

Effect of Additional Boron Amount on Surface Roughness after Lathe Turning in h-BN Dispersed Type 304 Stainless Steels

Masahiro KAWAJIRI,¹⁾ Satoshi EMURA,^{2)*} Xiaohua MIN,³⁾ Shigeo YAMAMOTO,²⁾ Kazuyuki SAKURAYA²⁾ and Kaneaki TSUZAKI^{2,4)}

1) Formerly Graduate Student, Graduate School of Pure and Applied Sciences, University of Tsukuba. Now at Seiko Epson Corp., 2070, Kotobuki Koaka, Matsumoto, Nagano, 399-8702 Japan. 2) National Institute for Materials Science, 1-2-1, Sengen, Tsukuba, Ibaraki, 305-0047 Japan. 3) Formerly National Institute for Materials Science. Now at Dalian University of Technology, No. 2 Linggong Road, Ganjingzi District, Dalian, Liaoning Province, 116024, P. R. China. 4) Formerly Graduate School of Pure and Applied Sciences, University of Tsukuba. Now at Kyusyu University, 744, Motooka, Nishi-ku, Fukuoka, 819-0395 Japan.

(Received on November 30, 2015; accepted on January 28, 2016; originally published in *Tetsu-to-Hagané*, Vol. 100, 2014, No. 12, pp. 1542–1547)

The authors have reported that the machinability (lathe turning, drilling and sawing) of SUS304 (Type 304) austenitic stainless steel is improved by precipitating hexagonal boron nitride (h-BN). In this study, we investigated the surface roughness after lathe turning in the h-BN precipitated SUS304 steels, where the nitrogen content was fixed at 0.2% and the boron content was changed as 0, 0.03, 0.05, and 0.1% (mass%). Surface roughness increased as the boron content increased, especially at a lower cutting speed of 22 m/min. However, SUS304 steel with boron content of up to 0.05 mass% had similar or smaller surface roughness compared with a commercial SUS304 steel, and the SUS304 steel containing 0.1 mass% boron had smaller surface roughness compared with a SUS303 (Type 303) sulfur-added free-cutting steel. Precipitation of h-BN increased the size of the build-up edge and increased the surface roughness. On the other hand, solute nitrogen increased the Vickers hardness, leading to decreased separation size of the build-up edge and decreased surfaced roughness.

KEY WORDS: austenitic stainless steel; machinability; hexagonal boron nitride; lathe turning; surface roughness.

1. Introduction

Austenitic stainless steels, such as JIS SUS304 (AISI Type 304), are widely used because of their excellent mechanical properties, superior corrosion resistance, and good plastic workability. However, their machinability is poor due to their high work hardening and low thermal conductivity.^{1,2)}

Various types of free-cutting steels that contain alloying elements, such as lead (Pb) and sulfur (S), which form free-cutting inclusions, are widely used.^{3–7)} However, further use of materials with lead additives is not feasible because of environmental and recyclability concerns. In addition, JIS SUS303 (AISI Type 303) steel, a widely used sulfur-added free-cutting austenitic stainless steel, has drawbacks such as anisotropic mechanical properties arising from the elongated shape of the manganese sulfide (MnS) free-cutting additives along the rolling direction,⁸⁾ and deteriorated corrosion resistance.⁹⁾

We have focused on hexagonal boron nitride (h-BN) as a free-cutting additive that improves the machinability of

austenitic stainless steels with no anisotropy in the mechanical properties and reduced corrosion resistance. Although studies on h-BN free-cutting steels have mainly been performed on carbon steels such as JIS S45C (AISI 1045),^{10–12)} we have developed an h-BN free-cutting austenitic stainless steel containing homogeneously precipitated spherical h-BN particles with a diameter of 1 to 3 μm .¹³⁾ The steel was obtained by melting commercial SUS304 austenitic stainless steel and a commercial ferrobore under a reduced-pressure nitrogen atmosphere, followed by h-BN dissolution and re-precipitation heat treatment. This h-BN free-cutting austenitic stainless steel exhibited improved machinability and other advantages, such as weak anisotropy of mechanical properties, high corrosion resistance equivalent to that of SUS304 steel and superior to that of SUS303 steel, and the availability of existing stainless steel production lines that use similar manufacturing processes.¹³⁾

In the previous paper,¹⁴⁾ we have investigated the mechanism of the improvement in machinability in h-BN precipitated free-cutting SUS304 austenitic stainless steel containing 0.016 mass% B. During lathe turning, the tool-chip contact length was reduced by the decrease in adhesion and increase in lubrication between the chip and the tool caused by h-BN, and improved machinability, such as

* Corresponding author: E-mail: EMURA.Satoshi@nims.go.jp
DOI: <http://dx.doi.org/10.2355/isijinternational.ISIJINT-2015-684>

reduced resultant cutting force and suppressed tool wear, was achieved. During drilling and sawing operations, where the formation of a build-up edge (B. U. E.) was expected, improved machinability such as reduced drilling force, suppressed drill wear and improved sawability, was observed, which resulted from internal lubrication by h-BN particles in front of the B. U. E.

In some applications of free-cutting steels, the surface roughness after cutting is important. It is critical to achieve dimensional accuracy in small parts, such as shafts and precision screws, for precision machines, including hard disk drives and printers.¹⁵⁾ Increasing the cutting speed is an effective way to obtain superior surface properties, although it is not suitable for producing small parts. During low-speed cutting, the formation of a B. U. E. occurs readily and this B. U. E. formation increases the surface roughness. In sulfur-added free-cutting steels, the formation of B. U. E. and the presence of MnS make it difficult to improve the surface roughness. Compared with MnS free-cutting stainless steels, h-BN free-cutting stainless steels are expected to have more improved surface properties owing to the spherical shape, higher lubricity, and homogeneous distribution of h-BN precipitates. However, further investigation of surface roughness is needed before h-BN free-cutting stainless steels are used for small parts.

In this study, we investigated the effects of h-BN particle precipitation on the surface roughness of SUS304 austenitic stainless steels after lathe turning. We prepared SUS304 stainless steels containing 0.2 mass% nitrogen and different boron content of up to 0.1 mass% as work materials, and used commercial SUS304 and SUS303 stainless steels for comparison. To simulate the production of small parts for precision machines, lathe turning was performed at low cutting speeds, where B. U. E. is expected to form.

2. Experimental Procedure

2.1. Sample Preparation

A commercial SUS304 steel round bar (diameter 55 mm) and a commercial ferroboron (Fe-19.2 mass% B) were used as raw materials. The chemical compositions of SUS304 steel used as a raw material, the SUS304 steel used as a control, and the SUS303 steel are shown in **Table 1**. The SUS304 steel was melted with ferroboron at target boron contents of up to 0.1 mass% by cold crucible levitation melting (CCLM) to obtain a 2 kg reverse bell shape ingot. The steel was melted under a nitrogen atmosphere with a partial pressure of 0.07 MPa to adjust the concentration of nitrogen in the molten steel to a target value of 0.2 mass%. The chemical composition of the ingot was kept the same as the SUS304 raw material in the CCLM, apart from the

additives.¹⁶⁾ After the top of the cast ingot was removed, the ingot was hot forged into 38 mm square slabs at 1 373 K and then caliber bar rolled into 21.3 mm square bars at 1 373 K. First, h-BN solution treatment was performed on the forged and rolled bars, consisting of heat treatment in air for 1.8 ks at 1 523 K, followed by water quenching. Next, h-BN precipitation treatment was performed, consisting of heat treatment in air for 3.6 ks at 1 323 K, followed by water quenching. Work samples 0B, 300B, 500B, and 1000B with different boron contents were prepared. For sample 0B, SUS304 steel was melted under a reduced-pressure nitrogen atmosphere. For the other three samples, the numbers in their names denoted the target boron content in parts per million; for example, the target boron content in sample 300B was 300 ppm (0.03 mass%). The nitrogen content in the ingot was analyzed by the inert gas fusion thermal conductivity method. The total boron content of the heat-treated samples was analyzed by inductively coupled plasma optical emission spectrometry (ICP-OES) according to JIS G 1258-5:2007. The soluble boron content was also analyzed by dissolution in aqua regia, filtration, and ICP-OES.

2.2. Observation of h-BN Particles

The h-BN precipitates in the samples were observed by scanning electron microscopy (SEM). To avoid the dropout of h-BN particles during SEM sample preparation, the fracture surface observation was adopted.¹⁷⁾ Round bars with a diameter of 3.6 mm and a length of approximately 50 mm were cut from samples after heat treatment, where the longitudinal direction of the bars was parallel to the rolling direction. A 2-mm-deep circumferential notch was cut 7 mm from the end of the bar. The bar was bent and broken at the notch, and the fracture surface was observed by SEM and analyzed by energy-dispersive X-ray spectroscopy (EDS) to identify the inclusion particles. The observed surface was normal to the rolling direction.

2.3. Vickers Hardness Testing

The addition of nitrogen and h-BN precipitation affects the hardness of samples, which may affect the machinability, including surface roughness. Therefore, the Vickers hardness values of the samples were measured after heat treatment. The applied load was 98 N and the holding period was 15 s. A total of 10 measurements were taken for each sample, and the Vickers hardness value of each sample was determined as an average of eight measurements, excluding maximum and minimum values. The Vickers hardness values of commercial SUS303 (average of three measurements) and SUS304 (average of 4 measurements) steel were also determined.

Table 1. Chemical compositions of commercial SUS304 steel (raw material and used as control) and SUS303 steel (sulfur-added free-cutting stainless steel) (mass%).

Type	Lot	C	Si	Mn	P	S	Ni	Cr	Fe
304	Raw material	0.07	0.49	1.12	0.025	0.024	8.06	18.05	bal.
	Control	0.07	0.33	1.15	0.036	0.022	8.07	18.03	bal.
303		0.05	0.33	1.79	0.028	0.29	9.02	17.9	bal.

2.4. Lathe Turning and Evaluation of Surface Roughness

After removing the mill scale by lathe turning, samples 0B, 300B, 500B, and 1000B, and 55-mm-diameter round bars of commercial SUS304 and SUS303 steel, which chemical compositions are shown in Table 1, were lathe turned and their surface roughnesses were evaluated. WC-TiC(TaC)-Co cemented carbide throw-away inserts (M30) with a chip breaker (TNGG160404) were used in the turning process. The shape of the insert was as follows: front top rake: -6° ; side rake: -6° ; front clearance: 6° ; side clearance: 6° ; end cutting edge angle: 45° ; side cutting edge angle: 15° ; and tool edge radius: 0.4 mm. The samples were turned with a cutting depth of 0.5 mm and a feed rate of 0.08 mm/rev to simulate finish turning. Cutting speeds of 22 (low speed), 60 (medium speed), and 100 m/min (high speed) were applied. No cutting oil was used.

Surface roughness after lathe turning was measured by using a confocal scanning laser microscope (Lasertec, 1LM21). Surface roughness values were measured over a length of 450 μm along the rolling direction (parallel to the

rolling axis of lathe turning), and 10-point average roughness values were calculated. **Figure 1** shows a schematic of the calculation method. The heights of peaks (P) and the depths of valleys (V) were measured by using the horizontal line in Fig. 1 as baseline. The average absolute values from the first ($P1$) to the fifth ($P5$) highest peaks and the average absolute values from the first ($V1$) to the fifth ($V5$) deepest valleys were summed to give the 10-point average roughness value (R_z) (Eq. (1)).

$$R_z = \frac{|P1 + P2 + P3 + P4 + P5| + |V1 + V2 + V3 + V4 + V5|}{5} \quad (1)$$

Ten-point roughness values of 20 randomly chosen places on the surface of each sample (10 places for SUS303 and SUS304 steel cut at medium and high speed, and 19 places for SUS303 steel cut at low speed) were averaged. The surface quality of the samples after lathe turning was observed by optical microscopy.

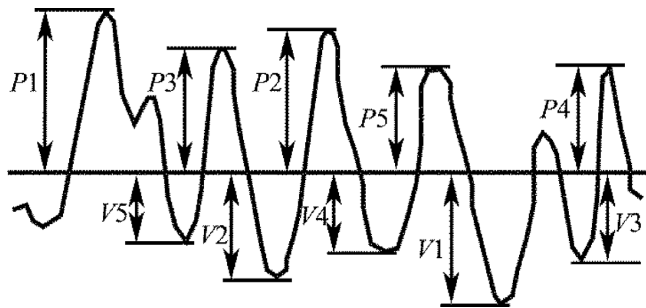


Fig. 1. Schematic of the surface roughness measurement.

Table 2. Chemical compositions of the samples.

Sample	Total N (mass%)	Total B (mass%)	Soluble B (mass%)
0B	0.22	—	—
300B (0.03)*	0.23	0.029	0.005
500B (0.05)*	0.23	0.047	0.006
1000B (0.1)*	0.22	0.093	0.010
304	0.061	—	—
303	0.049	—	—

* Target value of B content (mass%)

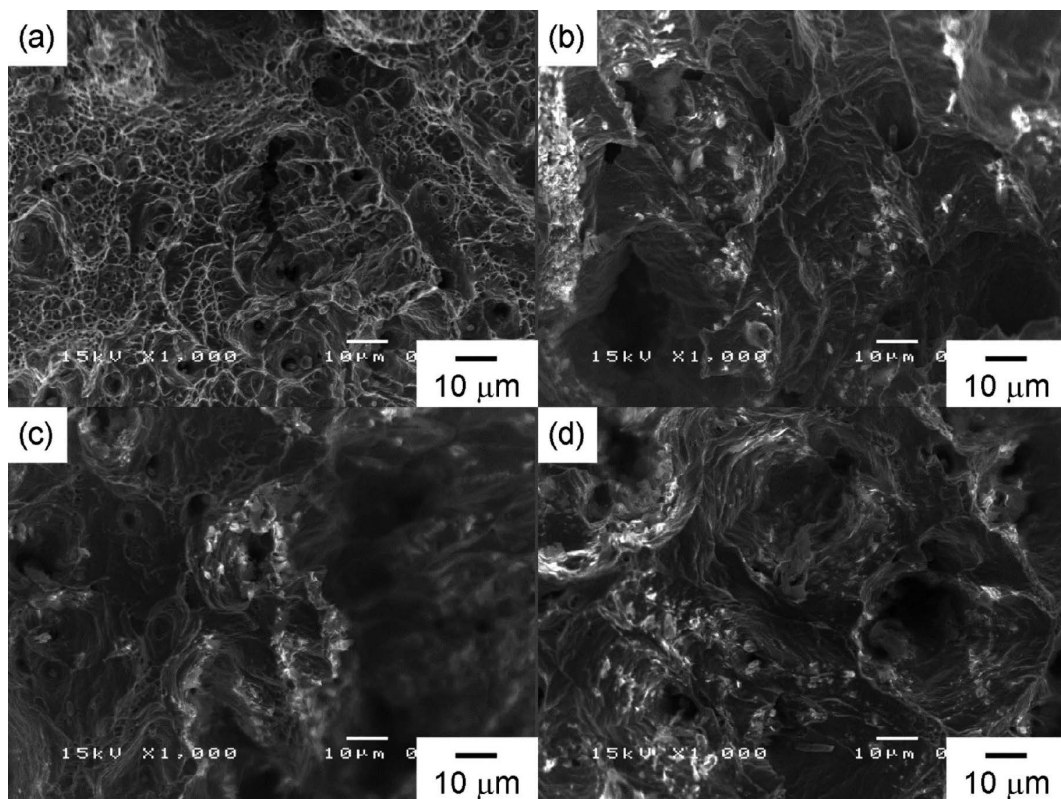


Fig. 2. SEM images of inclusions on the fractured surface of sample (a) 0B, (b) 300B, (c) 500B, and (d) 1000B.

3. Results and Discussion

3.1. h-BN Particle Precipitation and Vickers Hardness Values

Table 2 shows the nitrogen contents in the ingots of sample 0B, 300B, 500B, and 1000B and the total and soluble boron contents in the corresponding samples after forging, rolling and heat treatment, along with the target total boron contents. In all samples, the nitrogen contents were close to their target values of 0.2 mass%, and much higher than SUS303 and SUS304 steel. The total boron content in each sample was also close to the target value, although the soluble boron contents were only 10%–17% of the total boron content. Therefore, it was assumed that most of added boron precipitated in the samples as h-BN, and the amount of h-BN precipitate increased with the boron content.

Figure 2 shows SEM micrographs of precipitated h-BN particles on the fracture surfaces of samples 0B, 300B, 500B, and 1000B. The observed planes were normal to the rolling direction. In sample 0B, without addition of boron, significant inclusions were not found, whereas the other samples that contained boron, numerous inclusions with a white or gray contrast were observed. Many of these inclusions were identified as h-BN by EDS analysis, and others were identified as MnS, which were formed from the Mn in the alloy and S unavoidable impurities present in SUS304 steel. Samples with a larger boron content appeared to contain a larger amount of h-BN precipitate, although a firm conclusion cannot be drawn from Fig. 2 alone because fractures tend to occur more easily at locations containing more inclusions.¹⁴⁾

The Vickers hardness values of samples 0B, 300B, 500B, 1000B, SUS304 steel, and SUS303 steel are shown in Fig. 3. The hardness values of samples 0B, 300B, and 500B were higher than those of SUS303 and SUS304 steel. This was because of the nitrogen addition of 0.2 mass%, some of which reacted with boron and formed h-BN, and the remainder of which contributed to solution strengthening in the stainless steel matrix. Sample 0B, which did not contain added boron, exhibited the highest Vickers hardness values, and the hardness values decreased as the boron content increased. Sample 1000B, with a target boron content of

1 000 ppm (0.1 mass%), had similar or lower hardness values than SUS303 and SUS304 steel. The decrease in the amount of solute nitrogen owing to h-BN precipitation and the increase in the amount of h-BN precipitate with lower hardness values probably decreased the hardness values.

3.2. Surface Roughness after Lathe Turning

Figure 4 shows surface roughness of samples after lathe turning at different cutting speeds. The samples cut at 100 m/min (Fig. 4(c)) exhibited similar surface roughness. However, as the cutting speed decreased, the difference in

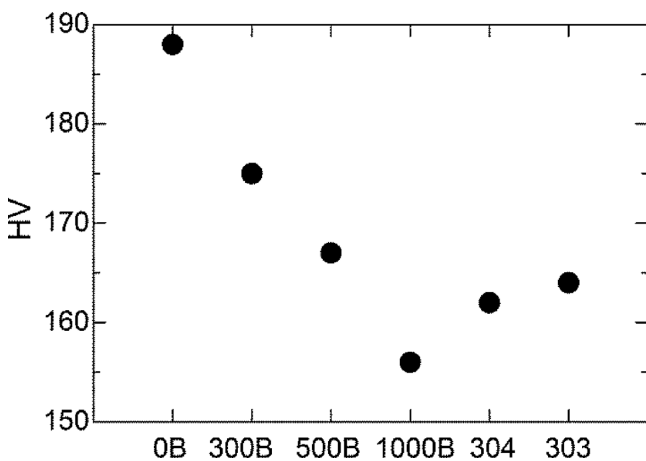


Fig. 3. Vickers hardness values of samples. The hardness decreased as the boron concentration increased because the concentration of nitrogen in solution decreased.

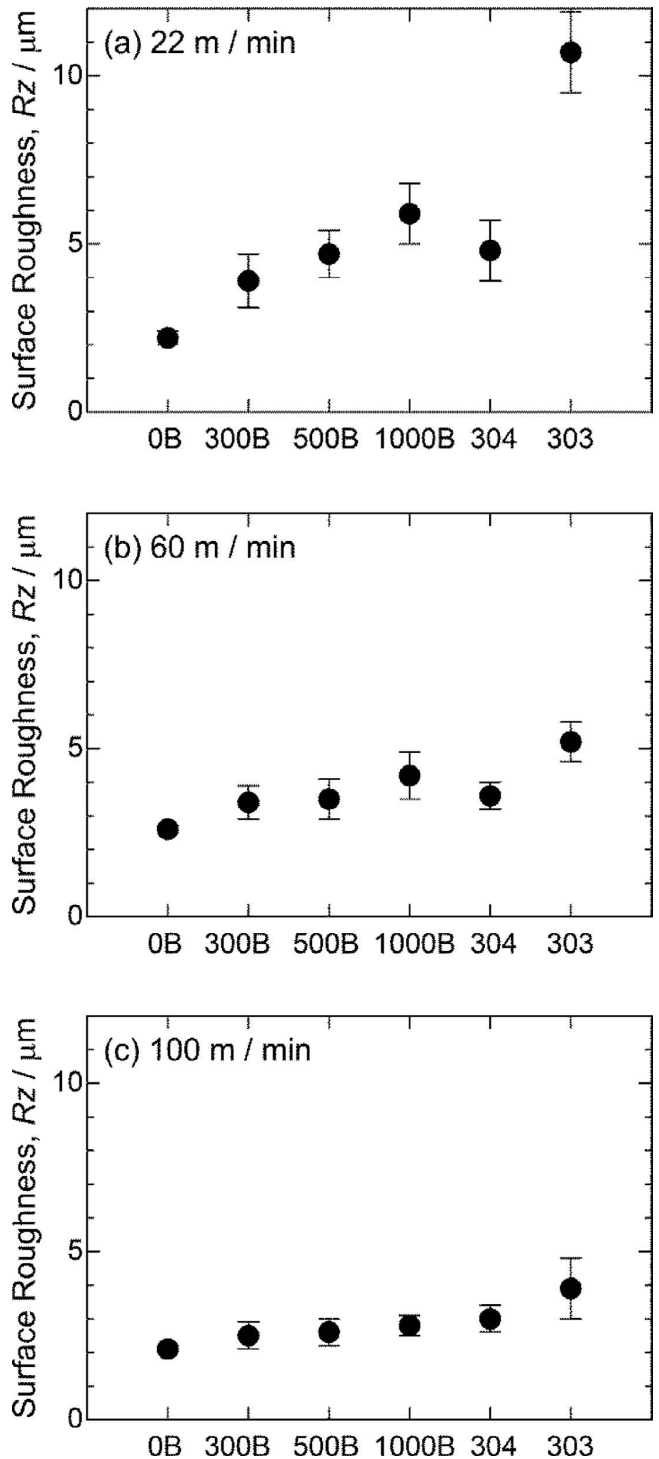


Fig. 4. Surface roughness of samples after machining at a cutting speed of (a) 22 m/min, (b) 60 m/min, and (c) 100 m/min.

the surface roughness of samples increased. At a cutting speed of 22 m/min (Fig. 4(a)), SUS303 steel containing MnS as a free-cutting additive, had the largest surface roughness. Sample 0B, which only had nitrogen added, had the smallest surface roughness. The surface roughness after lathe turning increased with the boron content. The surface roughness of sample 500B was similar to that of SUS304 steel, and samples 0B and 300B, which had a smaller boron content, had a smaller surface roughness than SUS304 steel.

The surface roughness of sample 1000B was larger than that of SUS304 steel, but smaller than that of SUS303 steel.

Figure 5 shows the lathe-turned surfaces of sample 0B, 300B, 500B, and 1000B cut at 22 m/min, where the difference in surface roughness was largest. A large number of accretions that increased the roughness were observed on the surfaces (indicated by arrows in Fig. 5), in addition to tool feed marks. The formation of B. U. E. was expected at a cutting speed of 22 m/min, so the accretions were thought

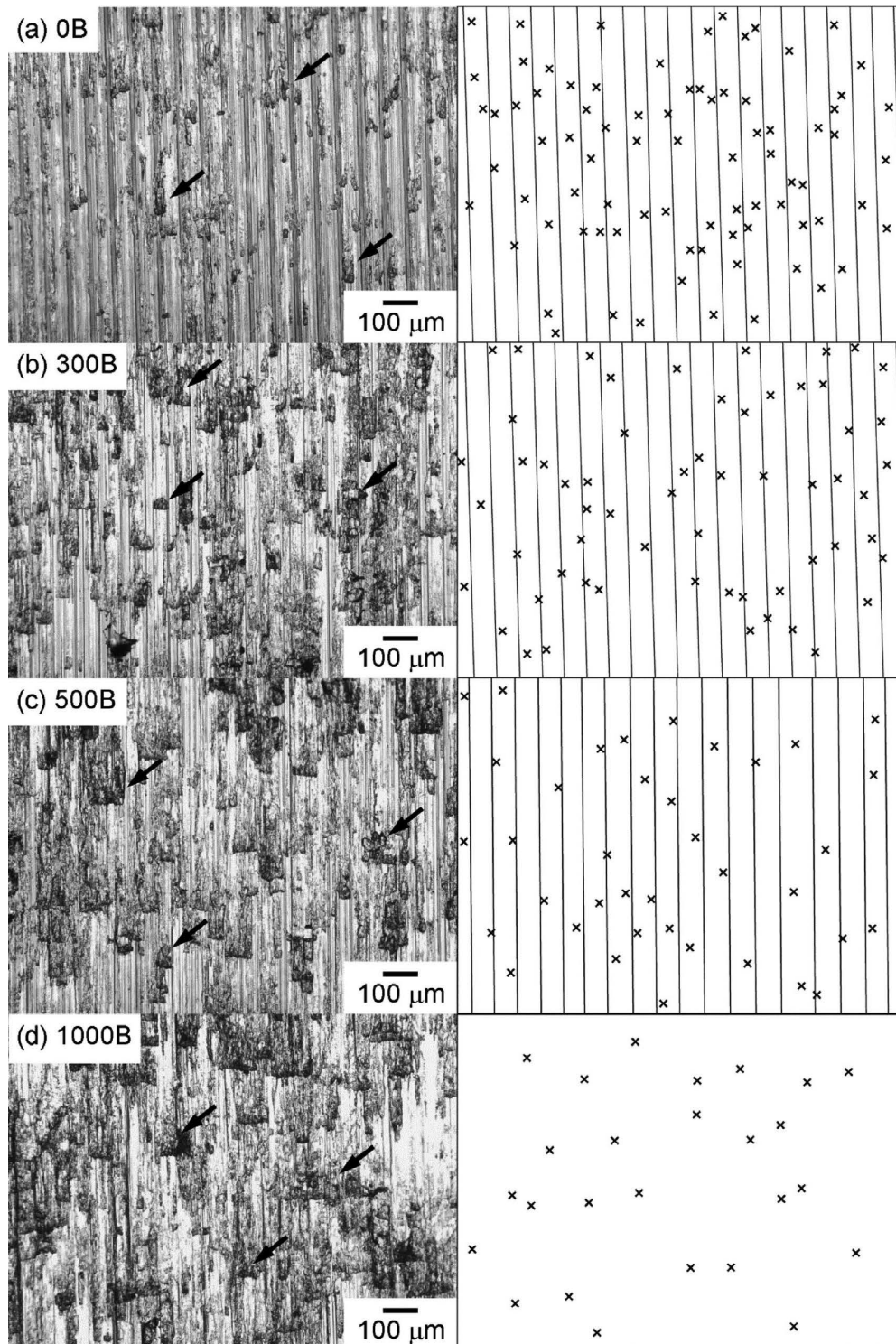


Fig. 5. Accretions on the machined surface after machining at a cutting speed of 22 m/min for samples (a) 0B, (b) 300B, (c) 500B, and (d) 1000B. Typical accretions are indicated by arrows in the left-hand figures and all accretions are indicated by crosses in the right-hand figures.

to be B. U. E.s detached from the tool tip.¹⁸⁾ The positions of the accretions are schematically indicated by crosses in the right-hand figures in Fig. 5. As the boron content increased, the size of and interval between accretions increased.

Figure 6 shows the average intervals between accretions, measured as the distances between the accretion centers along the cutting direction, in multiple views of samples. In sample 1000B, the accuracy in measuring the intervals and the average intervals (open circle, Fig. 6) was low because the accretions were large with vague boundaries. The interval between accretions increased as the boron content increased.

3.3. Effect of B. U. E. Formation on Surface Roughness

Below, we discuss the surface roughness after lathe turning at 22 m/min. The observed accretions on the lathe-turned surface originated from B. U. E.s. There are two mechanisms that could explain the effect of B. U. E.s on the surface roughness after lathe turning. In the first mechanism, part of a B. U. E. is separated when it reaches a maximum size and the fragment adheres to the lathe-turned surface, which increases the surface roughness. In the second mechanism, the cutting position is displaced by the growth of the B. U. E., affecting the surface roughness. In this work, the first mechanism was dominant because the increase in surface roughness was caused by accretions.

As described in Section 3.2, the size and the interval of accretions increased as the boron content increased, which increased the surface roughness. This means that samples that form larger B. U. E.s during lathe turning have larger surface roughnesses. In our previous paper,¹⁴⁾ we compared the B. U. E.s of h-BN precipitated SUS304 steel with 0.016 mass% boron and 0.2 mass% nitrogen addition, with that of SUS304 steel with only 0.2 mass% nitrogen addition. The size of the B. U. E. increased with h-BN precipitation. The force applied to the B. U. E. was reduced because h-BN precipitation reduced the cutting force, which increased the growth of B. U. E. The effects of the boron content on the shape and size of B. U. E. were unclear, although the separation of large B. U. E.s arising from h-BN precipitation may degrade the surface roughness. However, as the hardness of samples increased (Fig. 3), the surface roughness after lathe

turning decreased (Fig. 4), except for SUS303 steel, which showed a large increase in surface roughness.

One of the authors investigated the relationship between tip radius of B. U. E. and hardness of work samples in Cr–Mo steel with various hardness values by using multiple regression analysis, and reported that the tip radius decreased as the hardness of the work samples increased.¹⁹⁾ These results suggest that in SUS304 steel containing boron, a smaller boron content results in higher hardness and a smaller B. U. E. tip radius. B. U. E.s with a small tip radius are easily separated and adhere to the turned surface. Therefore, a large number of small accretions were observed. As the boron content increased, the hardness of the sample decreased and the B. U. E. tip radius increased. Larger B. U. E.s have a low frequency of separation, so the number of accretions decreases and the size increases.

To summarize, the increase in B. U. E. size arising from the reduced cutting force, and the reduced separation size of B. U. E. caused by the solute nitrogen hardening affected the surface roughness. Samples 0B and 300B, which had a lower boron content, also contained a small amount of h-BN precipitate, so the size of the B. U. E. was smaller. Furthermore, the hardness of these samples was larger than that of SUS304 steel because of the larger amount of solute nitrogen, so the separation size of B. U. E. was also smaller. Therefore, the surface quality of these samples was better than that of SUS304 steel. Further studies that include the effects of h-BN precipitation on the size and shape of B. U. E. are required.

On the other hand, the surface roughness of SUS303 steel, which had a similar hardness to SUS304 steel, was large compared with the other samples. **Figure 7** shows the B. U. E.s of SUS304 steel, which contained no boron or nitrogen, and SUS303 steel obtained by the quick stop test during lathe turning²⁰⁾ at a cutting speed of 22 m/min. The observed plane was the cross section of the B. U. E. at the center of the chip width. In SUS303 steel, the size of the B. U. E. increased even though the hardness values were similar and the cutting conditions were the same as for SUS304 steel. In SUS303 steel, the reduction of the cutting force was large because of the precipitation of MnS free-cutting

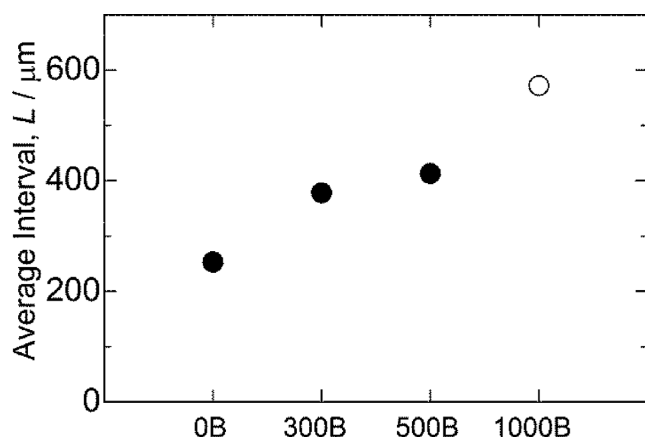


Fig. 6. Average intervals between accretions after machining at a cutting speed of 22 m/min. Open circle (1000B) indicates less accurate values owing to the limitations of measurement accuracy.

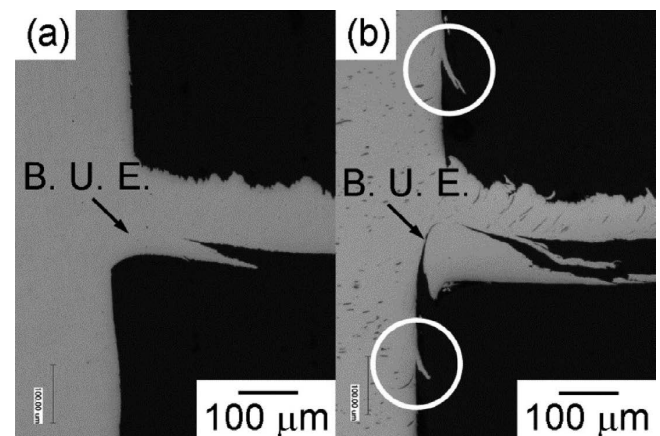


Fig. 7. Optical micrographs of build-up edges (B. U. E.s) obtained by the quick stop device during machining at a cutting speed of 22 m/min for (a) SUS304 and (b) SUS303 steel. A larger B. U. E. is seen in (b) SUS303 steel.

additives. Therefore, the size of B. U. E. was larger than that of steels containing h-BN precipitates. The larger B. U. E.s were easily separated and adhered to the turned surface (indicated in Fig. 7(a) by white circles), which increased the surface roughness of SUS303 steel after lathe turning.

Sample 0B, which only contained nitrogen, exhibited the lowest surface roughness, and the surface roughness increased with the boron content. As we described previously,¹⁴⁾ the addition of 0.016 mass% boron reduced the cutting force and increased the tip disposability. Therefore, the amount of boron added to improve machinability should be minimized for applications in which the surface roughness after lathe turning is important. However, sample 1000B, which had the highest boron content, exhibited better surface quality after lathe turning compared with SUS303 steel. Therefore, improving the machinability of austenitic stainless steel by h-BN precipitation produced smaller surface roughness than adding sulfur.

4. Conclusion

The effects of hexagonal boron nitride (h-BN) precipitation on the surface roughness of SUS304 austenitic stainless steels after lathe turning were investigated. Lathe turning was performed mainly at low cutting speed, to simulate the production of small parts for precision machines. We can draw the following conclusions from our results.

(1) SUS304 steel ingots containing h-BN precipitates were obtained by adding 0.2 mass% nitrogen and a maximum 0.1 mass% boron. The amount of h-BN precipitate increased as the boron content increased.

(2) The Vickers hardness values of the SUS304 steels containing nitrogen and boron were higher than those of SUS304 and SUS303 steels (sulfur-added free-cutting stainless steel). As the boron content increased, the hardness values decreased.

(3) The surface roughness of SUS304 steel containing nitrogen and boron after lathe turning at low cutting speed (22 m/min) increased as the boron content increased. However, the surface roughness of samples containing less than 0.5 mass% boron was similar to or better than that of SUS304 steel, and all boron-containing samples had lower surface roughnesses than SUS303 steel.

(4) The increase in surface roughness at low cutting speed was caused by the separation and adhesion of the build-up edge (B. U. E.) formed at the tool tip. In SUS304 steel containing h-BN precipitates, the increase in the B. U. E. size because of the reduced cutting force and the reduced separation size of B. U. E. owing to the solute nitrogen hardening affected the surface roughness. In SUS303 steel, the surface roughness increased greatly because of the large B. U. E.

Acknowledgement

The authors are grateful to the Materials Manufacturing and Engineering Station of NIMS for their assistance in melting and forming the samples, and to the Materials Analysis Station of NIMS for supporting chemical analysis. The authors thank the Iketani Science and Technology Foundation for financial support.

REFERENCES

- 1) Z. Tekiner and S. Yesilyurt: *Mater. Design*, **25** (2004), 507.
- 2) K. Karino: Nansaku-zai no jozuna kezurikata, Stainless Steels, Nikkan Kogyo Shimbun Ltd., Tokyo, (2010), 36 (in Japanese).
- 3) H. Yaguchi: *Tetsu-to-Hagané*, **77** (1991), 683 (in Japanese).
- 4) K. Ono, M. Yanagida, T. Kohno and N. Shibata: *Denki Seiko*, **54** (1983), 265 (in Japanese).
- 5) M. C. Shaw, E. Usui and P. A. Smith: *Trans. ASME B*, **83** (1961), 181.
- 6) M. E. Merchant and N. Zlatin: *Trans. ASM*, **41** (1949), 647.
- 7) E. M. Trent: *J. Iron Steel Inst.*, **12** (1963), 1001.
- 8) M. Somekawa, M. Kaiso, Y. Matsushima and H. Yaguchi: *Kobe Steel Eng. Rep.*, **51** (2001), 13 (in Japanese).
- 9) T. Koga, T. Shimizu and M. Okabe: *Denki Seiko*, **67** (1996), 75 (in Japanese).
- 10) T. Hanyuda and S. Nakamura: *Denki Seiko*, **65** (1994), 4 (in Japanese).
- 11) Y. Yamane, R. Tanaka and N. Narutaki: *J. Jpn. Soc. Prec. Eng.*, **64** (1998), 1370 (in Japanese).
- 12) T. Murakami, K. Tomita and T. Shiraga: *JFE Giho*, **23** (2009), 10 (in Japanese).
- 13) K. Sakuraya, S. Yamamoto and K. Tsuzaki: *Materia Jpn.*, **46** (2007), 689 (in Japanese).
- 14) S. Emura, M. Kawajiri, X. H. Min, S. Yamamoto, K. Sakuraya and K. Tsuzaki: *ISIJ Int.*, **53** (2013), 1841.
- 15) K. Takano, S. Fukumoto, K. Amafuji, M. Kizaki and K. Yoshino: *Materia Jpn.*, **49** (2010), 26 (in Japanese).
- 16) S. Iwasaki, K. Sakuraya and A. Fukuzawa: *Tetsu-to-Hagané*, **88** (2002), 413 (in Japanese).
- 17) K. Sakuraya, H. Okada and F. Abe: *Energy Mater.*, **1** (2006), 158.
- 18) K. Uegami and K. Tamamura: *J. Jpn. Soc. Prec. Eng.*, **54** (1988), 1490 (in Japanese).
- 19) S. Yamamoto, H. Nakajima and H. Miyaji: *Tetsu-to-Hagané*, **80** (1994), 469 (in Japanese).
- 20) T. Araki, S. Yamamoto and Y. Uchinaka: *Tetsu-to-Hagané*, **54** (1968), 444 (in Japanese).