al. [7] indicated that the concurrent application of direct current (DC) pulses rendered significant enhancement of the rates of recovery and recrystallization during the isochronal annealing of cold-worked copper. Jiang et al. [8] and Zhu et al. [9] studied that electroplasticity is in favor of enhancement of strength applied within a short time and lower temperature during the heat treatment and/or deformation. Therefore, due to the very short time of EPT, the nuclei have not sufficient time to grow, and then fine grains can be obtained finally. The application of high-density electropulsing is proved to be an effective method for improving the microstructures and properties of materials.

It is regretful that most of surface modification methods are high-cost and low-efficiency methods, which severely hinder the further development in the materials application. Hence, we integrated the SSPD and EPT methods into single plastic deformation in order to improve efficiency and quality of workpieces. Nevertheless, the effect of UESM treatment has not yet been investigated in depth. In particular, it is still unknown if the UESM treatment have limit effects on the surface properties of different heat-treated 40Cr17Mo steel. The aim of this work was to investigate the UESM effects on the surface microstructure evolution and mechanical properties of different heat-treated conditions of 40Cr17Mo steel.

2. Experimental procedure

The samples were preliminarily strengthened on a self-designed platform based on the CJK0632 lathe and ultrasound installation with steel balls was used as a working tool. A schematic diagram for the experimental platform is presented in figure 1. Balls were rotated to contact the surface of rods directly by automatic controlling forced under the defined pressure recorded by the resistance dynamometer. The electropulsing procedure was performed by capacitor banks of 100 F self-designed power generator and it characterizes a special sharp wave pulse current (as shown in figure 1), which is liable to exert a strong electro-plasticity effect on materials.

Figure 1. Schematic diagram of USM and UESM treatments.
All the rods were pre-processed to the diameter of 16 mm by the traditional dry cutting. The 40Cr17Mo steel was mainly composed of the α-phase and the carbide and its chemical composition of the investigated alloys listed in Table 1. In the first group, the 40Cr17Mo steel annealed at 750~800 oC for 1~3 h after furnace cooling was investigated. The revolving speed of the lathe spindle was fixed at 500 r/min. The motion times (t) of the ultrasound installation acted on the specimens surface was equal to 1, 2 and 3 under the ultrasonic pressure of 730 N with assistance of electropulsing of the frequency of 400 Hz and voltage of 60 V. The current density of electropulsing jmax was 6.3106 Am-2 and the pulse duration tp was 58 μs. Three specimens of each condition were treated (Group I).

Table 1. The chemical composition of the investigated alloys (wt. %).

|   | C    | Cr   | Mo   | Si  | S   | P   | Mn   | Ni  |
|---|------|------|------|-----|-----|-----|------|-----|
|   | 0.35~0.43 | 16.01~16.10 | 0.94~1.01 | 0.36~0.48 | 0.001 | 0.017 | 0.32~0.37 | 0.19~0.21 |

The 40Cr17Mo steel quenched with nitrogen gas by vacuum heating to 1030 °C for 1.5 h and then tempered at 400 °C for 3 h was investigated. The revolving speed of the lathe spindle was fixed at 900 r/min. The motion times (t) of the ultrasound installation acted on the specimens surface was equal to 1, 3 and 5 under the ultrasonic pressure of 1000 N with assistance of electropulsing of the frequency of 500 Hz and voltage of 70 V. The current density of electropulsing jmax was 6.0×106 A·m−2 and the pulse width was 58 μs, which were labeled as Group II.

The surface roughness of the specimens was tested on a contact surface profiler (Taylor SURTRONIC 25). The microhardness was characterized using a micro-Vickers hardness tester (HVS-1000B) on the cross section of samples. The parameters used in the microhardness test were 0.987 N and dwell time of 15 s. Each sample was measured 5 times to obtain the mean value. The Nano Indenter G200 was used to test the nano-hardness, Young's modulus and the friction-wear characteristics. The sapphire spherical head with the curvature radius of 500 μm was selected in the friction-wear test. To compare the change of the surface structure, three-dimensional (HIROXKH-7700 digital microscope) test was carried out to observe the microstructure. By setting the bottom zone and the top zone under the lamp scope, composite image of 20 photos was produced. The etching solution was composed of HF, HNO3 and H2O in the ratio of 1:3:7. The microstructure of the samples was observed using high resolution of scanning electron microscope (Hitachi S4800).

3. Results

3.1. Surface roughness and surface topography

Figure 2 shows the surface roughness and macrostructure evolution of 40Cr17Mo steel after conventional cutting and UESM treatments. For the Group I, the Ra value by initial dry cutting is 3.31 μm. The surface roughness of UESM at 1t, 2t, and 3t were 0.29 μm, 0.26 μm, and 0.29 μm, respectively. UESM at 2t has the lowest surface roughness and the best surface quality. In this study, UESM technology can do obtain a good surface. Suh et al [10]. has reported that the surface roughness Ra value of SKD-61 was 0.08 μm after UNSM, and Lee et al [11]. has reported the surface roughness of A6061-T6 after UNSM was 0.17 μm. Therefore, it is reasonable to expect a smoother surface for 40Cr17Mo steel if the vibration numbers and other parameters of UNSM are predefined appropriately. Many parallel lines generated by the conventional cutting process were clearly observed from the surface features of the specimen. Cao et al [12]. found that these lines should be the process which induce stress concentration and accelerate fatigue fracture in the fatigue tests. 3D digital micrographs reveal the surface features of UESM treatments. From this, it can be concluded that the UESM treatments can reduce many microcracks and improve the surface quality of 40Cr17Mo steel.

For the Group II, as for the conventional cutting without any auxiliary field, the Ra value was reached 1.95 μm in the figure 2. It can be seen that UESM treatment decreased surface roughness
significantly from 1.95 to 0.25 μm. The surface quality after conventional cutting caused non-smooth and visible parallel lines distribution as shown in the surface macrographs. In contrast, UESM at 1t, 3t and 5t show good surface quality without obvious defects. To be sure, UESM at 3t had the best surface quality.

**Figure 2.** Surface roughness and macrostructure evolution after conventional cutting and UESM treatments of 40Cr17Mo steel with two groups.
3.2. Microhardness
The micro-Vickers hardness along the depth from the UESM treated external surface layer was measured for cross-sectional samples of two groups, as depicted in figure 3. There was a remarkable increase in the surface hardness for all the samples after UESM treatment. As shown in figure 3a, the surface hardness of cutting sample is only 301HV by the single drying cutting effect. Under the UESM, the microhardness is increased gradually. Introduction of UESM at 1t and UESM at 3t improves the microhardness considerably. When UESM motion times were added to 2t, the surface microhardness is even improved by 81.7% compared with that of the cutting sample. Most importantly, the peak surface hardness value is about twice than that of the original coarse grained matrix after cutting treatment. It can be observed that number in the flat curve had no significant effect on the subsurface hardness, and Group II had a thinner deformation zone than Group I. The difference is the surface layer in a depth of ~150 µm significantly varied with the different strike numbers.

UESM also enhances noticeably the surface microhardness of 40Cr17Mo steel as shown by figure 3b. The microhardness of the dry cutting of 40Cr17Mo specimens was about 468 HV. The value of microhardness of UESM at 1t, 3t and 5t was 555 HV, 620.7 HV and 564.3 HV (which is about twice that of the coarse grained matrix), respectively. The microhardness after UESM rapidly decreases to about 50 µm and then decreases more gradually down to 400 HV at a depth of 100 um. Noticeably, the first 2 points of UESM at 3t have a hardness of about 570 HV and 418.5 HV. Because their distances from the top surface to the inner refined layer are 21 µm, and 31 µm, they are refined structure layer of the specimen instead of the nanocrystal layer. The UESM treatment could harden the surface to improve the fatigue strength, but at the same time, it also induced micro cracks on the surface that could become fracture starting points. At low static loads, the effects of the UESM-induced improve hardness, so the fatigue strength was enhanced. However, when excessive static loads were exerted, the specimen surface could be broken, and more surface cracks could be induced, which counteracted the enhanced hardness and made the fatigue strength decrease (as shown in figure 3).

![Figure 3](image-url)

**Figure 3.** Hardness profile of conventional cutting and auxiliary field cutting of (a) Group I; (b) Group II.

3.3. Microstructure evolution
The microstructure of 40Cr17Mo steel near the treated surface is depicted by figure 4 and figure 5, which illustrates that a refining layer and a diffusion zone were formed on the 40Cr17Mo steel sample’s surface during UESM process. The bainite structure after conventional cutting was observed in figure 4a, which presents uniform microstructure before treatment. When UESM at 2t treatment is applied on the materials surface, a thin surface layer of plastic strain (about 120 µm) is introduced with compressed grains and smashed grain boundaries, as shown by figure 4b. SEM micrographs showing the microstructure of the UESM specimens at 2t were presented in figure 4c, figure 4d and figure 4e, which shows that matrix structure, and the treated surface was composed of the refined grains. Figure 4d reveals that on the top of the refined layer grain size was decreased to a few submicrometer or
nanometers. Both the deformation bands and particles of ferrite can be discerned clearly. Additionally, a large amount of deformation carbide particles were also present. As shown in figure 4e, broken particles about 400 nm were present, and it was shown that 20~30 nm scale particles appeared on the grain boundaries in the central zone. Many initial tiny particles were accumulated during the deformation. In addition, the ferrite and carbide were smashed into pieces due to the micro-fatigue damage.

Figure 4. 3D micrograph of cross-section specimens of Group I after treatment of: (a) conventional cutting; (b) UESM at 2t; SEM micrograph showing the microstructure of the UESM specimens at 2t of (c) central zone; (d) surface zone; (e) surface zone.

Figure 5 shows the microstructure evolution of the 40Cr17Mo specimens of Group II under UESM treatment at 3t. It can be seen that compared with the parent phases (shown in figure 5a), the treated surface are composed of refined grains and the width of the refined zone was about 50 μm, as can be seen by figure 5b. To further study the microstructure of the surface, SEM was utilized to observe the surface of the specimens. The cross-sectional SEM images for the specimens treated with UESM at 3t are shown in figure 5c, figure 5d and figure 5e. From the SEM images of figure 5c, it is easy to see that the fracture of the specimens was initialized from the surface. Compared with figure 5c and figure 5d, it is obvious that the surface microstructures have severe plastic deformation (mainly in the blocky ferrite). Both the deformation bands and particles of ferrite can be discerned clearly. Additionally, a number of deformation carbide particles were also present. As shown in figure 5e, broken ferrite particles about 300 nm were presented, and it was shown that a few of nano-particles
appeared in the blocky ferrite and the central zone. The UESM surface also showed a gradient grain size distribution from the top surface to the interior.

Figure 5. 3D micrograph of cross-section specimens of Group II after treatment of: (a) conventional cutting; (b) UESM at 3t; SEM micrograph showing the microstructure of the UESM specimens at 3t of (c) central zone; (d) surface zone; (e) surface zone.

4. Discussion
Cao et al. [12] confirmed that ultrasonic nano-crystal surface modification (UNSM) can improve the surface roughness, microhardness and compressive residual stress; however, the working surface could deteriorate to a certain extent. Except for the common shear deformation, local fatigue damage is thought to be another mechanism under UESM, which favors the decrease of the deformation resistance. In this case, electroplastic processing not only can improve the surface quality, but also can decrease a number of defects as well as improve the plasticity of the materials. The surface roughness value for all UESM specimens was kept identical.

According to the previous study, Rabinowice [13] indicated that the surface hardness has a close relationship with the electric current. In the process of UESM treatment, increased surface microhardness results from the increase in piled-up dislocations and the decrease in mobile dislocations induced by UESM. When the motions times of UESM treatment is relatively low or overtop, the microhardness increases considerably. The athermal effect of UESM assists the
movement of dislocations and vacancies, which decreases the density of piled-up dislocations. Ye et al. [14] indicated that the electron wind force induced by electropolishing assists dislocation motion and opens tangles of dislocations, which is facilitated in introducing more mobile dislocations of ultrasonic shock and forming subgrains through dislocations climbing ahead of dynamic recrystallization. Both of the effects of UESM substantially accumulate more piled up dislocations and improve the microhardness. In the meantime, the improvement of store energy is facilitated in spreading the plastic strain of ultrasonic shock into the materials interior, which increases the processing depth and strain capacity with the occurrence of deformation zones. Furthermore, the increase of the mobility of the dislocation will lead to a decrease in macrodefects growth rate. Indentation of microhardness is the macro-measurement of local region so that the increased processing depth of plastic strain layer is facilitated in microhardness improvement. For UESM sample at suitable motion times, the microhardness is further noticeably improved to the maximum (550 HV and 620.7 HV). Conrad [15] and Gai et al. [16] found that except the athermal effect, the thermal effect caused by Joule heating plays an important role in assisting the movement of dislocations and atoms diffusion. As a results, an ideal improvement in microhardness is obtained at a relatively low temperature and a high strain capacity.

Another reason is that the refined grains are expected to increase in hardness as a consequence of the predictions based on the Hall-Petch relationship. Previous studies conducted by Zhou et al. [17] and Lee et al. [18] had confirmed that α-phase grain more easily possesses nano-size properties with S2PD treatment for multi-phase alloys, on account of the hard particles, and forms a deeper deformation layer. α-Phase structure can be broken into pieces, resulting in the formation of the refined layer. It is well known that plastic deformed layers have a strong correlation with microstructures and mechanical properties in many metallic materials. This plastically deformed layer leads to strain hardening and induces compressive stress at the surface of the metallic materials. Also, grain boundaries became less apparent by the deformation of ferrites and carbides were crushed after the UESM treatment.

Enhancement of the mechanical properties accompanies the existence of the change of microstructure. In a later study Wang et al. [19] further specified a main role strain rate in obtaining the structural features on the nanometer scale which favor good mechanical properties of copper. In the UESM process the velocity of the balls on the ultrasonic device determines the strain rate in the treated sample. Microstructural investigations have revealed that the UESM process can introduce ultrafine-grained microstructures in the surface layer of materials. The closer the distance from the top surface of the layer, the finer of the grains size was obtained, due to the increment of strain over the whole deformed layer. Three levels of grain sizes are present from the surface: (1) nano-grained structure (first level), (2) submicro-grained structure (second level), and (3) interior matrix grains (third level). As the top surface is approached, the grains appear finer, more misoriented and more uniformly distributed. Hansen [20], Liu et al. [21] and Hansen et al. [22] found that dislocation gliding, accumulation, interaction, tangling, and spatial rearrangement cause grain subdivision in order to accommodate plastic strains during deformation in polycrystalline materials. Several plastic straining could produce a high density of dislocation, which are effective at blocking slip at increasing strains and as a result, the mechanism responsible for accommodating large amounts of plastic straining is to subdivide original grains into subgrains with dislocations forming their boundaries. The multidirectional peening may lead to the change of slip systems with the strain path even inside the same subgrain, much different from the deformation mode caused by other UESM processes. Wu et al. [3] concluded that the dislocations not only interact with other dislocations in the current active slip systems, but also interact with inactive dislocations generated in previous deformations. This will promote the deformation of subgrains. As a consequence, the effectiveness of grain refinement is enhanced.

Fu et al. [23] and Kumar et al. [24] have previously reported that improvement in surface hardness by SMAT was beneficial in increasing the friction and fretting wear resistance. It was also inferred that UESM treatment was an effective method to mitigate fretting wear. This improvement may be
attributed to the increased hardness and low friction coefficient. Therefore, as for the low surface roughness, it may play an important role in minimizing the fretting wear rough surface.

4.1. Nano-hardness
The nano-indentation hardness test is carried out at room temperature. A normal load of 5g is used for the two groups. Figure 6 shows the nano-hardness of two groups and the samples are divided into 2 parts. One part is the dry cutting, the other is processed by UESM. The reported nano-hardness is measured along the direction from the top surface to the central zone, which are obtained at different locations on the polished and etched sample. As shown in figure 6a, the result of two parts samples are closer to nano-hardness under the given load, but it can be seen that the general nano-hardness of UESM samples is more higher than that of the untreated sample under the same load. There are a few data not according with the trend and the effect of that may be carbides. The hardness after the distance of 220 μm from the edge is changed to be steady, which is consistent with the above-mentioned results of vickers hardness.

The curve of nano-hardness distribution of the Group II is shown in figure 6b. The average nano-hardness of the cutting sample is about 4 GPa, while that of UESM is much higher, which is because that the number of refined particles after UESM treatment is increased. The bits of data are opposite to the trend, which is for the ferrite matrix selected as the measuring point. After the distance of 230 μm from the edge, the curve is gradually stable. This means that UESM treatment is efficient to improve surface hardness no matter the heat-treated conditions for 40Cr17Mo steels.

4.2. Supplement of in-depth studying in annealed 40Cr17Mo steel
Hardness and elastic modulus are measured by the patent technology of continuous stiffness measurement conducted by Oliver and Pharr [25]. Each sample needs to be processed the indentation tests with 10 different locations at least. High load cells are used to get the larger pressure depth and the total indentation is about 5-6 N. A is the drying cutting sample and B is UESM 2t sample.

4.2.1. Nano-hardness and Young’s modulus. Both continuous stiffness measurement technique and high load function are applied to obtain the curve of the average hardness or Young’s modulus vs indentation depth, as shown in figure 6 and figure 7. Figure 6 shows that the modulus increased up to a value of 250 GPa during the first 400 nm and gradually decreased slightly. However, there are a few differences between sample A and B. Among 1-2 μm, a slightly lager gap have been produced. That is mainly for the uneven distribution of carbides in the original materials. By comparison, the sample after UESM treatment has better uniformity, as similarly seen in figure 7 of the tendency of hardness. This illustrates that UESM treatment has little difference on the Young’s modulus of 40Cr17Mo steel, but not for hardness.
The curve of hardness distribution in the drying cutting and UESM treatment are shown in figure 8, respectively. The reported hardness is measured along the direction from the top to the central zone on the sample of half rods. As seen in figure 8a, it is worth to notice that the experiment results on different locations of indentations have obvious dispersion. The annealed 40Cr17Mo steel mainly consists of ferrites and carbides. As for the great difference of hardness between matrix and carbides, the result is inhomogeneous. Severe plastic deformation on the surface leads to the hardness’s fluctuation in 1μm. In figure 8b, we compared the curve of hardness of the sample after UESM 2t. The
hardness increased from an initial value of 3 GPa up to a value of 6.5 GPa during the first 400 nm and gradually decreased slightly to stabilize to a value of about 4 GPa. In addition, it can be seen that the hardness is 50% larger than that of the central zone. What’s more, the more near to the surface, the higher to the hardness, as the increase of depth, hardness is gradually decreased. When the displacement is beyond 4 μm, hardness is carried to stabilization. It can be induced that the comprehensive hardness of samples after UESM treatment has improved so that it has the good uniformity and repeatability, including the ferrite matrix and carbides.

Figure 8. Hardness of test samples: (a) A; (b) B.

4.2.2. Friction and wear properties. As shown in figure 9, the relationship between wear depth and distance is investigated. 1:1 is for the primary morphology, 1:2 is the first wear morphology, 1:11 is the tenth and the rest is done in the same manner. Figure 9a shows that all curves have better coincidence. In the scratch distance of 200 μm, the most wear depth is 1.3 μm. However, as shown in figure 9b, all curves were worn less than the original curve, the wear depth of which were nearby surface closely. In the measured range of the scratch distance, the wear loss of all curves showed tends to softly fluctuant on the surface. This means that UESM treatment is more efficient in improving the wear resistance of the 40Cr17Mo steel own to the surface refined layers.

Figure 9. Relationship between wear depth and distance: (a) sample A; (b) sample B.

Figure 10 shows the friction coefficient as a function of scratch distance for 40Cr17Mo steel specimens before and after the UESM treatment. For the A sample, the friction coefficient increased within 200μm of scratch distance up to 0.23 and down to 0.08. Also, the friction coefficient fluctuated
after it increased abruptly. The fluctuation of the friction coefficient may be attributed to the localized fracture of the transfer layer and interaction of particles at the sliding interface. Waterhouse [26] has well reported that titanium alloys tend to experience material transfer to the counter surface when rubbed against other metals or ceramics. For the sample B, the friction coefficient decreased to 0.1 around in the measured range of 200μm, which is lower than that shown in figure 10a. The friction coefficient of the sample of A is unstable mutations. On the contrary, all curves of B have good coincidence and been gentle. It was postulated that the observed reduction in friction coefficient of the UESM-treated specimen compared to that of the untreated specimen was related to the increase in hardness and compressive residual stress as well as alteration in the microstructure after the UESM treatment.

![Figure 10. Variation of the friction coefficient of 40Cr17Mo steel samples: (a) A; (b) B.](image)

Because refined layer of sample B has high strength and hardness, grinding grain into the depth of the surface is small and match pair moving relative to the surface resistance is small so that it has lower friction coefficient and wear loss. Meanwhile, Wang et al. [27] found that under the same load, fatigue wear is difficult to occur on the sample with refined surface layer comparing to the original sample because that nano-structure layers go against the crack propagation on account of the surface of which has small amount of repeated plastic deformations. The reasons of the above mentioned preferential effects may include two: one is the surface hardening effect provided by UESM treatment, the other is the lubrication effect owing to the lower surface roughness conducted by UESM treatment.

5. Conclusions

The effect of ultrasonic-electric surface modification treatment on the surface microstructure evolution and mechanical properties of different heat-treated conditions of 40Cr17Mo steel was investigated. Based on the above experimental results, the following conclusions may be drawn:

1. By UESM treatment, Group I and Group II specimen surface roughness was drastically decreased from 3.31 μm and 1.95 μm to 0.26 μm and 0.25 μm, respectively.

2. Surface hardness of Group I and Group II specimen increases from 301 HV to 550 HV and from 468 HV to 621 HV, respectively, after the UESM treatment.

3. The optimized parameter for UESM treatment for 40Cr17Mo steel of Group I and Group II in cutting processing was at 2t and 3t, respectively.

4. The strengthened surface layer comprised of a gradient of grain sizes distribution from the top surface with submicron or nanometers to the interior with micrometers.

5. The mechanism for the above phenomenon is attributed to the micro-fatigue damage associated with decreasing deformation resistance and enhanced the dislocation mobility.

6. UESM can decrease friction coefficient and wear loss efficiently for the high surface hardness and low roughness.
References

[1] Tao N R, Wang Z B, Tong W P, Sui M L, Lu J and Lu K 2002 Acta Mater. 50 4603-16
[2] Hanus E, Ericsson T, Lu J and Decomps F 1993 J. Phys. IV France 3 1817-20
[3] Wu X, Tao N, Hong Y, Xu B, Lu J and Lu K 2002 Acta Mater. 50 2075-84
[4] Dai K, Villegas J, Stone Z and Shaw L 2004 Acta Mater. 52 5771-82
[5] Lu K and Lu J 1999 J. Mater. Sci. Technol. 15 193-7
[6] Conrad H 2000 Mater. Sci. Eng. A 287 227-37
[7] Okazaki K, Kagawa M and Conrad H 1979 Scripta Metall. 13 473-7
[8] Jiang Y B, Tang G Y, Shek C, Zhu Y H and Xu Z H 2009 Acta Mater. 57 4797-808
[9] Zhu R F, Liu J N, Tang G Y, Shi S Q and Fu M W 2012 J. Alloy. Compd. 544 203-8
[10] Suh C M, Song G H, Suh M S and Pyoun Y S 2007 Mater. Sci. Eng. A 443 101-6
[11] Lee C J, Murakami R I and Suh CM 2010 Int. J. Mod. Phys. B 24 2512-17
[12] Cao X J, Pyoun Y S and Murakami R 2010 Appl. Surf. Sci. 256 6297-303
[13] Rabinowice E 1967 Friction and Wear of Materials Wiley New York pp 10-30
[14] Ye X X, Liu T, Ye Y D, Wang H B, Tang G Y and Song G L 2015 J. Alloy. Compd. 621 66-70
[15] Conrad H 2002 Mater. Sci. Eng. A 322 100-7
[16] Gai P L, Zhang K and Weetrman J 2007 Scripta Mater 56 25-8
[17] Zhou L, Liu G, Ma X L and Lu K 2008 Acta Mater. 56 78-87
[18] Lee W B, Cho K T, Kim K H, Moon K I and Lee Y 2010 Mater. Sci. Eng. A 527 5852-57
[19] Wang K, Tao N R, Liu G, Lu J and Lu K 2006 Acta Mater. 54 5281-91
[20] Hansen N 1990 Cold deformation microstructures Mater. Sci. Technol. 6 1039-47
[21] Liu Q, Jensen D J and Hansen N 1998 Acta Mater. 46 5819-38
[22] Hansen N, Huang X and Hughes D A 2001 Mater. Sci. Eng. A. 317 3-11
[23] Fu Y Q, Loh N L, Batchelor A W, Liu D X, Zhu X D, He J W and Xu K W 1998 Surf. Coat. Technol. 106 193-7
[24] Kumar S A, Raman S G S and Narayanan T S N S 2012 Adv. Mater. Res. 463 137-41
[25] Oliver W C and Pharr G M 1992 J. Mater. Res. 7 1564-83
[26] Waterhouse R B 1992 Fretting fatigue Int. Mater. Rev. 37 77-98
[27] Wang Z B, Yong X P, Tao N R, Li S, Liu G, Lu J and Lu K 2001 Acta Metall. Sin. 37 1251-55