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Nano-Texturing onto Tool-Surface by the Femtosecond Laser Processing

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Abstract

Two types of femtosecond laser nano-texturing procedures were proposed to form the nano-structured AISI316L and SKD11 punches. The plasma-nitrided AISI316L flat substrate with its head size of 10 mm x 20 mm was post-treated as a punch to imprint the tailored nano-textures onto the AA1060 aluminum plate with the thickness of 1.0 mm. In second, the plasma nitrided SKD11 cylindrical punch with the diameter of 2 mm was employed to form the nanostructures on its side surface by the femtosecond laser trimming. This nanotexture was imprinted onto the hole surface concurrently with piercing a circular hole into electrical steel sheet.

Keywords: Femtosecond laser machining, Nano-texturing, Imprinting, Decorative surfaces, Nano-grooving, Piercing punch

1. Introduction

Femtosecond laser processing has grown up as a powerful tooling system in industries [1]. Among their several features, LIPSS (Laser Induced Periodic Surface Structuring) has attracted many researchers since its first finding [2]. Through micro-/nano-texturing by the femtosecond laser processing, the original hydrophilic surfaces of AISI304 substrates were controlled to be super-hydrophobic [3-6]; e.g., the static contact angle increased to 170.4^{o}, nearly equal to the critical angle by theoretical estimate [7]. In addition to this surface property control, optical properties were also tuned by this femtosecond laser irradiation [8-9]. Hence, the femtosecond laser nano-texturing becomes a key technology to modify and control the physical and chemical properties on various materials surface in practice [10]. As surveyed in [10-11], this nanotexturing process is useful to fabricate the nano-textured punches and dies for transcription of the surface nanostructure onto the metal, polymer and oxide-glass products by stamping. In addition to this direct printing of nano-structured pattern by stamping, there are many ways to imprint the tailored nanotextures onto the selective surface areas during the metal forming [12].

In the present paper, two femtosecond laser nano-texturing procedures are proposed to form the tailored nano-textures onto the surface of nitrided punch for micro-embossing and micro-piercing, respectively. These formed nanotextures on the surface of punch are imprinted onto AA1060 plate surface as well as the pierced hole surface of electrical steel sheet.

2. Experimental Procedure

2.1. Femtosecond Laser Processing System

A femtosecond laser machining system is utilized to form the tailored nano-textures onto the nitrided AISI316L punch with the head size of 10 mm x 20 mm surface, as shown in Figure 1. This system is also used to make laser-trimming on the nitrided SKD11 cylindrical punch with the diameter of 2 mm. The wave length of femtosecond laser was 515 nm, the pulse width, 200 fs, and, the repetition rate, 20 MHz. The maximum power in average was 40 W, and, the maximum pulse energy, 50 μJ. Hence, the power by irradiation of a single pulse is estimated to be 0.25 GW. The beam spot diameter is 1 μm.

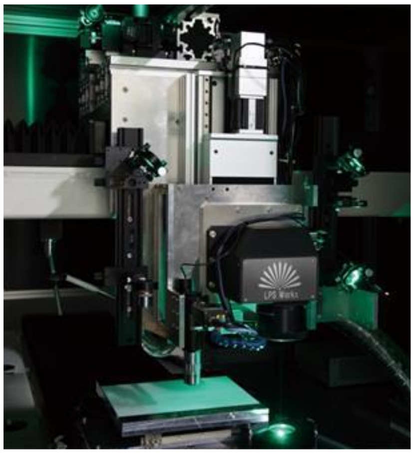

Figure 1. Femtosecond laser machining system with the work space of 300 mm x 300 mm.

2.2. Nanotexturing by optical control

Nanotextures induced by LIPSS are controllable by the optical path control.

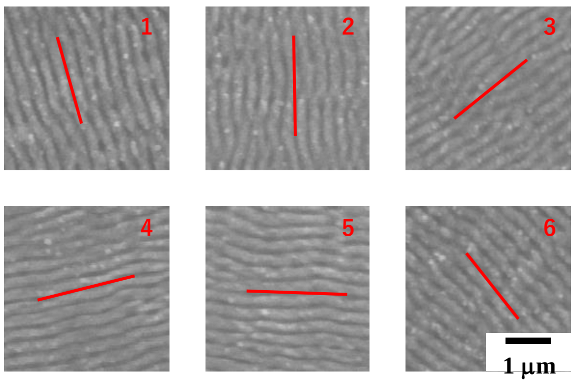

Figure 2. Six nano-textures formed onto the stainless steel plates by the optical path control.

Figure 2 depicts how to control the orientation of nanotextures. The width of each ripple is mainly determined by the pulse width. As had been discussed in [8, 9], this orientation control of nanotextures reflects on the surface plasmonic diffraction. The above six orientations are varied in each square segmentation on the matrix with eight rows x eight columns as shown in Figure 3. Then, the nanotextured panel by this matrix on the AISI316L plate has surface plasmonic colors in Figure 4. This qualitative correlation between the nanotextures by LIPSS and the surface plasmonic colors is employed to identify the presence of nanotextures on the laser-processed surfaces on the nitrided punch as well as the replica surfaces on the products.

3	4	5	6	1	2	3	4
1	2	3	4	5	6	1	2
5	6	1	2	3	4	5	6
3	4	5	6	1	2	3	4
1	2	3	4	5	6	1	2
5	6	1	2	3	4	5	6
3	4	5	6	1	2	3	4
1	2	3	4	5	6	1	2

Figure 3. Digital classification of nanotextures for segmentation in laser nano-texturing.

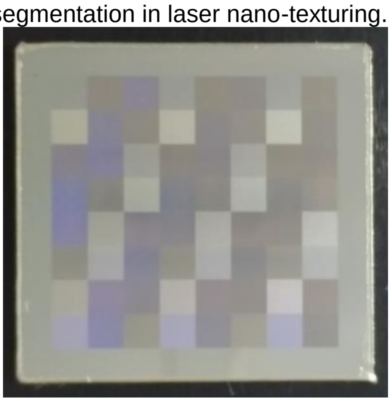

Figure 4. Nano-textured panel with 8 x 8 segments identified by the different surface-plasmonic reflection.

2.3. Nanotexture imprinting methods

These nano-textures are transcribed from the punch surfaces to the AA1060 aluminium plates and electrical steel sheets by micro-embossing and micro-piercing, respectively.

3. Experimental Results and Discussion

Two types of the plasma nitrided punches at 673 K for 14.4 ks by 70 Pa were prepared for laser nano-texturing; e.g., AISI316L punch with its head size of 10 mm x 20 mm and SKD11 cylindrical punch with the head diameter of 2 mm.

3.1. Nanotexturing onto plasma nitrided punch

An AISI316L flat punch with the average roughness less than 0.1 μm was plasma nitrided at 673 K for 14.4 ks by 70 Pa under the supply of nitrogen – hydrogen mixture gas. As depicted in Figure 5, no significant change at the surface roughness is observed on this plasma nitrided punch. This punch was nano-textured with the use of femtosecond laser machining system. Three circular patterns with the diameter of 4 mm and three polygonal patterns with its circumscribing circle diameter of 4 mm were micro-textured onto the punch together with a star-shaped pattern with its outer circumscribing diameter of 4 mm. The cut depth was 5 μm.

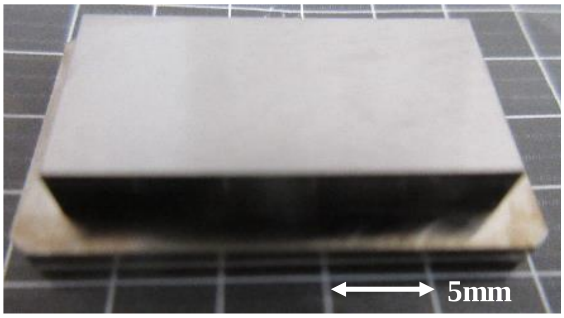

Figure 5. Uniformly plasma nitrided AISI316L punch with the head size of 10 mm x 20 mm.

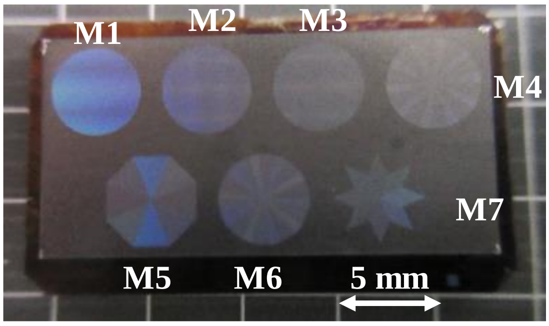

Figure 6. Micro-textured AISI316L punch with the use of the femtosecond laser machining. Seven microtextures are formed from three circular patterns (M1, M2 and M3), three polygonal patterns (M4, M5, M6) and, M7, star-shaped one.

Figure 6 shows seven patterns (M1…M7) micro-textured onto the surface of nitrided AISI316L punch. As stated in [10], each micro-textured pattern is dark blue colored by surface plasmonic brilliance in optics. Once the nano-textured ripples superpose on each microtexture, it has fine optically diffracted color with dependence on the orientation of nanotextured ripples.

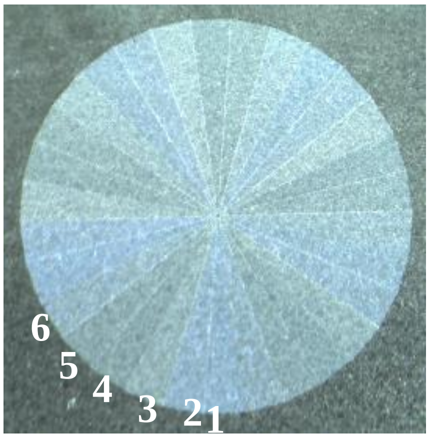

Figure 7. Optical microscopic image on the microtexture M6 among seven textures on the die.

Figure 7 depicts the optical microscopic image on the polygonal microtexture, M6. This microtexture consists of five repetitive sections; each section is further divided into six segments from #1 to #6 in Figure 7 with different nanotextures. As introduced in Figures 2-4, each segment has different surface plasmonic brilliance with dependence on the orientation of nanotextures. Figure 8 lists the SEM images on the nanotextures of each segment in the microtexture of M6 on the die. The orientation of nanotexture is controlled to rotate clockwise from a) to f) in correspondence from segment #1 to #6 in Figure 7. Irrespective of this rotational control, the spatial periodicity of nanotextures is constant by 300 nm and its depth is 0.4 μm for all segments.

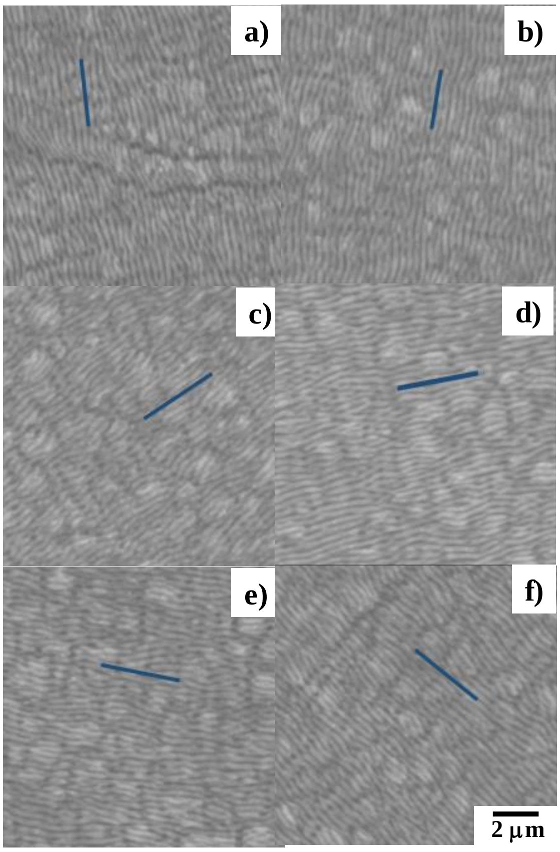

Figure 8 Nanotextures of six segments in M6 with clockwise rotation of their orientations from a) to f) in correspondence of #1 to #6 in Figure 7 by the femtosecond laser texturing.

3.2. Nanotexture imprinting by stamping

CNC (Computer Numerical Control)-stamping system was utilized to imprint seven microtextures with the tailored nanotextures onto the surface of AA1060 aluminium plate with the thickness of 1 mm.

A single-mode loading sequence was used to compress the upper punch with the constant velocity. Figure 9 depicts the embossed AA1060 aluminium plate after single-shot loading down to 150 μm from the original position where the punch touched just on the work material surface. This larger stroke than the heights of microtextures and nanotextures in Figures 7 and 8, included the elastic response in the support of work as well as the deformation of rough plate surfaces.

Seven microtextures are seen on the plate also to have the surface plasmonic brilliance. This proves that the nanotextures in Figure 8 are also coined into the pure aluminium plate surface.

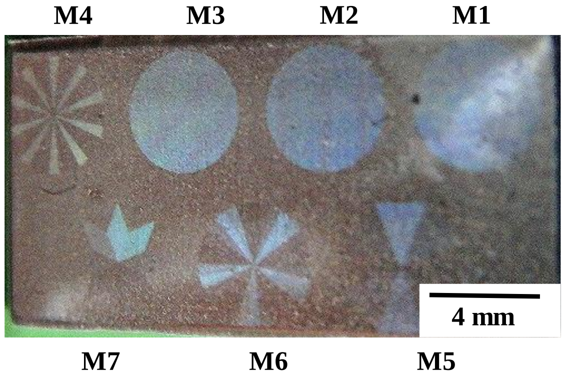

Figure 9. AA2060 pure aluminium plate with the transcribed seven microtextures.

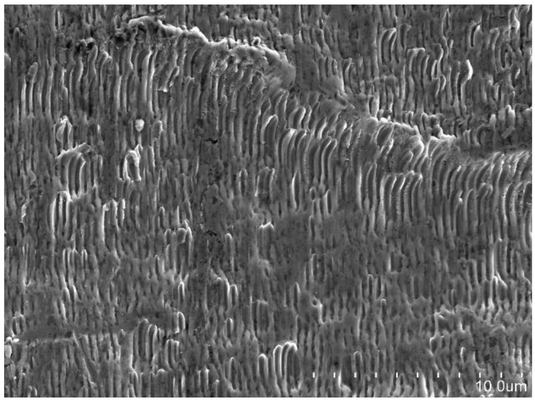

Figure 10. Nanotextures formed onto the AA1060 pure aluminium plate by micro-embossing the micro-/nano-textured punch in Figure 6.

SEM analysis with high magnification was made to describe the nanotextures imprinted onto the aluminium plate together with transcription of the microtexture #M6 in Figure 7. Figure 10 depicts the coined nanotexture onto the aluminium plate surface in correspondence to the nanotexture in the segment #1 of the microtexture M6. Each nanotexture is aligned in the uniaxial directions with the same ripple width and depth as seen in Figure 8a). The directivities of nanotextures both in Figs. 8a) and 10 are just in mirror reflection by coining the nanotexture on die surface onto the work material surface. This comparison of nanotextures reveals that the tailored microtextures in Figure 7 and nanotextures in Figure 8 are concurrently imprinted accurately onto the work material surface.

3.3. Trimming of nitrided punch with nano-texturing

Both the head and shoulder surfaces of plasma nitrided cylindrical punch with the diameter of 2 mm were trimmed by the femtosecond laser processing to sharpen its edge and to lower the surface roughness. Figure 11a) depicts the trimmed side surface of nitrided punch. This punch side surface was laser-trimmed down to the depth of 6 μm along the length of 300 μm. Nanotextured grooves are expected to superpose onto the trimmed surface simultaneously with femtosecond laser trimming process. Owing to two-step laser trimming on the punch head and side surfaces, the punch edge was sharpened as shown in Figure 11b). The original dull edge width around 10 μm was sharped down to 1.5 μm by this trimming.

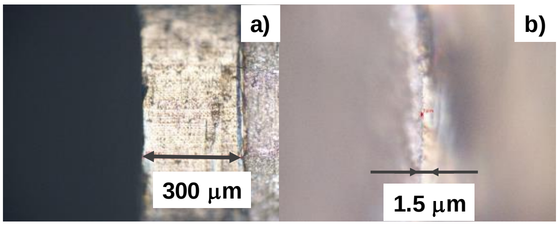

Figure 11 Optical and laser microscopy images on the trimmed punch surface and edge width. a) Trimmed surface from the punch head and b) sharpened punch edge.

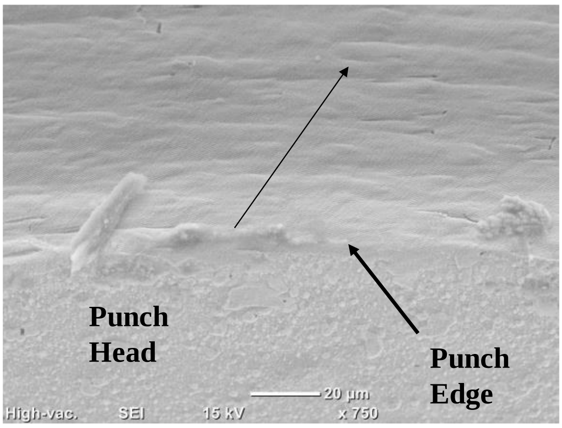

Figure 12. SEM image on the nitrided SKD11 punch after femtosecond laser trimming.

Figure 12 depicts the SEM image on the microstructure from the punch head across the punch edge to the side surface of nitrided SKD11 punch after femtosecond laser trimming. Nanotextures with the LIPSS ripple width of 300 nm superpose on the trimmed side surface.

3.4. Nanotexture imprinting by piercing

CNC-stamping system was also used to make piercing into the electrical steel sheet (0.2 mm) by this trimmed punch. As shown in Fig. 13, unidirectional nanotextures are formed concurrently onto the hole surface with piercing process.

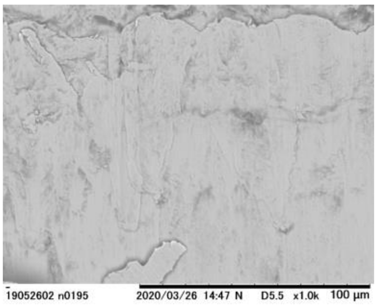

Figure 13. SEM image on the hole surface pierced into electrical steel sheet by the trimmed punch.

4. Conclusion

The laser nanotexturing process directly works as a tool to build up a master-piece for duplication of tailored nano-textures onto the metallic and polymer products. Owing to the nitrogen supersaturation at 673 K into the die substrate, the laser-nanotextured die is responsible for long-term usage in this duplication processes. In particular, this nitrided die has sufficient chemical stability and heat resistance to make high temperature injection molding and mold stamping for this repetitive duplication operations.

This femtosecond laser nanotexturing also works to form the unidirectional nanotextures onto the trimmed punch side surface. Both the laser trimming and nanotexturing processes simultaneously co-work to adjust the surface roughness and geometric irregularities by trimming and to superpose the nanotextures onto the trimmed surface.

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