

Article

Micromorphology, Microstructure, and Wear Behavior of AISI 1045 Steels Irregular Texture Fabricated by Ultrasonic Strengthening Grinding Process

Jinrui Xiao ^{1,2,*}, Zhuan Zhao ^{1,3}, Xincheng Xie ^{1,4}, Zhongwei Liang ^{1,2} , Zhaoyang Liu ^{1,2}, Xiaochu Liu ^{1,2,*} and Ruizhi Tang ²

¹ Guangdong Engineering Research Centre for Strengthen Grinding and Micro/Nano High-Performance Machining, Guangzhou University, Guangzhou 510006, China; zhaozhuan2008@gmail.com (Z.Z.); cxixie@163.com (X.X.); liangzhongwei@gzhu.edu.cn (Z.L.); liuzy@gzhu.edu.cn (Z.L.)

² School of Mechanical and Electrical Engineering, Guangzhou University, Guangzhou 510006, China; tangruizhi1988@163.com

³ School of Physics and Materials Science, Guangzhou University, Guangzhou 510006, China

⁴ School of Electromechanical Engineering, Guangdong University of Technology, Guangzhou 510006, China

* Correspondence: meexiaojinrui@gzhu.edu.cn (J.X.); xiaochuli64@163.com (X.L.)

Abstract: In this study, the tribological properties of three AISI 1045 steel samples were investigated. Two samples were treated with ultrasonic shot peening (USP) and ultrasonic strengthening grinding process (USGP), respectively, while the other one was only treated with a polishing process. Sample properties, such as surface morphology, roughness, microhardness, elastic modulus, frictional coefficient, and phase structures were analyzed. Results show that the sample treated with USGP had the best tribological properties. It realized the highest surface roughness, microhardness, and elastic modulus. Compared with a polished sample, the roughness of the sample treated with USGP increased by 157%, and the microhardness and elastic modulus improved by 32.8% and 21.3%, respectively. Additionally, USGP provided an average frictional coefficient of 0.4, decreasing approximately 45% compared to polishing. The possible mechanisms of USGP surface texturing were discussed. The findings denote that USGP could be an efficient approach to improve the fatigue life of some mechanical components.

Keywords: ultrasonic strengthening grinding process; irregular texture; micromorphology; microstructure; microhardness; tribological properties



Citation: Xiao, J.; Zhao, Z.; Xie, X.; Liang, Z.; Liu, Z.; Liu, X.; Tang, R. Micromorphology, Microstructure, and Wear Behavior of AISI 1045 Steels Irregular Texture Fabricated by Ultrasonic Strengthening Grinding Process. *Metals* **2022**, *12*, 1027. <https://doi.org/10.3390/met12061027>

Academic Editor: Slobodan Mitrovic

Received: 21 May 2022

Accepted: 13 June 2022

Published: 16 June 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Tribological properties are an essential factor affecting the stability and reliability of mechanical equipment, especially in the components of the automated transmission system, such as bearing rollers and gears [1]. The intense friction on a surface will lead to severe surface wear and even driving failure [2,3], which is mainly due to the rupture of oil film and lubricant failure, resulting in dry friction. Therefore, it is necessary to enhance the anti-wear properties of the contact surfaces to prevent them from experiencing dry frictional wear. Many solutions have been proposed to address this issue, such as surface alloying [4], surface coating [5,6], surface texturing [7,8], and surface nanocrystallization [9,10]. Surface texturing has emerged as a promising solution in recent decades [11–14]. The mechanical components with textured surfaces show an excellent load capacity, wear, and friction resistance. So far, various techniques have been proposed for surface texturing, such as mechanical processing [9], ion beam etching [15], and chemical etching [16]. In particular, laser technology has been widely used for surface texturing due to its benefits in efficiency and environment adaptability [17,18]. Nevertheless, the high energy effect of the pulse laser needs to be controlled carefully, since it might result in severe oxidization during

the processing [19,20]. This issue will cause poor surface quality and accuracy, which will further cause non-ignorable errors and negative effects in practical application [21,22].

As an alternative, ultrasonic surface rolling processing (USRP) offers a new solution to produce textures on metallic material surfaces. USRP is a strengthening machining technique which avoids removing any additional materials. Thus, it leads to higher surface integrity and quality. The primary work mechanism of USRP is the employment of vibration and applied load simultaneously on the treated surface along a direction. Consequently, the machined surface can produce considerable residual compressive stress, high hardness, and a nano-grain deformed layer. However, the rolling process is challenging to control. It cannot process parts with poor rigidity, such as slender rods and thin wall pipe fittings, mainly due to the severe deformation that frequently occurs on their surface [23].

On the other hand, ultrasonic shot peening (USP) opens up the possibility of achieving good tribological properties on metallic material surfaces [24,25]. In USP, a dynamic loading is driven by the vibrations and applied on the treated surface, producing a lower roughness and gradient microstructure, along with the advantages of low energy consumption and high controllability of process parameters [26]. For example, Yue et al. found that an extremely fine gradient nanostructure is formed after USP treatment, significantly improving the mechanical strength [27]. Nevertheless, the hardened layer formed by USP treatment is relatively thin and uneven, which will cause surface damage when the mechanical components work in a harsh working environment [28].

Ultrasonic strengthening grinding process (USGP), which uses fused ceramic balls, brown corundum, and strengthened liquid for treating target samples is an efficient approach for obtaining high-quality surface textures. It has been poorly investigated so far. The impact and scratching of brown corundum by the ceramic ball and brown corundum on the machined surface can obtain irregular micro-dimples that are conducive to friction reduction and wear resistance [29].

In this work, the tribological properties of three AISI 1045 steel samples were investigated. Two samples experienced surface texturing by USP and USGP, respectively, while another one was only treated with polishing for experimental comparison. The texture micromorphology and its structural characteristics were analyzed. The surface roughness, microhardness, and elastic modulus, as well as the friction coefficient, were measured. These properties are further explained by phase and misorientation analysis. The results of this work indicate that USGP has the potential to be used for improving the fatigue life of some mechanical components, such as crank shaft bearing [30] and hydrodynamic journal bearing [11].

2. Materials and Methods

2.1. Samples Preparation

Three AISI 1045 steel samples were employed in this study. Their main chemical composition is reported in Table 1, and the element ratio is based on the standard EN 10083-2. Samples with geometrical parameters of 90 mm × 45 mm × 3 mm (See Figure 1a) initially experienced a heating treatment process (See Figure 1b). First, all the samples were quenched at 830 °C using water at room temperature to obtain good surface strength and hardness. Then, the samples were treated with a tempering process of 30 min at 180 °C to maintain good hardness and wear resistance and simultaneously reduce the residual stress and brittleness of the quenched workpiece. Finally, the samples were cooled in the air. Before the experiments, the surfaces of samples were polished with 300# sandpaper to ensure the roughness of $R_a < 0.1 \mu\text{m}$ and then cleaned with alcohol through an ultrasonic bath.

Table 1. The chemical composition of AISI 1045 steel (wt %).

Elements	C	Si	Mn	Cr	S	Fe
Content	0.39	0.26	0.71	0.26	0.03	bal

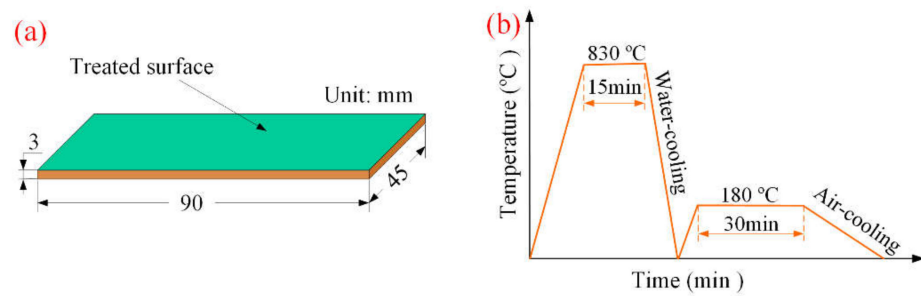


Figure 1. (a) The geometric parameters of samples, (b) The procedure of heating processing.

2.2. Surface Texture Fabrication

Two samples experienced a process of surface texture fabrication while the other one did not, for result comparison. The surface texture was fabricated using either USP or USGP treatments, both based on an ultrasonic strengthening device (See Figure 2a). In the USP, an electro-mechanical ultrasonic transducer generated ultrasonic waves, which were then applied to a workpiece, as shown in Figure 2b. An acoustically tuned resonator bar was caused to vibrate by energization with an ultrasonic transducer. The energy produced from these impulses was imparted to treat the surface through the ceramic balls. Compared with USP, the USGP uses different materials for treating target samples, which mix ceramic balls, brown corundum, and strengthened liquid, as shown in Figure 2c. The strengthened liquid is mainly made up of extrusion additive, triethanolamine, and water. The USP and USGP treatment parameters applied in this work are shown in Table 2. The sample without texture fabrication was named the polished sample, while the other two samples subjected to USGP and USP process were named sample USGP and sample USP, respectively.

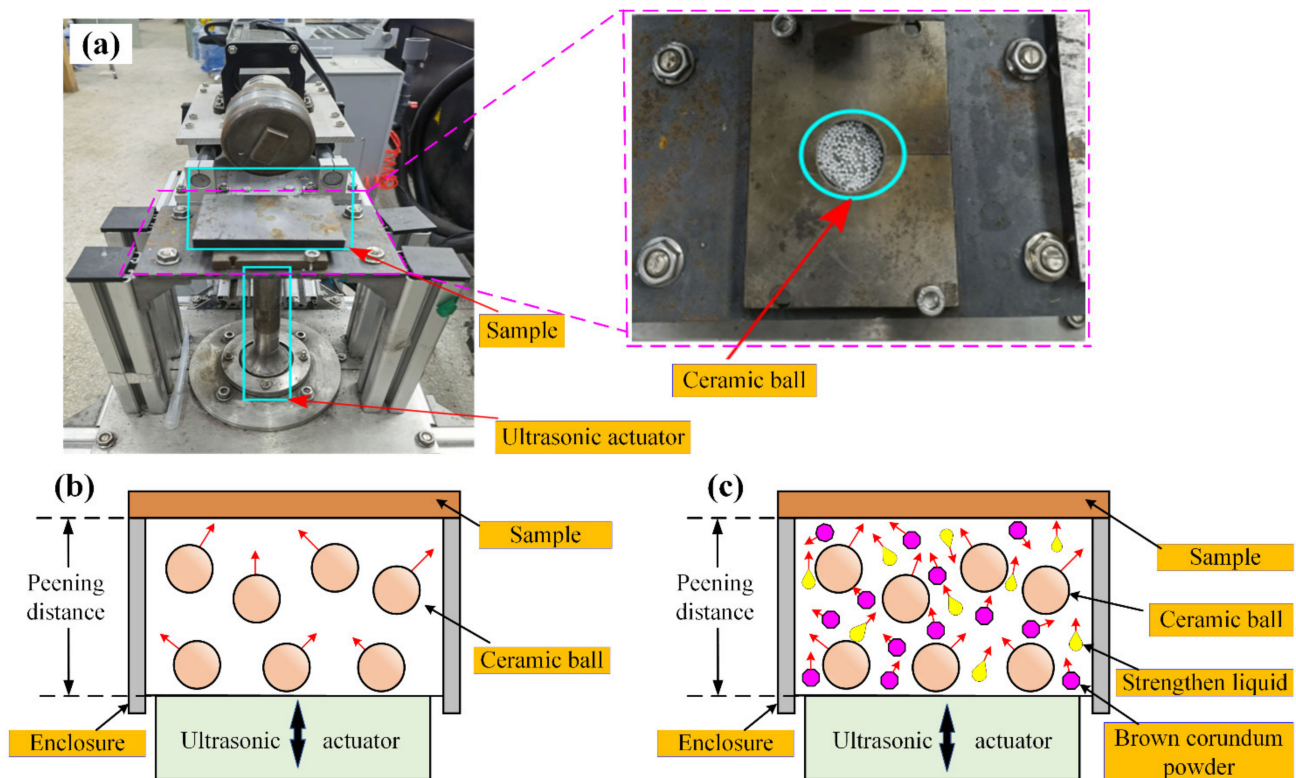


Figure 2. Schematic of the ultrasonic processing equipment (a), USP treatment (b), and USGP processing (c).

Table 2. USP and USGP treatment parameters.

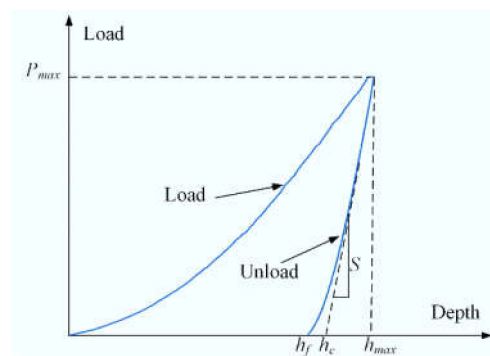
Parameters	Value
Vibration frequency (kHz)	20
Peening distance (mm)	30
Processing time (min)	3
Diameter of ceramic balls (mm)	1
Grain size of brown corundum (μm)	15

2.3. Materials Characterization

Three samples with geometrical parameters of $12\text{ mm} \times 12\text{ mm} \times 3\text{ mm}$ were taken from the processed sample to collect statistics and calculate median values. The tested samples were cut using electrical discharge wire cutting, and the cross-section surfaces were mechanically polished. The scanning electron microscope (SEM, TESCAN MIRA4, TESCAN Inc., Brno, Kohoutovice, Czech Republic) was used to characterize the surface morphology of samples. The white light interferometer (Bruker Countour GT K 3D, BRUKER Inc., Karlsruhe, Germany) was utilized to obtain surface microtopography and roughness. The nano-indenter (Bruker Hysitron TI980, BRUKER Inc., Karlsruhe, Germany) was employed to measure the microhardness. The least square method was used to fit 25% to 30% of the top of the unloading curve (See Figure 3), and the contact load P was calculated by Equation (1).

$$P = a(h - h_f)^m \quad (1)$$

where m and a are the number of array and constant, respectively.

**Figure 3.** Schematic of the microhardness testing.

The contact stiffness S and the contact depth were obtained by Equations (2) and (3), respectively.

$$S = \left(\frac{dP}{dh} \right)_{h=h_{max}} \quad (2)$$

$$h_c = h_{max} - \varepsilon \frac{P_{max}}{S} \quad (3)$$

In Equation (3), ε is a constant related to the shape of the indenter, which is 0.75 in this work. The contact area was calculated by Equation (4).

$$A = f(h_c) \quad (4)$$

Finally, the microhardness H was obtained by Equation (5).

$$H = \frac{P_{max}}{A} \quad (5)$$

The elasticity modulus was calculated based on the Oliver Pharr method [31]. The detected distance is below the treated surface, ranging from 10 μm to 160 μm with a step of 30 μm . Those measurements were repeated three times, and the average values were calculated. The loading, holding, and unloading times were 5s, 2s, and 5s, respectively. The maximum loading force (F_n) was set at 5 mN.

The microstructural composition was measured by an X-ray diffractometer (Rigaku + Ultima IV, Rigaku Corp, Akishima, Tokyo, Japan) with Cu K α radiation. The phase change and kernel average misorientation distributions of the polished, USP, and USGP samples were investigated by electron back-scattered diffraction (EBSD Oxford Symmetry, Oxford Instruments, Abingdon, UK). The 5 mm $\times$ 5 mm $\times$ 3 mm blocks were prepared; the cross-sectional surfaces were mechanically polished, chemically etched, and ultrasonically cleaned with alcohol. The detected areas were 200 μm $\times$ 200 μm at a depth of 10 μm below the treated surface, and the step size was set at 0.25 μm .

2.4. Frictional Wear Tests

The frictional wear properties tests were performed on the ball-on-disk reciprocating friction sliding tester (MQP-5H, Jinan Heng Xu Testing Machine Technology Inc., Jinan, China) at a temperature of 20 $^{\circ}\text{C}$ and an ambient humidity of $\sim 35\%$. GCr15 steel balls with a diameter of 7.85 mm and a hardness of 700 ± 20 HV were utilized in the tests. It was used to slide reciprocally against the fixed samples at a speed of 20 mm/s, a weight of 20 N, and a 10 mm linear stroke. The frictional force in the sliding plane was measured continuously, and the friction coefficient was calculated. The wear tracks were detected by SEM micrographs and white light interferometer, respectively.

3. Results and Discussion

3.1. Characteristics of Surface Texture

3.1.1. Surface Morphologies of Different Samples

SEM and white light interferometer maps were employed to analyze the morphology of the polished, USP, and USGP samples. The micrographs of the polished sample are depicted in Figure 4. In general, the machined surface of this sample is relatively smooth, along with some irregular tracks, micro-bulges, and micro-dimples distributed on the surface (Figure 4a). These micro-bulges and micro-dimples are mainly accumulated near the tracks. The tracks are not oriented in one direction and typically have an irregular micro shape; the largest width of the track region is over 10 μm (See Figure 4b–d). This can be explained by considering the surface plastic deformation that occurred under the effects of micro-stretch and vibratory shock in the polishing process.

Figure 5 reports the micrograph of sample USP. The peaks and dimples on the surface are visible, and the height between peaks and valleys reaches approximately 24.13 μm (Figure 5a). It is noted that the peaks are oscillating down in the direction of length (Figure 5b), accompanied by different micro-dimple shapes. These irregular micro-dimples can be observed in Figure 5e, which are characterized by a diameter ranging from 2 to 5 μm . Surprisingly, some nano-particles are observed in Figure 5f, which have a diameter of approximately 100 nm. These can be attributed to the fact that a micro-dimple can store the abrasives in a frictional wear process [32].

A significant difference is observed in the USGP sample, where many granular bumps along with micro-dimples appear on the surface (Figure 6). The surface texture is relatively uniform, and the maximum value between peaks and valleys drops compared with that of the USP sample. This is because the mixed abrasives consist of ceramic balls, brown corundum, and strengthened liquid, which lead to less severe plastic deformation. The micro-cutting and extrusion of these mixed materials further reduce protruding regions. Such a texture matches various shapes of abrasive particles, making it more reliable to absorb and prevent them from rolling on the friction surface.

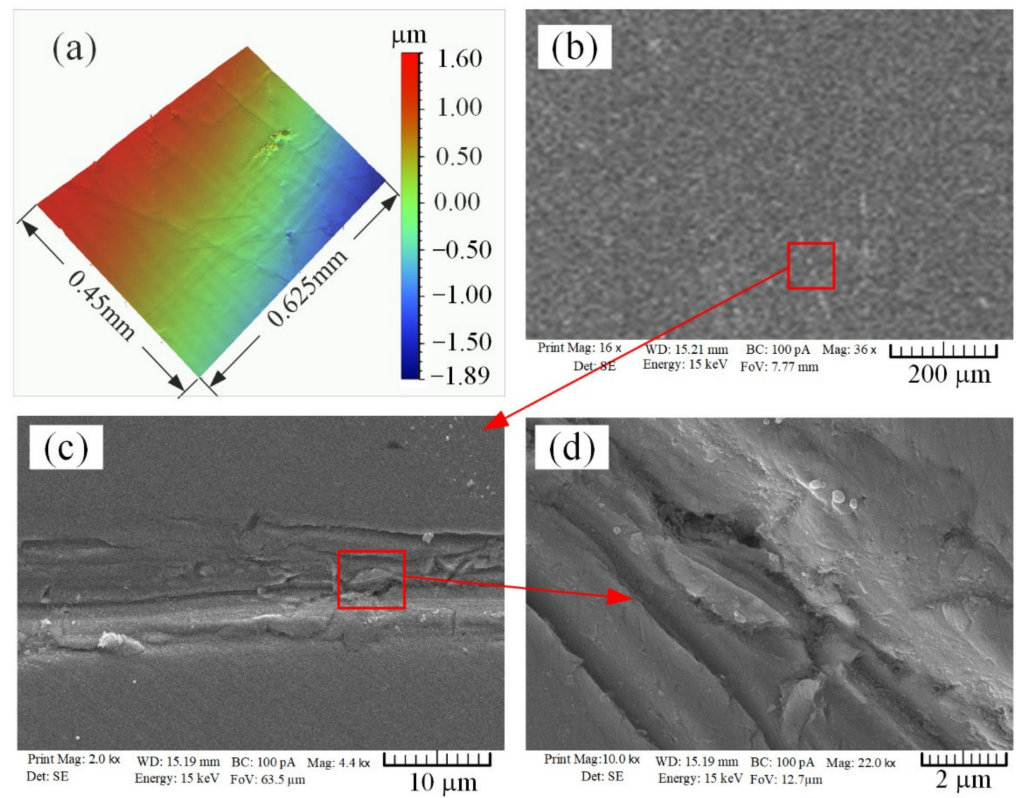


Figure 4. Three-dimensional surface topography (a) and SEM micrographs of the polished sample and its enlarged appearance (b–d).

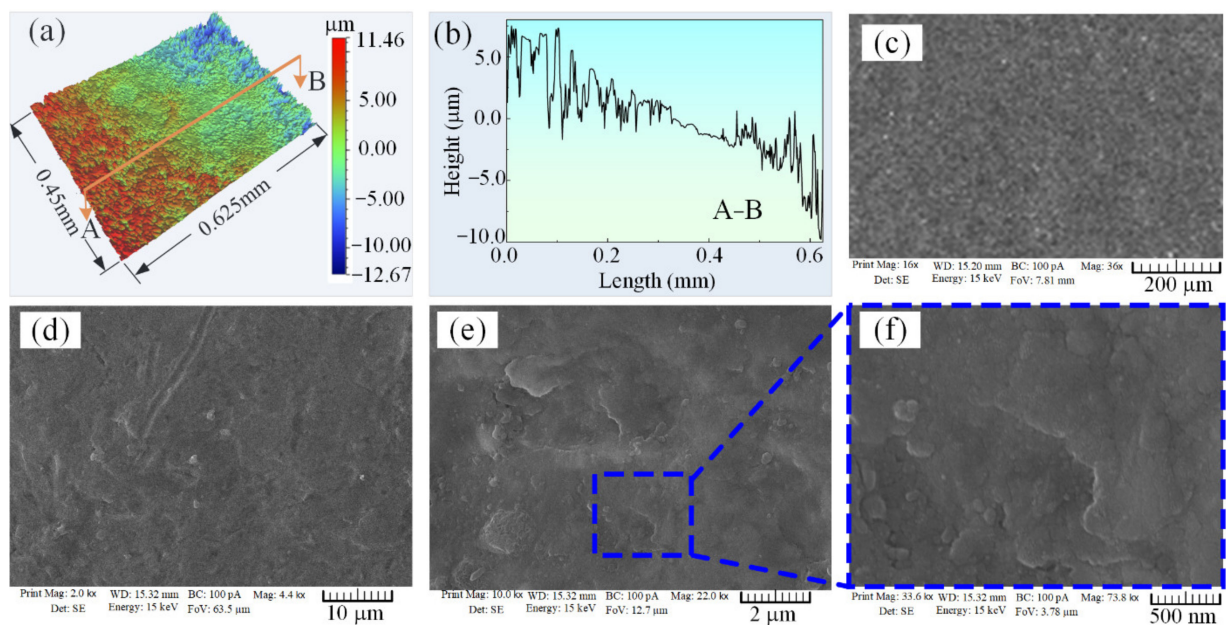


Figure 5. The optical micrographs (a), height profile images (b), SEM micrographs and their enlarged appearances (c–f) of USP specimen. A–B means the cross section of micrographs through line AB.

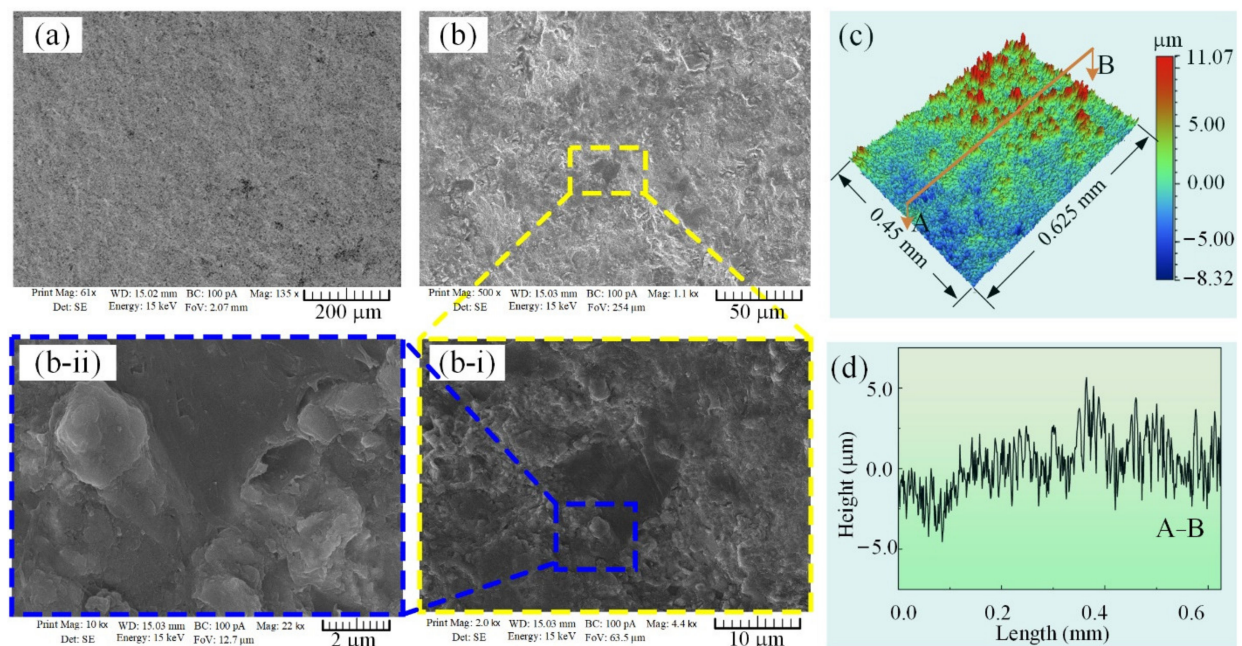


Figure 6. SEM micrographs and their enlarged appearances (a,b), 3D micrographs (c), and height profile images (d) of USGP sample. A-B means the cross section of micrographs through line AB.

3.1.2. Surface Roughness of Specimens

Arithmetic mean height R_a of all the samples was measured, and the obtained results are reported in Figure 7. The polished sample shows the lowest roughness of $0.5485 \mu\text{m}$, while the roughness of the USGP and USP samples is apparently higher, realizing a value of $1.412 \mu\text{m}$ and $1.3475 \mu\text{m}$, respectively. This could also be explained considering that the irregular micro-grooves in the USGP sample and the polished sample increased the roughness. In the USGP process, the mechanical micro-cutting removed part of the material, and such a condition will not occur in a USP treatment. Therefore, the roughness of the USGP sample is slightly increased compared with the USP sample.

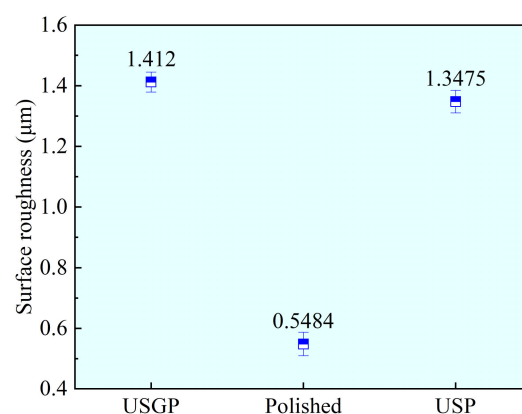


Figure 7. Surface roughness R_a of USGP, polished, and USP specimens.

3.1.3. Microhardness (H) and Elastic Modulus (E) of Samples

The load–displacement curves of the sub-surface for each sample are shown in Figure 8. The USGP Sample offers the highest hardness H value of 5.35 GPa , which is approximately 30% larger than that of the USP sample. The lowest H value of 4.03 GPa is found in the polished sample, as expected. It can also be seen that the elastic modulus E value behaves in a similar way and also follows the rank: $E_{\text{USGP}} > E_{\text{USP}} > E_{\text{Polished}}$, although they are very close in the USGP and USP samples. These results reveal that USP and USGP treatments

will enhance the microhardness and elastic modulus of the samples. On the other hand, a higher microhardness and elastic modulus will result in higher stiffness, which may further improve wear resistance.

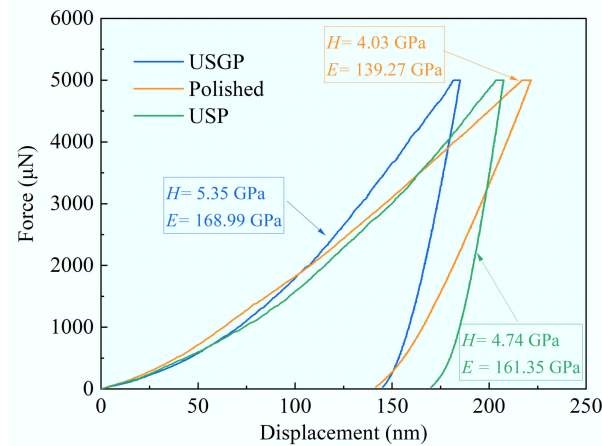


Figure 8. Load–displacement curves of the sub-surface of USGP sample, polished sample, and USP sample. The letters H and E stand for microhardness and elastic modulus, respectively.

The sample microhardness as a function of the distance between the sub-surface and the substrate is reported in Figure 9. The microhardness of the polished sample initially drops rapidly and then gradually reaches a stable value of approximately 2.5 GPa, while the microhardness of the USGP and USP samples behaves a little differently, decreasing slowly with the increase in the distance from the surface. However, in general, a similar tendency is observed: the microhardness decreases as the distance increases. When the distance reaches 130 μm , the microhardness of the three samples is almost equal. The higher microhardness in the sub-surface can be attributed to the thermal, polishing, USP, and USGP treatments. In addition, since the mixed abrasives, which were used in the USGP treatment, have higher-impact kinetic energy and lower elastic energy than those ceramic balls, the work-hardening capacity of the USGP is better than that of the USP. Therefore, the microhardness of the USGP sample is higher than that of the USP sample.

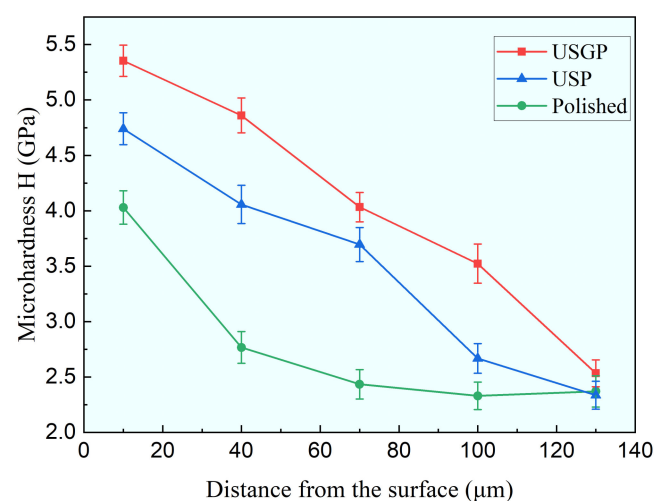


Figure 9. The microhardness H variation from sub-surface to substrate of USGP, USP, and polished samples.

The ratio of microhardness H to elastic modulus E represents the elastic strain properties of a material, which is an important index for evaluating the wear resistance of metals. It is also employed to predict the friction behavior and to explain the mixture of

elastic and plastic deformation characteristics. The previous study demonstrated that a higher H/E value leads to higher toughness and better tribological properties [19]. As shown in Figure 10, the H/E value of the USGP sample is slightly higher than that of the polished sample and the USP sample. Consequently, the USGP sample may possess a better tribological performance.

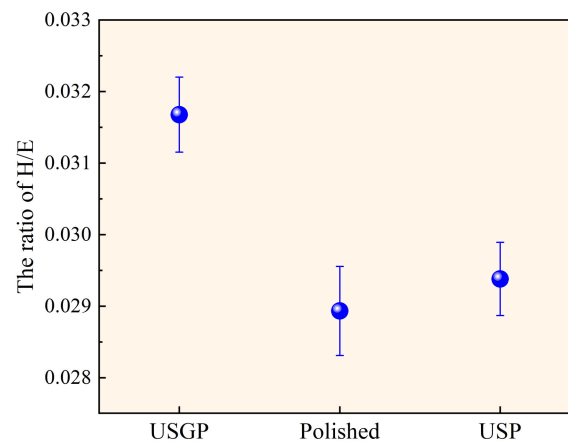


Figure 10. The H/E value variation of the sub-surface of USGP, USP, and polished samples.

3.1.4. XRD Diffraction Patterns of Surface Textures

The X-ray diffraction patterns of the top surface for each sample are shown in Figure 11. The $\{110\}$, $\{200\}$, and $\{211\}$ crystal planes could be found in all the samples, which indicate a ferrite. It can be observed that some new diffraction peaks appeared in the USGP sample. This could be explained by phase transition and Fe_3C phase precipitating. In the USGP treatment, severe plastic deformation occurred on the samples' surface layer owing to the impact of mixed abrasives. A subsequent dislocation multiplication and stress concentration occurred in the distorted grain boundaries, which made it possible for phase transformation and element diffusion [27,33], followed by the decomposition of the ferritic and Fe_3C phase formation. Fe_3C is further confirmed by the following EBSD analysis. A shift of diffraction peaks of $\{110\}$ and $\{200\}$ crystal planes is also observed in the USP and USGP samples, which could be attributed to the lattice distortion and grain refinement caused by the generation of dislocations [34].

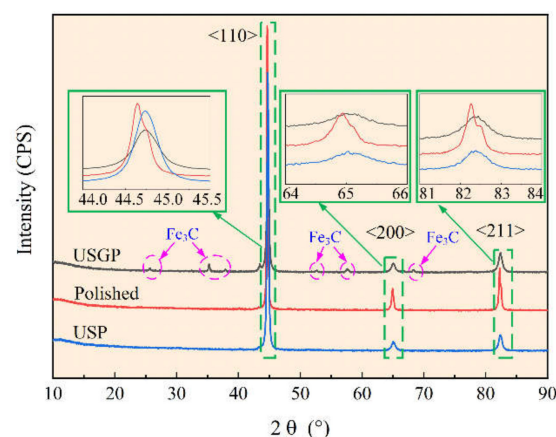


Figure 11. The X-ray diffraction pattern characteristics of the samples' surface.

3.1.5. Distributions of Phase and Kernel Average Misorientation

EBSD analyses were performed to observe the distributions of phase and kernel average misorientation on the samples' cross-section (See Figure 12). As presented in

Figure 12a–c, mass alpha iron accompanied by a small amount of gamma iron and Fe_3C could be seen. The amount of Fe_3C in the USGP and USP samples is more considerable than that of the polished sample. This is because the phase change occurred during the USP and USGP processes, and higher efficiency of phase transformation was found in USGP. The Fe_3C phase is cementite, which shows the properties of high hardness and high brittleness; therefore, a harder surface layer can be obtained in the USGP sample. The kernel average misorientation of each sample is shown in Figure 12d–f. Obviously, many misorientations are distributed around the alpha iron in the USGP sample, which forms a network of enhanced layers. At the same time, a small amount of misorientation is found in the polished and USP samples.

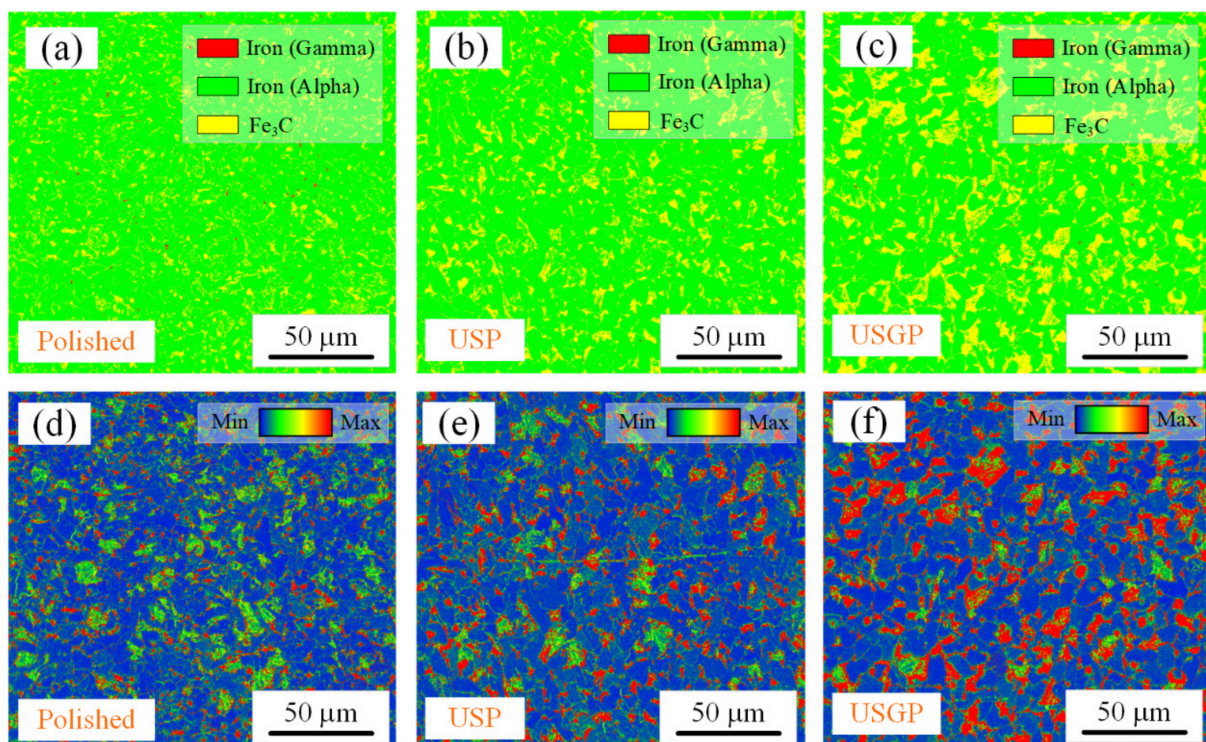


Figure 12. EBSD analyses for the distributions of phase and kernel average misorientation of samples' cross-section. Phase distributions of polished (a), USP (b), and USGP samples (c); Kernel average misorientation distributions of polished (d), USP (e), and USGP samples (f).

3.2. Tribological Properties Characterization of Different Samples

The frictional coefficients of each sample versus time were investigated, as shown in Figure 13. The frictional coefficient of the polished sample initially increased slowly and then sharply increased at the sliding time of ~80 s. Finally, it reached a stable state with an average value of ~0.98. The frictional coefficient of the USP and USGP samples behaves slightly differently, increasing slowly at the beginning and then fluctuating at an average value of 0.81 and 0.71, respectively. At the initial phase of the friction of the polished sample, the surface is relatively smooth. As time rises, the surface starts to wear down and forms abrasive particles [35], which roll between the sliding interfaces or adhere to the frictional surface, thus increasing the frictional force. Finally, the contacted surface material is softened with the rise in frictional temperature, which results in a higher frictional coefficient. In the USP sample, the contact areas are decreased due to surface micro-dimples, which can capture the wear debris and alleviate wear [5]. Moreover, the increase in hardness benefits the friction reduction [36]. In the USGP sample, a lower frictional coefficient is represented in the first 300 s, which can mainly be attributed to

the coupling effect of a higher microhardness, a larger area of micro-dimples, and a large number of misorientations on the surface.

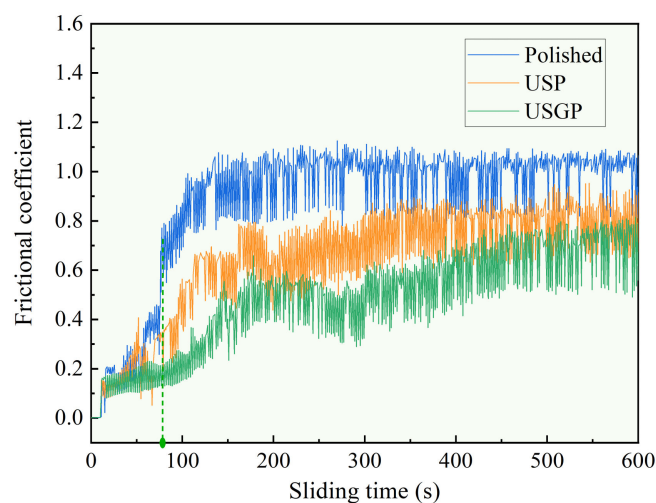


Figure 13. Variations of frictional coefficient for USGP, USP, and polished samples with the sliding time of 600 s.

To better understand the tribological characteristics of the samples, they were observed by SEM after sliding for 600 s (See Figure 14). The wear track width of the polished sample is about 470 μm , and the morphology exhibits a compression fissure with a mass of abrasive particles and furrows (See Figure 14a). It can be observed that furrows were dispersed along the wear track along with some abrasive particles. These abrasive particles show a diameter of approximately 0.5–2 μm . This evidence indicates that a severe adhesive existed in the contact region, which further verifies that adhesive wear occurs during abrasive wear [37]. The abrasive particles and debris began to form when the polished surface was rubbed by the steel ball because of the concentration of alternating stress, which resulted in high temperature over time. The high temperature softened the debris, making it adhere to the contact surface. Sample USP has a wear track of approximately 360 μm , severe delamination spalling, and furrows along the sliding direction are observed on the surface (See Figure 14b). Material spalling is mainly due to plastic deformation in the process of hardening the contact surface. The furrows are formed when the hardened debris is peeled off and rubbed on the surface. In the USGP sample, some chipping pits and abrasive particles were also formed (See Figure 14c). The deep dimples with different peaks and valleys decreased the abrasive wear of the material. In addition, a higher microhardness is obtained in this sample, which improved the resistance to wear. Therefore, the friction and wear performance of the USGP sample is the result of the combined effects of dimples, abrasive particles, and surface hardness.

Figure 15 reports the micromorphology and cross-sectional profiles of the samples' wear tracks after sliding for 600 s. Both the polished sample and the USP sample have a deep wear track, exhibiting a depth of $\sim 7\ \mu\text{m}$ and $\sim 6\ \mu\text{m}$, respectively. The wear mechanisms are primarily adhesive wear and abrasive wear and are accompanied by significant volume loss in the track center and material accumulation on the track flanks. In the USP sample, both adhesive wear and abrasive wear show a depth of $\sim 9\ \mu\text{m}$, while in the USGP sample, slightly abrasive and adhesive wear were observed, which increased the stability of the sample in the friction and wear test.

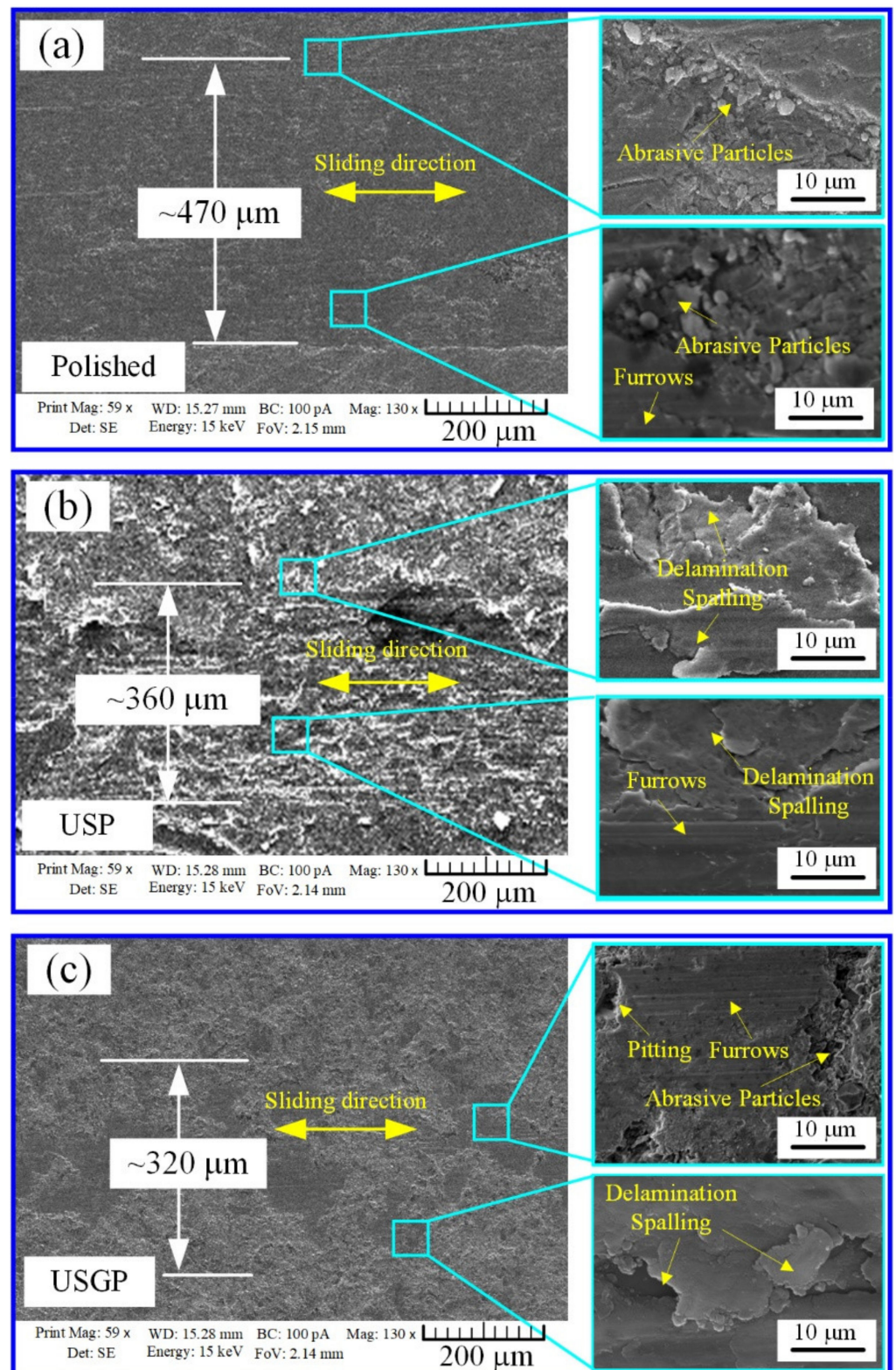


Figure 14. SEM images that were taken in the middle of the wear track for polished (a), USP (b), and USGP samples (c) after sliding for 600 s.

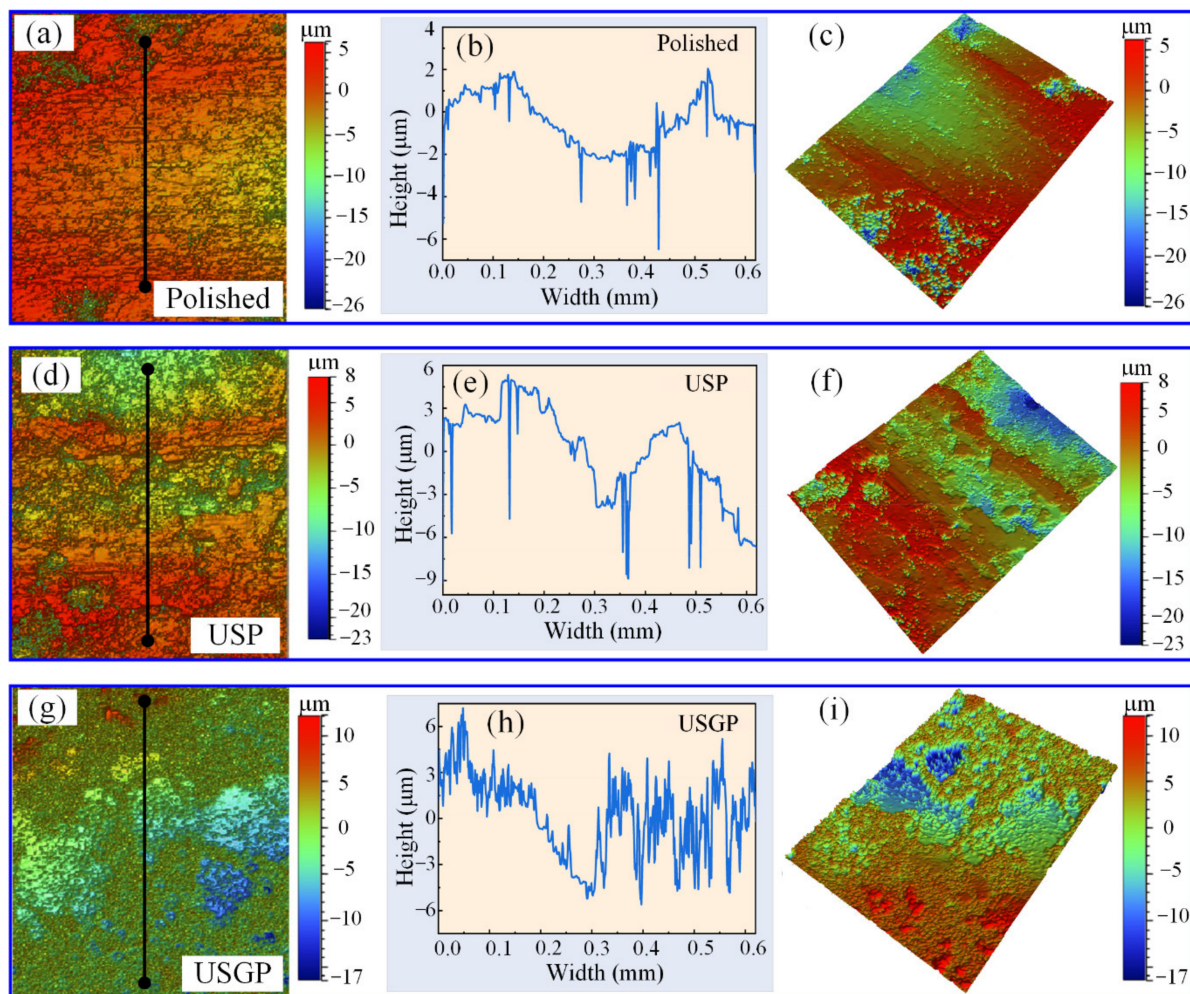


Figure 15. The micromorphology and cross-sectional profiles that took in the middle of the wear tracks of polished (a–c), USP (d–f), and USGP samples (g–i).

4. Conclusions

In this paper, the AISI 1045 steel surface texturing by polish grinding, USP, and USGP treatments was demonstrated, which are named sample polished, sample USP, and sample USGP, respectively. Their tribological properties were investigated according to the analysis of their surface topography, surface roughness, microhardness, elastic modulus, phase, as well as frictional coefficient.

The polished sample had some irregular tracks, along with little micro-bulges and micro-dimples. The USP sample had many irregular and deep micro-dimples, as well as some nano-particles, while the USGP sample had more uniformly distributed micro-dimples along with granular bumps.

Compared with the other two samples, the USGP sample showed the largest surface roughness, microhardness, and elastic modulus, exhibiting a value of $1.141 \mu\text{m}$, 5.35 GPa , and 168.99 GPa , respectively. These behaviors can be attributed to the fact that the impact and scratching of brown corundum by the ceramic ball on the machined surface resulted in the transformation of the Alpha Fe phase to Fe_3C and to more uniform irregular micro-dimples and network misorientations.

In addition, the lowest coefficient (i.e., 0.6) was obtained in the USGP sample, mainly due to the coupling effect of misorientation, cementite, and micro-dimples induced by USGP treatment, which formed a hardened layer on top of the surface and reduced the abrasive wear.

Author Contributions: Conceptualization, methodology, and writing—original draft, J.X. Software and formal analysis, Z.Z. and X.X. Resources and writing—review and editing, Z.L. (Zhongwei Liang). Data curation and validation, Z.L. (Zhaoyang Liu) and R.T. Investigation, visualization, and project administration, X.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (52075109, 51975136), the Science and Technology Plan of Guangzhou (202102080225), National Key Research and Development Program of China (2018YFB2000501), the Science and technology Special Fund program of Guangdong Province (2019B020404, 2019B090917004), and Guangzhou University Research Project (YJ2021002).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the article.

Acknowledgments: We thank the Guangzhou Key Laboratory of High-Performance Metal Grinding Processing of Guangzhou University.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kango, S.; Singh, D.; Sharma, R.K. Numerical investigation on the influence of surface texture on the performance of hydrodynamic journal bearing. *Meccanica* **2012**, *47*, 469–482. [\[CrossRef\]](#)
2. Andreas, R.; Henara, L.C.; Mehmet, Z.B.; Ashlie, M. Synergetic effects of surface texturing and solid lubricants to tailor friction and wear—A review. *Tribol. Int.* **2021**, *155*, 106972. [\[CrossRef\]](#)
3. Luo, J.B.; Liu, M.; Ma, L.R. Origin of friction and the new frictionless technology—Superlubricity: Advancements and future outlook. *Nano Energy* **2021**, *86*, 106092. [\[CrossRef\]](#)
4. Fals, H.C.; Roca, A.S.; Fogagnolo, J.B.; Fanton, L.; Belem, M.J.X. Erosion-corrosion resistance of laser surface alloying of NbC thermal spray coatings on AISI 304L steel. *J. Therm. Spray Technol.* **2020**, *29*, 319–329. [\[CrossRef\]](#)
5. Li, X.; Deng, J.; Yue, H.; Ge, D.; Zou, X. Wear performance of electrohydrodynamically atomized WS₂ coatings deposited on biomimetic sharkskin textured surfaces. *Tribol. Int.* **2019**, *134*, 240–251. [\[CrossRef\]](#)
6. Meng, W.; Zhu, H.; Wang, X.; Li, G.; Fan, Y.; Sun, D.; Kong, F. Electrochemical behavior and surface conductivity of C/TiC nanocomposite coating on titanium for PEMFC bipolar plate. *Metals* **2022**, *12*, 771. [\[CrossRef\]](#)
7. Kromer, R.; Verdy, C.; Costil, S.; Liao, H. Laser surface texturing to enhance adhesion bond strength of spray coatings—cold spraying, wire-arc spraying, and atmospheric plasma spraying. *Surf. Coat. Technol.* **2017**, *352*, 642–653. [\[CrossRef\]](#)
8. Li, S.S.; Chen, H.; Luo, T.; Xiao, G.C.; Yi, M.D.; Chen, Z.Q.; Zhang, J.J.; Xu, C.H. Tribological properties of laser surface texturing modified GCr15 steel under graphene/5CB lubrication. *J. Mater. Res. Technol.* **2022**, *18*, 3598–3611. [\[CrossRef\]](#)
9. Zhao, X.; Xue, G.; Liu, Y. Gradient crystalline structure induced by ultrasonic impacting and rolling and its effect on fatigue behavior of TC11 titanium alloy. *Results Phys.* **2017**, *7*, 1845–1851. [\[CrossRef\]](#)
10. Sun, R.; He, G.; Bai, H.; Yan, J.; Guo, W. Laser shock peening of Ti6Al4V alloy with combined nanosecond and femtosecond laser pulses. *Metals* **2022**, *12*, 26. [\[CrossRef\]](#)
11. Vlădescu, S.C.; Fowell, M.; Mattsson, L.; Reddyhoff, T. The effects of laser surface texture applied to internal combustion engine journal bearing shells—An experimental study. *Tribol. Int.* **2019**, *134*, 317–327. [\[CrossRef\]](#)
12. Zum, G.K.H.; Mathieu, M.; Brylka, B. Friction control by surface engineering of ceramic sliding pairs in water. *Wear* **2007**, *263*, 920–929. [\[CrossRef\]](#)
13. Braun, D.; Greiner, C.; Schneider, J.; Gumbsch, P. Efficiency of laser surface texturing in the reduction of friction under mixed lubrication. *Tribol. Int.* **2014**, *77*, 142–147. [\[CrossRef\]](#)
14. Yousfi, M.; Țălu, Ș. The impact of helical slide honing on surface microtexture compared to plateau honing process through relevant characterization methods. *Microsc. Res. Tech.* **2022**, *03*, 24096. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Patel, D.S.; Jain, V.K.; Shrivastava, A.; Ramkumar, J. Electrochemical micro texturing on flat and curved surfaces: Simulation and experiments. *Int. J. Adv. Manuf. Technol.* **2019**, *100*, 1269–1286. [\[CrossRef\]](#)
16. Yang, B.; Lee, M. Fabrication of honeycomb texture on poly-Si by laser interference and chemical etching. *Appl. Surf. Sci.* **2013**, *284*, 565–568. [\[CrossRef\]](#)
17. Fang, S.; Llanes, L.; Baehre, D. Laser surface texturing of a WC-CoNi cemented carbide grade: Surface topography design for honing application. *Tribol. Int.* **2018**, *122*, 236–245. [\[CrossRef\]](#)
18. Mwema, F.M.; Akinlabi, E.T.; Oladipo, O.P.; Fatoba, O.S.; Akinlabi, S.A.; Țălu, S. Advances in manufacturing analysis: Fractal theory in modern manufacturing. In *Modern Manufacturing Processes*, 1st ed.; Woodhead Publishing: Cambridge, UK, 2020; pp. 13–39. [\[CrossRef\]](#)
19. Meng, Y.; Deng, J.; Zhang, Y.; Wang, S.J.; Li, X.M.; Yue, H.Z.; Ge, D.L. Tribological properties of textured surfaces fabricated on AISI 1045 steels by ultrasonic surface rolling under dry reciprocating sliding. *Wear* **2020**, *460–461*, 203488. [\[CrossRef\]](#)

20. Wang, F.; Men, X.H.; Liu, Y.J.; Fu, X.L. Experiment and simulation study on influence of ultrasonic rolling parameters on residual stress of Ti-6Al-4V alloy. *Simul. Model. Pract. Theory* **2020**, *104*, 102121. [\[CrossRef\]](#)
21. Wang, S.Q.; Wang, L.; Zhao, Y.T.; Sun, Y.; Yang, Z.R. Mild-to-severe wear transition and transition region of oxidative wear in steels. *Wear* **2013**, *306*, 311–320. [\[CrossRef\]](#)
22. Lao, Y.X.; Du, H.; Xiong, T.Y.; Wang, Y. Evolution Behaviors of Oxides in Severely Plastic Deformed Region of AISI 52100 Steel during Dry Sliding Wear. *J. Mater. Sci. Technol.* **2017**, *33*, 330–337. [\[CrossRef\]](#)
23. Pang, Z.W.; Wang, S.X.; Yin, X.L.; Yu, S.M.; Du, N. Effect of spindle speed during ultrasonic rolling on surface integrity and fatigue performance of Ti6Al4V alloy. *Int. J. Fatigue* **2022**, *159*, 106794. [\[CrossRef\]](#)
24. Chen, Y.; Liu, F.L.; He, C.; Li, L.; Wang, C.; Liu, Y.J.; Wang, Q.Y. Effect of ultrasonic peening treatment on the fatigue behaviors of a magnesium alloy up to very high cycle regime. *J. Magnes. Alloy.* **2022**, *10*, 614–626. [\[CrossRef\]](#)
25. Panin, A.; Dmitriev, A.; Nikonov, A.; Perevalova, O.; Kazantseva, L.; Bakulin, A.; Kulkova, S. Transformations of the Microstructure and Phase Compositions of Titanium Alloys during Ultrasonic Impact Treatment Part II: Ti-6Al-4V Titanium Alloy. *Metals* **2022**, *12*, 732. [\[CrossRef\]](#)
26. Jamalian, M.; Field, D.P. Effects of shot peening parameters on gradient microstructure and mechanical properties of TRC Az31. *Mater. Char.* **2019**, *148*, 9–16. [\[CrossRef\]](#)
27. Yue, X.; Hu, S.; Wang, X.K.; Liu, Y.X.; Yin, F.; Hua, L. Understanding the nanostructure evolution and the mechanical strengthening of the M50 bearing steel during ultrasonic shot peening. *Mater. Sci. Eng. A* **2022**, *836*, 142721. [\[CrossRef\]](#)
28. Chen, C.; Zhang, H.J. Characteristics of friction and wear of Al-Zn-Mg-Cu alloy after application of ultrasonic shot peening technology. *Surf. Coat. Technol.* **2021**, *423*, 127615. [\[CrossRef\]](#)
29. Liu, X.C.; Huang, J.F.; Liang, Z.W.; Huang, W.F.; Zhu, R.; Gao, W.L.; Xiao, J.R. Preparation and Properties of the Composite Enhancement Layer of Bearing Ring. *World J. Mech.* **2020**, *10*, 139–153. [\[CrossRef\]](#)
30. Sharma, S.; Jamwal, G.; Awasthi, R.K. Enhancement of steady state performance of hydrodynamic journal bearing using chevron-shaped surface texture. *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.* **2019**, *233*, 1833–1843. [\[CrossRef\]](#)
31. Oliver, W.C.; Pharr, G.M. An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. *J. Mater. Res.* **1992**, *7*, 1564–1583. [\[CrossRef\]](#)
32. Vishnoi, M.; Kumar, P.; Murtaza, Q. Surface texturing techniques to enhance tribological performance: A review. *Surf. Interfaces* **2021**, *27*, 101463. [\[CrossRef\]](#)
33. Yang, C.; Li, M.Q.; Liu, Y.G. Characterization of face-centered cubic structure and deformation mechanisms in high energy shot peening process of TC17. *J. Mater. Sci. Technol.* **2022**, *110*, 136–151. [\[CrossRef\]](#)
34. Amanov, A.; Umarov, R. The effects of ultrasonic nanocrystal surface modification temperature on the mechanical properties and fretting wear resistance of Inconel 690 alloy. *Appl. Surf. Sci.* **2018**, *441*, 515–529. [\[CrossRef\]](#)
35. Ramesh, C.S.; Keshavamurthy, R.; Channabasappa, B.H.; Pramod, S. Friction and wear behavior of Ni-P coated Si₃N₄ reinforced Al6061 composites. *Tribol. Int.* **2010**, *43*, 623–634. [\[CrossRef\]](#)
36. Guo, D.; Chi, T.K.; Tam, L.M.; Zhang, D.W.; Li, X.G. Hardness, microstructure and texture of friction surfaced 17-4PH precipitation hardening stainless steel coatings with and without subsequent aging. *Surf. Coat. Technol.* **2020**, *402*, 126302. [\[CrossRef\]](#)
37. Chen, Y.X.; Gong, W.J.; Kang, R. Review and propositions for the sliding/impact wear behavior in a contact interface. *Chin. J. Aeronaut.* **2020**, *33*, 391–406. [\[CrossRef\]](#)