Cutting Characteristics of Duplex Stainless Cast Steel
X2CrNiMoN25-7-3

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Abstract: X2CrNiMoN25-7-3 duplex stainless steel is suitable for chloride-containing environments such as seawater because it has excellent pitting corrosion resistance. Duplex stainless cast steel is often used to accommodate the complexity of part geometry at joints. However, machining after casting is indispensable. This study evaluated the cutting characteristics of stainless cast steel. Adhesion of the cutting edge was weak at high cutting speeds, but tool wear was large. Diffusion and reactions between the work-pieces and the tool edge were investigated. Slight inter-diffusion and a reaction phase were observed, but the bond-ability was low.

Key words: Duplex stainless steel, sintered carbide tool, cermet tool, mach-inability, stainless cast steel, adhesion.

1. Introduction

Stainless steels have attracted attention because they offer high strength, heat resistance, corrosion resistance, and recyclability [1]. Among the various kinds of stainless steel, duplex stainless steel is suitable for use in chloride-containing environments such as seawater. It is widely used for transportation pipelines in chemical industrial plants, food plants, and offshore oilfields because it shows excellent pitting corrosion resistance [2].

Cast material is used to form the duplex stainless steel joints connecting such pipelines because the joints have complex geometries. However, because casting alone cannot create a final product, machining processing after casting is indispensable.

Many studies on the mach-inability of stainless steel, including those by Ito [3], have been conducted. The mach-inability of stainless cast steel was studied by Agrawal et al. [4] while the mach-inability of duplex stainless steel was investigated by Krolczyk et al. [5]. However, few studies exist on the mach-inability of duplex stainless cast steel.

Generally, adhesion occurs on the cutting edge during the machine cutting of stainless steel because of the high affinity of the sintered carbide (WC) tool material with the work materials, this decreases tool life and deteriorates the properties of the finished surface [6-8]. Cermet tools have low affinities with work materials, but are mainly used for finish machining because they are low in toughness [9-10]. In terms of suppressing adhesion, the productivity of duplex stainless steel parts would be improved if cermet tools could be used effectively for rough or semi-finishing machining.

Therefore, this study performed turning processing using a sintered WC tool and a cermet tool for the stainless cast steel X2CrNiMoN25-7-3. The cutting force, tool wear, and cutting characteristics of this material were evaluated. In addition, an evaluated the problem of adhesion phenomenon on the tool edge at following method. That the diffusion and reactions between the tools and material were investigated by diffusion bonding tests [11] for adhesion occurring at
the cutting edge of the tool while evaluating the relationship with tool damage. This experiment was conducted as a comparative test for duplex stainless steel X2CrNiMoN25-7-3 formed by extrusion, using the same material composition and strength.

The main purpose of this experiment is to evaluate mach-inability of stainless cast steel and evaluation of effectiveness of cermet tool to stainless cast steel.

2. Experimental Method and Conditions

2.1 Work Materials

Tables 1 and 2 show the chemical compositions and mechanical properties at the time of factory shipment of the duplex stainless cast steel X2CrNiMoN25-7-3 used in this experiment. In addition, stainless steel molded at a forging ratio of 22.3 \( S \) was used as a comparative material. The chemical composition and the mechanical properties of the material are equivalent to those of the stainless cast steel shown in Tables 1 and 2. Fig. 1a shows the stainless cast steel and Fig. 1b shows the forged stainless steel.

Fig. 1 shows the structural state of the workpiece, with the surface observed from a direction perpendicular to the axial direction of the round bar. As can be seen from Fig. 1a, the grain size of the cast steel is larger than that of the forged steel. In addition, it is confirmed that the crystal orientation of the forged steel is elongated in the axial direction, the two materials have different structures.

2.2 Experimental Method for Turning

In this experiment, we used a CNC (computer numerical control) lathe (Takisawa Machine Tool Co., Ltd., TAC-360). The cutting force and tool wear were measured to evaluate the cutting characteristics. The cutting force was recorded on a data logger (PC) via a strain gauge-type cutting tool dynamometer (Miho Electric Manufacturing Co., Ltd.) and a dynamic strain amplifier (Kyowa Electronic Instruments Co., Ltd.).

| Table 1  Chemical composition (wt%). |
| C | Si | Mn |
|---|---|---|
| 0.022 | 0.43 | 0.69 |
| P | S | Ni |
| 0.022 | 0.001 | 6.59 |
| Cr | Mo | N |
| 25.47 | 3.03 | 0.15 |

| Table 2  Mechanical properties. |
| Yield strength (N/mm\(^2\)) | 612 |
| Tensile strength (N/mm\(^2\)) | 788 |
| Elongation (%) | 38 |
| Reduction of area (%) | 75 |
| Hardness (HBW) | 255 |

**Fig. 1**  Microstructures of X2CrNiMoN25-7-3.

Table 3 shows the cutting conditions. In this experiment, the feed rate was constant at five different cutting speeds and a 10-m cutting test was performed with each tool. Then, a tool life test was conducted using the cutting conditions producing minimal cutting edge damage. The tool life test was performed using a data logger (PC) via a strain gauge-type cutting tool dynamometer (Miho Electric Manufacturing Co., Ltd.) and a dynamic strain amplifier (Kyowa Electronic Instruments Co., Ltd.).

| Table 3  Cutting conditions. |
| Cutting speed | Feed rate | Depth of cut |
| m/min | mm/rev | mm |
|---|---|---|
| 40 | | |
| 70 | | |
| 100 | 0.2 | 0.5 |
| 130 | | |
| 160 | | |
for a cutting time reaching 300 s. The cutting force and tool wear were measured at 15, 30, 60, 120, 180, 240, and 300 s. In addition, all cutting was performed by dry machining.

A square-type insert with a nose radius of 0.8 mm was attached to a tool holder (DSBNR 2020 K12). Sintered carbide and cermet tools were used without coating treatment of the tool surfaces.

2.3 Diffusion Bonding Method

Experiments conducted in advance showed that deposits were adhered to the cutting edge when sintered carbide tools were used on stainless steel. The diffusion reactions between the tool material and the work material were investigated because such deposits and the detachment thereof cause tool damage, such as the chipping of the cutting edge.

Fig. 2 shows a schematic of the diffusion bonding test, and Table 4 shows the test conditions. The bonding time was set to 1,500 s considering general solid-phase diffusion bonding. The bonding pressure was calculated from the principal cutting force when turning under the conditions of a cutting speed of 100 mm/min, feed rate of 0.2 mm/rev, and depth of 0.5 mm, divided by the cutting area of the tool used.

Diffusion bonding tests were performed in the following combinations: stainless cast steel (width (W) 5 × depth (D) 5 × thickness (t) 4.75 mm) and sintered carbide (carbide K) (W5 × D5 × t5 mm), stainless steel (W5 × D5 × t4.75 mm) and sintered carbide.

3. Results

3.1 Relationship between Cutting Force and Cutting Speed

Fig. 3 shows the results for the cutting force measurements with each tool as a function of the cutting speed.

The cermet tool shows a lower cutting force than the sintered carbide tool. As the cutting speed is increased, the cutting force is decreased. This is attributed to the softening of the work material from the heat generated during cutting. However, adhesion of the cutting edge is weak in the high-speed range of cutting speed but tool wear of flank face was large.

For the sintered carbide tool, the cutting force is low at the cutting speed of 40 m/min. The cutting force increases once at 70 m/min, and then decreases until 160 m/min. The rate of decrease in the cutting force is similar to that for the cermet tool.

![Fig. 2 Image of diffusion bonding test.](image1)

![Fig. 3 Relationship between cutting force and cutting speed (Feed rate: 0.2 mm/rev, depth of cut: 0.5 mm, cutting distance: 10 m for each cutting speed, dry machining).](image2)

| Table 4 Test conditions for diffusion bonding. |
|-----------------------------------------------|
| Heating rate (K/min)  | 40 |
| Bonding temperature (K) | 1,173 |
| Bonding time (s)        | 1,500 |
| Cooling rate            | Furnace cooling |
| Atmosphere              | Vacuum (< 7 × 10⁻³ Pa) |
| Bonding pressure (MPa)  | 1,500 |
The reason underlying the decrease in cutting force at the cutting speed of 40 m/min is discussed below.

Fig. 4 shows the cutting edge after use with the cutting speed of 40 m/min. Adhesive similar to the built-up edge is confirmed on the cutting edge. However, traces of the built-up edge are found on neither the finished surface nor the cutting chip. The adhered deposit may act similarly to the built-up edge, and the cutting force is decreased as the actual rake angle increases.

Fig. 5 shows the adhesion of the cermet tool. Cermet tools have high adhesion resistance, but in this experiment, adhesion at the cutting edge occurs at the cutting speed of 40 m/min. However, compared to that of the sintered carbide tool shown in Fig 4, the adhesion is weak. This is attributed to the higher cutting force, because the low affinity of the cermet tool is affected and the adhesion indicates that the actual rake angle is unchanged.

The changing of cutting force showed no clear difference in comparing stainless cast steel and stainless forged steel. Although these materials were refined differently by casting and forging, no change in cutting force occurred because the chemical compositions and mechanical properties are equivalent in the two materials. In addition, the tool type had a greater effect on the cutting force than the refinement method.

3.2 Results of Diffusion Bonding

Based on the results in the previous section, a diffusion bonding test was conducted to investigate the diffusion reactions between the sintered carbide tool and the work material.

Fig. 6 shows the results from EPMA (electron probe microanalysis) of the cross-section of the bonded interface and the corresponding SEM (scanning electron microscopy) observations. Measurements were performed for all elements present in the work piece and the tool material, but in Fig. 6 show the representative elements (Fe, Cr, Mo, C, W, and Co) that clearly experience diffusion reactions.

Diffusion phases are observed in Fe and Cr, which are the main components of X2CrNiMoN25-7-3. Although slight inter-diffusion and reaction phases are observed overall, the bond-ability between the X2CrNiMoN25-7-3 and WC is low. The inter-diffusion reaction is more pronounced in the case of the stainless cast steel.

3.3 Results of Tool Wear Test

Fig. 7 shows the results of transition for the tool wear width on the flank face at each measurement point during the tool wear test on stainless cast steel. Fig. 7 also shows the tool wear transition when forged stainless steel for a cutting time up to 200 s for comparison.

The tool wear measurement is the average value of the tool flank wear width (VB), excluding boundary wear on the major cutting edge part. The cutting conditions for this test considered tool wear and adhesion, with the cutting speed of 100 m/min, feed rate of 0.2 mm/rev, and radial depth of cut of 0.5 mm.
Fig. 6  Diffusion bonding observations (casting: stainless cast steel, forging: stainless steel, retention time: 1,500 s. From top to bottom: SEM photo of observation face, Fe, Cr, Mo, C, W, Co profiles).

The flank wear width is low for the cermet tool. Both tool types exceeded the cutting time of 40 s and then entered the stationary wear stage. The cermet tool shows a small wear width on the flank face. However, when cutting is continued under these conditions, the boundary wear of the major cutting edge part is increased at 240 s, and experiences severe damage that ends the tool life at 300 s.

Upon comparing the stainless cast steel and the stainless steel, the flank wear width is smaller for stainless steel under the same type of tool.

This is attributed to the effect of the high adhesive properties of stainless cast steel. The flank wear width is small with the cermet tool, which has a lower compatibility with the material.

Fig. 8 shows the relation between the cutting force and the tool wear measurement time on stainless cast steel. Fig. 8 also shows the results when forged stainless steel for a cutting time up to 200 s for comparison. The cutting force is lower with the cermet tool.

Upon comparing both materials, the stainless cast steel shows an increased cutting force with increased time, but the stainless steel shows a wavy fluctuation. This is attributed to the adhesion and detachment of deposits or the work-hardening of the material surface.

3.4 Tool Damage and Adhesion

Fig. 9 shows the boundary wear and tool damage of
Fig. 8 Relationship between cutting force and cutting time (cutting speed: 100 m/min, feed rate: 0.2 mm/rev, depth of cut: 0.5 mm, dry machining).

Each tool material type after machining the stainless cast steel. For the sintered carbide tool, some deposits adhere immediately after cutting begins. In addition, boundary wear occurs on the major cutting edge at 30 s, and blade tipping occurs at 180 s. From the results of the diffusion bonding test in the previous section, it is unlikely that diffusive wear occurs under the cutting conditions used in this experiment, as inter-diffusion is observed in stainless cast steel but the bond-ability is low. Therefore, the damage of the tool in this experiment is attributed to the separation of the adhered material arising from boundary wear.

On the other hand, boundary wear occurs in the major cutting edge after 30 s with a cermet tool. The boundary wear size is prominent after 120 s.

The adherent material begins accumulating as the flank wear progresses, but the damage on the rake face is small compared to that on the sintered carbide tool. The cermet tool has a lower affinity with the work material, but adhesion increases as tool wear progresses. After machining for 240 s, damage by the separation of the adhesion originating from boundary wear occurs and the tools reach the end of their lifetimes.

Compared to the WC tool, the cermet tool experiences less wear and uses a lower cutting force, but has a similar tool life. For cermet tools, the initial wear is small. However, the toughness of the tool is

Fig. 9 Tool damage and adhesion of flank face of cermet and WC tools (cutting speed: 40 m/min, feed rate: 0.2 mm/rev, depth of cut: 0.5 mm, dry machining).
low. The tool life is lost early by the abrasion of chips on the tool or work-hardening of the work material.

4. Conclusions

In this study, the turning processing of stainless cast steel X2CrNiMoN25-7-3 was performed. Our group confirmed the superiority of the cermet tool and got conclusion leading to improvement of mach-inability of stainless cast steel. From now on it is necessary to examine the cutting conditions in the cermet tool.

And the following conclusions were made:

1. The cermet tool has a lower cutting force;
2. Adhesion occurs on the cermet tool at a lower cutting speed;
3. Inter-diffusion occurs between the sintered carbide and X2CrNiMoN25-7-3, but the bond-ability of the two is low;
4. Adhesion increases as tool wear progresses;
5. Tool damage is strongly affected by the separation of adhered material;
6. The cermet and sintered carbide tools show no differences in tool life.

References

[1] Abe, M., Hiura, A., Ishida, K, and Nishizawa, T. 1984. “Grain Growth in Duplex Stainless Steels.” Tetsu-to-Hagane 70 (15): 2025-32.
[2] Ogawa, K. 2015. “Development and Recent Trend of Duplex Stainless Steel.” The Japan Welding Engineering Society WE-COM magazine 17: 1-11.
[3] Ito, T. 1969. “Machinability of Stainless Steels.” Denki-Seiko Electric Furnace Steel 40 (2): 47-56.
[4] Agrawal, S., Chakrabarti, A. K., and Chattopadhyay, A. B. 1995. “A Study of the Machining of Cast Austenitic Stainless-Steels with Carbide Tools.” Journal of Materials Processing Technology 52: 610-20.
[5] Krolczyk, G. M., Nieslony, P., Maruda, R. W., and Wojciechowski, S. 2017. “Dry Cutting Effect in Turning of a Duplex Stainless Steel as a Key Factor in Clean Production.” Journal of Cleaner Production 142: 3343-54.
[6] Honkawa, M., Sekiya, K., Yamane, Y., and Yamada, K. 2008. “Mirror Cutting of SUS 304 Stainless Steel.” In Proceedings of the 2008 JSPE Spring Conference, 925-6.
[7] Gertha, J., Gustavsson, E., Collin, M., Andersson, G., Nordh, L.-G., Heinrichs, J., and Wiklund, U. 2014. “Adhesion Phenomena in the Secondary Shear Zone in Turning of Austenitic Stainless Steel and Carbon Steel.” Journal of Materials Processing Technology 214: 1467-81.
[8] Wada, M., Kato, H., and Takase, N. 2015. “Study on the Cutting Properties of Super Duplex Stainless Steel.” In Proceedings of the 2015 JSPE Autumn Conference, 417-8.
[9] Narutaki, N., and Yamane, Y. 1980. “Thermal Wear and Cutting Performance of Cermet Tools.” Journal of The Japan Society of Precision Engineering 46 (4): 442-7.
[10] D’Errico, G. E., Bugliosi, S., Cuppiu, D., and Guglielmi, E. 1997. “A Study of Cerments’ Wear Behavior.” Journal of WEAR 203-204: 242-6.
[11] Ikuta, A., Shinozaki, K., Masuda, H., Yamane, Y., Kuroki, H., and Fukaya, Y. 2002. “Consideration of the Adhesion Mechanism of Ti Alloys Using a Cemented Carbide Tool during the Cutting Process.” Journal of Materials Processing Technology 127: 251-5.