Technical Paper:

Polishing Performance of a Recycled Grinding Wheel Using Grinding Wheel Scraps for the Wet Polishing of Stainless-Steel Sheets

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The surfaces of large austenitic stainless-steel sheets, which have side lengths of at least 1 m a sheet thickness of at least 6 mm, used for food tanks and sliding plates in seismic isolation devices, must be finished to a mirror surface. Polishing is performed to improve the surface quality of such sheets and dry machining is typically applied. The problems associated with dry machining are the exhaust heat of machining and treatment of chips. A transition to wet machining is required to solve these problems. In our laboratory, we have developed a wet polishing machine and researched the selection of grinding wheels to develop wet polishing technology for large stainless-steel sheets. In this study, to reduce tool cost and reuse resources, we attempted to manufacture a recycled grinding wheel using snippets of grinding wheel scraps. A polyvinyl alcohol (PVA) aqueous solution was used as the bonding agent for the recycled grinding wheel to reduce environmental load. To overcome the ease of dissolution of PVA in water, we attempted to improve the water resistance of the PVA aqueous solution by incorporating an organic titanium compound. This is one of our efforts to contribute to sustainable development goals. The results are summarized below. (1) A recycled grinding wheel was fabricated by kneading crushed pieces of grinding wheel scrap with a bonding agent. (2) The maintenance of the shape of the recycled grinding wheel was controlled by the concentration of the bonding agent. (3) The recycled grinding wheel with a PVA bonding agent was vulnerable to water. In contrast, the recycled grinding wheel to which the organic titanium compound was added exhibited improved water resistance. (4) The polishing of stainless-steel sheets using the plain PVA recycled wheel was relatively ineffective, but polishing using the recycled wheel with the titanium additive was comparable to polishing with a new grinding wheel.

1. Introduction

Stainless steel is a high-value-added material with excellent design capabilities, corrosion resistance, and functionality [1]. This material is widely used based on its excellent inter-granular corrosion resistance, cold deformability, deep drawability, and weldability. Additionally, stainless-steel surfaces do not need to be coated or painted and can be used in the raw state. For these reasons, stainless steel is processed using various methods according to its target application and is used in many fields ranging from western tableware to nuclear power plants [2, 3]. Polishing stainless steel is an important process that increases its added value. For example, the stainless steel X5CrNi18-10 is a traditional austenitic stainless steel with excellent resistance to atmospheric, organic, and inorganic chemicals. Large austenitic stainless-steel sheets (side length of at least 1 m and plate thickness of at least 6 mm) polished to a mirror surface are used for food tanks and sliding plates in seismic isolation devices.

The surface of a large stainless-steel sheet shipped from a steel mill is not glossy and polishing is essential to reach a practical surface finish. The process of mechanically polishing steel sheets can be roughly divided into two processes. The first process is a "rough grinding process" that removes the work-hardened layer of the steel sheet while improving the flatness of its surface. A grinding wheel or a flap wheel is used and dry processing is performed. The second step is the "finish polishing process," which imparts the desired surface finish. Buffing is performed using a buffing wheel and solid oil-based abrasive [4]. Austenitic stainless steel, which has physical characteristics of low thermal conductivity and a large coefficient of thermal expansion, is prone to excessive wear of abrasive grains, adhesion of chips, and thermal damage to the steel surface caused by the heat of processing. The rough grinding process using grinding wheels has high grinding

efficiency, but the work must be performed while monitoring the exhaust heat of the steel sheet. In contrast, a flap wheel suppresses the generation of grinding heat and is less likely to cause grinding burns on the surface of a steel sheet, but its grinding efficiency is low. Additionally, because the rough grinding process is a dry process, chips are emitted as dust in the factory, which poses the risk of health and environmental damage, as well as dust fires at the worksite and in neighboring areas [5, 6]. For environments where dust is generated, the Industrial Safety and Health Act has been established to protect workers and the working environment. Standards specifying equipment necessary for preventing or reducing the emission of dust are defined. Therefore, the main problems of the rough grinding process are the generation of grinding burns and chip dust. The improvement and suppression of these factors are critical. In real-world applications, the processing of steel sheets must rely on the experience and intuition of skilled workers.

The main approach to solving the problems caused by dry processing is a transition from dry processing to wet processing. The superiority and effectiveness of wet processing of austenitic stainless steel have been widely recognized [7]. However, large initial costs related to capital investment hinder the construction and development of wet processing technology, so wet grinding technology has not been well established. Various researchers have studied the grinding and/or polishing of stainless steel. Previous studies have considered mechanical grinding/polishing processes using micro-cutting abrasive grains [8–16], magnetic polishing processes based on the magnetic object transmission phenomenon [17–25], and electrochemical polishing processes based on corrosion by a solution and electrolyte [26–30]. However, these methods have the problems of limiting the size of steel sheets, narrowing the processing area, and disposing of machining liquid, so they are difficult to put into practical use for polishing large stainless-steel sheets.

We are actively researching the development and implementation of wet grinding and polishing technologies for large stainless-steel sheets. We aim to develop wet polishing technology for the generation of polished surfaces ranging from a No.1 finish to a #400 finish on large stainless-steel sheets. Thus far, we have focused on the trial production and development of wet polishing machines and grinding wheels that use only tap water as a grinding fluid. A No.1 finish is the finish achieved by annealing acid pickling sheets after hot rolling [31]. We have developed a wet polishing machine and selected grinding wheels that are suitable for the wet polishing of sheets. Evaluation experiments revealed that the polishing performance of silicon carbide abrasive grains is superior to that of alumina abrasive grains. When a polyvinyl alcohol (PVA) grinding wheel (SPW) classified as a sponge grinding wheel was used, the wear amount on the wheel and arithmetic mean roughness of the polished surface were 0.22 mm and $Ra = 0.3$ μm, respectively. The surface roughness value reached a suitable level before the final polishing (buffing) in the subsequent process was

performed. Polishing steel using silicon carbide abrasive grains is uncommon, but Goto [32] reported that the surface roughness of silicon carbide abrasive grains is acceptable.

In a previous report [31], the issues of steel plate size, polishing area, and drainage treatment were addressed, but the reduction of tool cost emerged as an important issue. In this study, to reduce tool cost and reuse resources, we fabricated a recycled grinding wheel (RGW) using pieces of grinding wheel scrap cutouts and analyzed the polishing performance of the manufactured grinding wheel. An aqueous solution of PVA was used as a bonding agent for the recycled grinding wheel to reduce environmental load, but the ease of dissolving PVA in water was a critical obstacle to performing the wet polishing of sheets. Therefore, we attempted to improve the water resistance of the PVA aqueous solution by adding a cross-linking agent in the form of an organic titanium compound.

2. RGW Components and its Manufacturing Methods

2.1. Abrasive Grains

SPWs are cut from 500 mm square flat plates into circles with a diameter of 65 mm using a hole saw. The remaining pieces after cutting out the SPWs have polishing performance, but cannot be used directly based on their irregular shapes. The amount of scrap amounts to 20% of the total grinding wheel material. Generally, scraps are treated as industrial waste and a collection cost for waste treatment is incurred, so the cost of tools is high. Scraps are typically reused as abrasives for barrel polishing and shot blasting, and as raw materials for refractory bricks in blast furnaces at steel plants with the goal of achieving zero emissions [33, 34]. However, there have been few reports on resource recycling in which scraps are reused to make additional grinding wheels.

The tool specifications of the SPWs used for the wet polishing of sheets are summarized below. The type of abrasive grain is silicon carbide and the particle size is #1000. The type of bonding agent is an acetal compound of PVA. This bonding agent provides much better water resistance, strength, and adhesion than a pure PVA bond [35]. Detailed information regarding the grade and structure of the SPWs considered in this study is unavailable because it has not been published.

RGW abrasive grains were obtained by crushing pieces of SPW and SPW scrap material. The crushing procedure is described below. First, a piece of SPW is crushed to a size of approximately 2 cm^2 using a chisel and hammer. Next, approximately 20 g of small pieces (pulverized material) are placed in a crusher and crushed for 1 min. Finally, lumpy pulverized material that cannot be powdered is removed. The remaining pulverized material is used as the abrasive grains for an RGW. By measuring the size of the pulverized material using

a laser-diffraction/scattering-type particle size measurement device, we determined that the median diameter was 16.4 μm. According to the JIS standard, the median diameters for #1000 grains according to the sedimentation tube testing method and electrical resistance testing method are 15.5$\pm$1.0 μm and 11.5$\pm$1.0 μm, respectively [36]. Although there is a difference in diameter with different testing method, if the approximate median diameter in the tests was 12–16 μm, then the measured diameter is slightly greater than the standard. The pulverized material is obtained purely through mechanical crushing and is not chemically treated to dissolve the original bonding agent. The pulverized product is covered with a bonding agent of PVA and the measured value is the value of the total diameter of the abrasive grain and bonding agent.

2.2. Bonding

A commercially available PVA aqueous solution was used as a bonding agent. PVA is a water-soluble synthetic resin obtained by hydrolyzing polyvinyl acetate, which is a polymer of vinyl acetate [37]. PVA is mainly used in aqueous solutions. Its solubility in water depends on its degree of hydrolysis, degree of polymerization, and degree of heat treatment received during the manufacturing process. PVA has a hydrophilic hydroxyl group (OH) and hydrophobic acetic acid group (CH_3COO) as a result of hydrolysis [38]. These hydroxyl groups induce strong inter- and intra-molecular hydrogen bonding. However, the residual acetate groups in partially hydrolyzed PVA are essentially hydrophobic. As the number of acetate groups increases, steric hindrance increases, disturbs the arrangement of intermolecular chains, and inhibits the formation of hydrogen bonds between molecular chains. Additionally, PVA is a typical biodegradable plastic that has been confirmed to be decomposed by microorganisms [39, 40]. Furthermore, its effect on the human body is very small [37]. Based on this property, it is commonly used in liquid glue, laundry starch, disposable contact base material, vinylon fiber raw material, etc. [41, 42]. Compared to other synthetic polymer bonding agents [42–44], PVA has less impact on the environment and human body and is easier to handle, so it was selected as a bonding agent for our RGWs.

The main component of the PVA aqueous solution used in our experiments was PVA and a very small amount of preservative was added. Formalin was not used. According to the material specifications, the specific gravity and concentration of the stock solution were 1.2 and 9$\pm$1%, respectively. Purified water was used to prepare the PVA aqueous solution and the concentration of the PVA aqueous solution was controlled using a dedicated densitometer. The PVA aqueous solution was stirred in a beaker for 10 min at a stirring rotation speed of 250 rpm using a stirrer. The water temperature was 293 K at this time. The beaker was then placed in a mantle heater and warmed until the PVA aqueous solution reached a water temperature of 363 K. The stirring time was 30 min. Finally, the power of the mantle heater was turned off and the PVA aqueous

Table 1. Properties of the organic titanium compound.

Chemical name	Titanium lactate (aqueous)
Formula	Ti(OH)$_2$[OCH(CH$_3$)COOH]$_2$
Content	44 wt%
Ti content	8.2 wt%
Specific gravity	1.2 (298 K)
Solvent	Water, 2-propanol

solution was slowly cooled with continuous stirring until the water temperature reached 293 K. In this manner, three PVA aqueous solutions with concentrations of 9.0%, 6.8%, and 4.5% were prepared.

2.3. Cross-Linking Agent

PVA contains many hydroxyl groups and reacts with various substances, so it is highly applicable. The most effective means of water resistance treatment for PVA is the formulation of a cross-linking agent. Compounds such as aldehyde compounds, amine compounds, hydrazine compounds, and metal compounds, are known as cross-linking agents for PVA-based resins [45]. The acetalization treatment for PVA water resistance is a treatment that uses an acid catalyst to cause a chemical reaction with formalin and other aldehydes to make PVA water resistant. This process is used in the manufacture of SPWs. To suppress the properties of OH groups, PVA is acetalized to reduce water immersion and increase water resistance. The problem with this process is the generation of toxic gas during the chemical reactions, which necessitates exhaust equipment, making it more difficult to fabricate SPWs.

As a premise of this research, it was assumed that RGWs can be easily manufactured at a polishing factory. Therefore, no additional equipment is considered for RGW production and materials that do not affect the surrounding environment must be selected, so options for RGW cross-linking agents are limited. In this study, we adopted a Ti-O-C bonded organic titanium compound. The general properties of this compound are presented in **Table 1**. This compound functions as a cross-linking agent for resins with functional groups such as hydroxyl groups, carboxyl groups, and epoxy groups. The chemical name is titanium lactate and it is used as a water-resistant agent for PVA resins [46]. It is a pale yellow liquid that dissolves in water. Its specific density is 1.2. This liquid is considered as a non-dangerous good under the Fire Service Act. Additionally, it is non-toxic. This liquid was added following the preparation of the PVA aqueous solution. The amount added was 20 wt%.

2.4. Manufacturing Method of RGWs

RGWs were prepared by altering the concentration of the PVA aqueous solution, compounding ratio of abrasive grains and bonding agent, and presence or absence of the

Table 2. Manufacturing conditions.

PVA concentration [wt%]	4.5	6.8	9.0
Weight ratio of abrasive grain to bond	1:1	3:2	1:3
Organic titanate compounds [wt%]	0	20	-

Table 3. Labelling for each manufactured condition of RGW.

Symbol	Sample code	PVA concentration [%]	Weight ratio	Abrasive grain volume percentage [%]	Organic titanate compounds
PVA-RGW	PVA-A	9.0	3:2	36	w/o (0 wt%)
	PVA-B	6.8			
	PVA-C	4.5			
	PVA-D	9.0	1:1	27	
	PVA-E	6.8			
	PVA-F	4.5			
	PVA-G	9.0	1:3	11	
	PVA-H	6.8			
	PVA-I	4.5			
Ti-RGW	Ti-A	9.0	3:2	36	w (20 wt%)
	Ti-B	6.8			
	Ti-C	4.5			
	Ti-D	9.0	1:1	27	
	Ti-E	6.8			
	Ti-F	4.5			
	Ti-G	9.0	1:3	11	
	Ti-H	6.8			
	Ti-I	4.5			

organic titanium compound. **Tables 2** and **3** list the manufacturing conditions and names of the grinding wheels, respectively. The compositions of abrasive grains and bonding agent are 1 : 1, 3 : 2, and 1 : 3 by weight. The abrasive grain volume percentages in these formulations are 27% at 1 : 1, 36% at 3 : 2, and 11% at 1 : 3. The RGWs without the addition of the organic titanium compound are denoted as PVA-RGW and the RGWs with the addition of the organic titanium compound are denoted as Ti-RGW. The names of the grinding wheels are subdivided into alphabetical characters from "A" to "I" under each header of PVA-RGW or Ti-RGW. As shown in **Table 3**, 18 types of grinding wheels were prepared.

PVA-RGWs were manufactured by kneading a pulverized material of SPWs and aqueous solution of PVA. First, masking tape was attached to the bottom of a PVC pipe and the kneaded product was placed in a mold. Pressure was applied at approximately 10 N for several seconds. The head of the pipe was then sealed with masking tape. Next, the mold was dried by a constant-temperature dryer. The drying conditions were set as follows. After drying at a furnace temperature of 323 K for 24 h, the PVC pipe was turned over and dried again at 323 K for 24 h. After the drying process was completed, the kneaded product was removed from the PVC pipe. The production of Ti-RGW is the same as that of PVA-RGW. The bonding agent was a mixed liquid containing the PVA aqueous solution and organic titanium compound. The abrasive grains were kneaded after the mixed liquid was prepared. The end faces of each RGW after drying were trued using a diamond dresser. When the abrasive grain volume percentage exceeded 50%, the abrasive grains could not be bonded by the bonding agent and could not be molded.
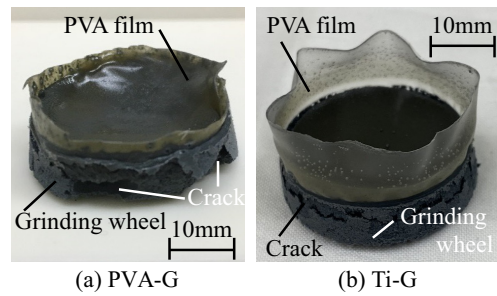

(a) PVA-G   (b) Ti-G

Fig. 1. Appearance of RGW made with an abrasive grain volume percentage of 11%.

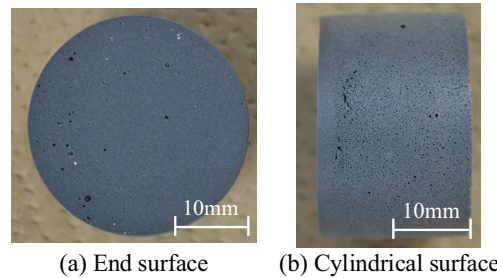(a) End surface   (b) Cylindrical surface

Fig. 2. Appearance of examined RGW as a possible candidate for grinding wheels (Ti-D).

3. Characteristic Survey of an RGW

3.1. Shape Observation of an RGW

The RGW used for a characteristic survey was made in a PVC pipe mold with an inner diameter of 31 mm and height of 25 mm.

Figures 1(a) and **(b)** present the appearance of PVA-G and Ti-G, respectively. In the case of the RGW with an abrasive grain volume percentage of 11%, a flexible film is formed on the surface of the grinding wheel, as shown in **Fig. 1**. This film is a dried PVA substance. The film formation is significant at an abrasive grain volume percentage of 11%. Compared to the other abrasive grain volume percentages, the amount of water contained in the kneaded product with an abrasive grain volume percentage of 11% is greater. It is hypothesized that the high-density abrasive grains sank to the bottom of the pipe during the drying process to form a sedimentary layer and that the bonding agent covered this sedimentary layer. The grinding wheel manufactured with this abrasive grain volume percentage was brittle and contained large cracks after the drying process, so it was judged that it would be difficult to use this grinding wheel. In contrast, as shown in **Fig. 2**, the grinding wheels manufactured under other conditions maintain a cylindrical shape and can be used as grinding wheels, so they were selected as a study target.

Figure 3 presents scanning electron microscopy photographs of an RGW and SPW. The RGW has an abrasive grain volume percentage of 27%. These grinding wheels consist of abrasive grains, bonding agents, and pores. The abrasive grains are gripped by the bonding agents. The
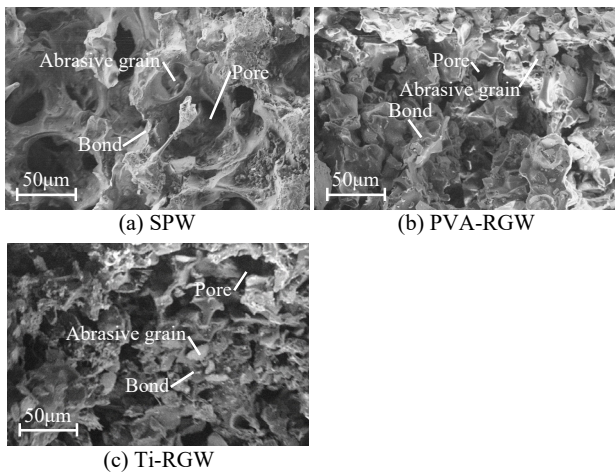
(a) SPW (b) PVA-RGW

(c) Ti-RGW

Fig. 3. Scanning electron microscopy photographs of SPW, PVA-RGW, and Ti-RGW.

(a) PVA-RGW

(b) Ti-RGW

Fig. 5. Durometer hardness values of grinding wheels.

$$\text{Shrinkage rate} = \frac{(\text{Volume of grinding wheel before drying}) - (\text{Volume of grinding wheel after drying})}{(\text{Volume of grinding wheel before drying}) \times 100} . \quad (1)$$

The PVA concentration does not affect the shrinkage of RGWs. For the PVA-RGWs, when compared in terms of the abrasive grain volume percentage, the PVA-RGW with an abrasive grain volume percentage of 27% exhibits the greatest shrinkage of at least 10%. The shrinkage rates of the PVA-RGW with an abrasive grain volume percentage of 36% and Ti-RGW with an abrasive grain volume percentage of 27% are approximately the same. The shrinkage rate of the Ti-RGW with an abrasive grain volume percentage of 36% is the smallest. Overall, the volume shrinkage tends to decrease as the water content of the kneaded product decreases.

3.3. Hardness of RGWs

For the hardness measurements of the RGWs, when an indentation-type measurement instrument was used, the indentations disappeared at the time of measurement. For this reason, the hardness of the RGWs was evaluated using a durometer. The push needle of the durometer protrudes downward from the pressurized surface of the instrument. When the push needle and pressure surface are pressed against the test piece, the push needle bites into the test piece under the force of a spring and deforms. On the pressurized surface, an upward force acts based on the elastic force of the test piece. When the force of the spring and force of the test piece are balanced, the push needle stops. When the tip of the push needle is on the same plane as the test piece, the hardness is 100. The greater the pushing force, the greater the hardness value, which indicates that the test piece is hard.

Figure 5 presents the durometer hardness (scale A) of the RGWs. The shape of the indenter forms a truncated

(a) PVA-RGW

(b) Ti-RGW

Fig. 4. Shrinkage ratios of grinding wheels.

distribution of abrasive grains in the RGW is denser than that in the SPW. The RGW contains pores like the SPW, but the pore size of the SPW was greater than that of the RGW. The pores of the SPW are generated by a pore-forming agent, but the pores of the RGW are generated when the PVA is agitated.

3.2. Shrinkage Ratio of RGWs

For all grinding wheels, the shrinkage in the radial direction was smaller than that in the height direction. The shrinkage ratio in the height direction was at least 55% and was the greatest in the grinding wheel with an abrasive grain volume percentage of 11%.

Figure 4 presents the shrinkage ratios of grinding wheels with abrasive grain volume percentages of 27% and 36%. The shrinkage ratios were calculated using Eq. (1).
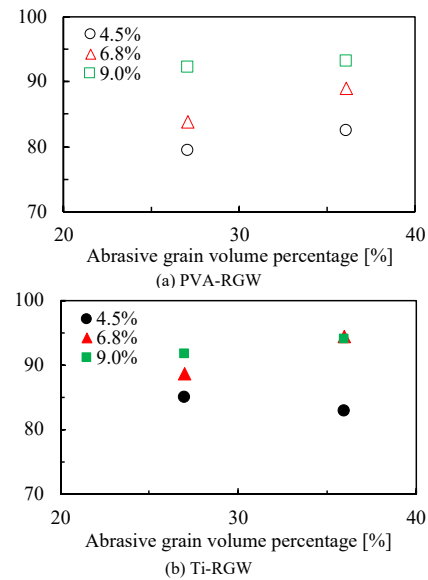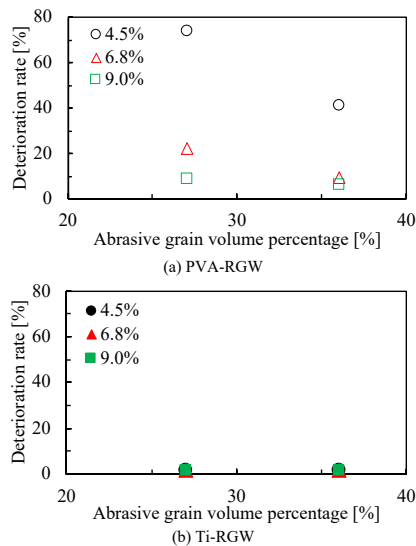
Fig. 6. Deterioration rates of grinding wheels.

Fig. 7. Schematic illustration of experimental device.

cone with a tip diameter of 0.79 mm and conical angle of 35°. The hardness of the RGWs ranges from approximately A80 to A95. The higher the PVA concentration, the higher the hardness. The hardness of the RGWs with the organic titanium alloy is slightly higher than that of the RGWs without this addition. The hardness values of PVA-A and Ti-A (abrasive grain ratio of 36%, PVA concentration of 9%), and Ti-B (abrasive grain ratio of 36%, PVA concentration of 6.8%) are the same as the hardness of the SPWs at A95. The hardness of Ti-B increases based on cross-linking reactions caused by the addition of titanium dioxide compounds. If the measured value is interpreted as a grade, then the magnitude of the force holding the abrasive grain is controlled by the magnitude of the PVA concentration.

3.4. Water-Resistant of RGWs

The RGWs were submerged in water and their water resistance was analyzed. Specifically, they were submerged in a water tank containing 1000 mL of tap water for 150 s. A plate weighing 100 g was placed on the upper surface of each RGW to prevent the RGW from floating. The water temperature was 288 K. The RGWs were removed from the water tank after 150 s and dried naturally until their weight stabilized. The water resistance was calculated using Eq. (2). The value yielded by this equation is called the deterioration rate.

$$\text{Deterioration rate} = \frac{\text{Lost weight}}{(\text{RGW weight before testing})} \times 100$$

$$. \quad (2)$$

The amount of lost weight in the formula is the difference between the RGW weight before immersion in water and RGW weight after removal from the water tank and drying. The smaller the deterioration rate, the higher the water resistance.

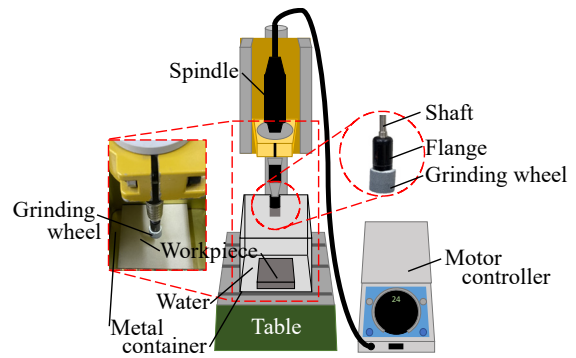**Figure 6** presents the deterioration rates of RGWs.

The rates of the PVA-RGWs are greater than those of the Ti-RGWs. In the PVA-RGWs, the deterioration rate decreases as the abrasive grain volume percentage increases. Additionally, the higher the PVA concentration, the smaller the deterioration rate. In contrast, there is no variation in the deterioration rates of the Ti-RGWs and the values are very small.

Based on the results discussed above, it can be concluded that in Ti-RGWs, the functional groups of PVA are connected by the organic titanium compound, the resin is polymerized, and the water resistance is improved.

4. Polishing Performance of RGWs

4.1. Experimental Method

Figure 7 presents a schematic illustration of the experimental device used in this study. The dimensions of the RGWs used in the polishing experiments were changed to a cylinder with a diameter of 13 mm and thickness of 15 mm based on the restrictions of the machine tool. The end faces of the RGWs were attached to the flange shaft using an adhesive and the shaft was gripped by a collet chuck inside the spindle. The spindle was fixed to the stand of the tabletop machine. The spindle revolution was controlled by the motor controller. The x-axis and y-axis did not move and a constant load was applied only in the z-axis direction. The workpieces were No.1 finished austenitic stainless-steel sheets (X5CrNi18-10) with a side length of 100 mm and thickness of 10 mm. The sheets were fixed by a jig in a water tank installed on the table. The amount of water in the water tank was just enough to cover the steel plate. The polishing conditions were a cutting speed of 245 m/min (spindle speed of 6000 rpm) and average load of 20.9 N on the z-axis. The processing time was 1 min. The abrasion loss of the RGWs and surface roughness values of the sheets were used as evaluation metrics for the RGWs. The surface roughness of the steel sheets was measured using a stylus-type surface roughness measurement instrument.

Figure 8 presents the appearance of the stainless-steel sheets before polishing. The arithmetic mean roughness of the sheets before polishing was $Ra = 4.8$ μm.
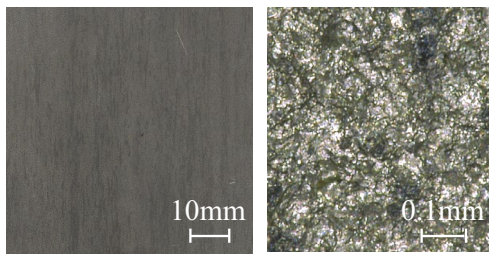
Fig. 8. Surface conditions of stainless-steel sheets before processing.

4.2. Abrasion Loss

Figure 9 presents the states of tool wear before and after polishing. The abrasion loss of the RGWs varies, but the state of wear is very even. **Fig. 10** presents the abrasion loss of the RGWs. The abrasion loss is the difference between the height of an RGW before polishing and the height of that RGW after polishing. The loss of the Ti-RGWs is less than that of the PVA-RGWs. The abrasion loss of the Ti-RGWs is approximately the same as that of the SPWs at 0.6–0.7 mm. The loss of the RGW with a PVA concentration of 4.5% and an abrasive grain ratio of 36% (PVA-C, Ti-C) is the greatest. When comparing these results to those in **Fig. 5**, one can see that when the hardness of an RGW was soft, its loss increases. This is likely because the holding power of the abrasive grains of PVA-C and Ti-C is low. Additionally, compared to the results in **Fig. 4**, the abrasion loss is increased under the action of the external force.

## 4.3. Surface Conditions and Surface Roughness

Figure 11 presents the surface conditions of the sheets. The surface conditions of the sheets were observed using a digital microscope. The sheets were successfully polished by some of the RGWs. Scratch marks were found on the surfaces polished by the PVA-RGWs. The scratch marks were uniform, but did not reach the base metal. On the surfaces polished by the Ti-RGWs, scratch marks and the base metal were observed at PVA concentrations of 6.8% and 9.0%. It is hypothesized that the mirror surface became wider as a result of extended processing time. However, at an abrasive grain ratio of 36% and PVA concentration of 4.5% (Ti-C), the surface resembled those polished by the PVA-RGWs, meaning little polishing was done.

Based on **Figs. 9** and **11**, we can conclude that the PVA-RGWs have low resistance to water, so the holding power of the abrasive grain by the bonding agent is reduced and processing progresses with frequent shedding. Additionally, the Ti-RGW with an abrasive grain ratio of 36% and PVA concentration of 4.5% (Ti-C) had the same effectiveness as the PVA-RGWs. In the other Ti-RGWs, the abrasion loss of the grinding wheel was small, so it can be concluded that an appropriate holding force was achieved.
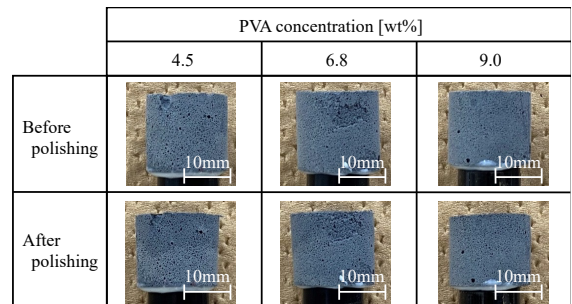
Figure 12 presents the surface roughness values of
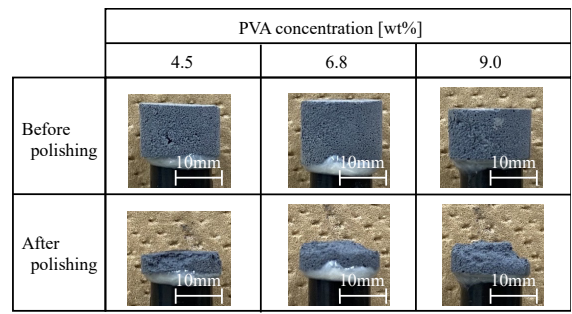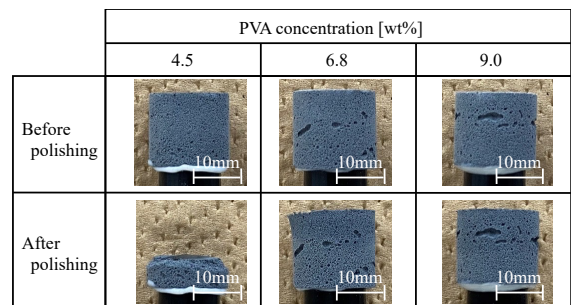

(a) Abrasive grain volume percentage of 27% for PVA-RGW
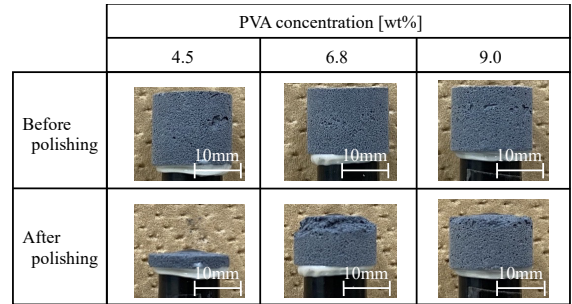
(b) Abrasive grain volume percentage of 36% for PVA-RGW

(c) Abrasive grain volume percentage of 27% for Ti-RGW

(d) Abrasive grain volume percentage of 36% for Ti-RGW

Fig. 9. Appearance of tool shape before and after processing.

the sheets. The surface roughness values achieved by the Ti-RGWs are smaller than those achieved by the PVA-RGWs. Additionally, approximately constant values were obtained, regardless of changes in the abrasive grain volume percentage and PVA concentration. The Ti-RGWs produced almost the same surface roughness values as the SPWs.

4.4. Grinding Performance of RGWs

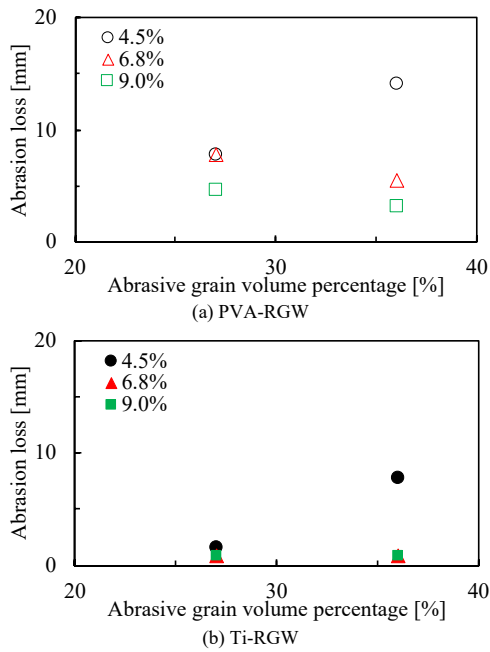The grinding ratio is an index of the wear resistance of a grinding wheel. This value is obtained by dividing
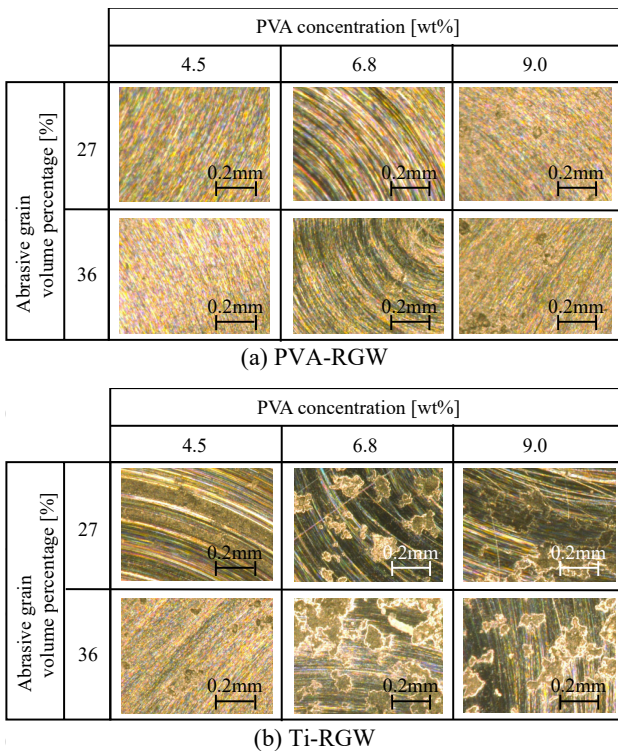
Fig. 10. Abrasion loss of grinding wheels.

(a) PVA-RGW

(b) Ti-RGW

Fig. 11. Surface conditions of steel sheets after processing.

(a) Arithmetic average height for PVA-RGWs

(b) Largest peak-to-valley height for PVA-RGWs

(c) Arithmetic average height for Ti-RGWs

(d) Largest peak-to-valley height for Ti-RGWs

Fig. 12. Surface roughness values of steel sheets after processing.

the removed volume of the work material by the worn
volume of the grinding wheel consumed during grinding.
However, the removed volumes in our experiments were
very small and it was difficult to measure the polishing
volumes. Therefore, it was assumed that the wear in the
radial direction was significantly smaller than that in the
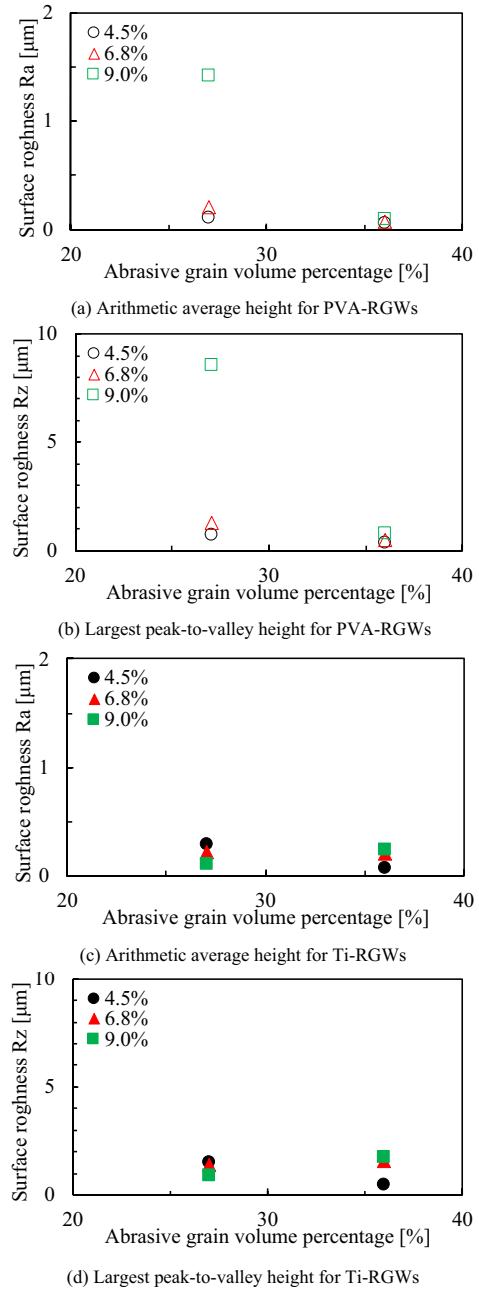height direction, so the improvement rate of the surface

roughness per amount of wear in the height direction of
the grinding wheels was evaluated. This value was de-
fined as the loss ratio.

Figure 13 presents the loss ratios of the RGWs.
The improvement rates of the Ti-RGWs at 6.8% and
9.0% PVA concentrations are significant relative to the
PVA-RGWs. The addition of the organic titanium alloy
contributes to the improvement of the water resistance of
the PVA bonding agent. For the Ti-RGWs with PVA con-
centrations of 6.8% and 9.0%, it was determined that self-
sharpening occurred, loading did not occur, and good pol-
ishing performance could be maintained.

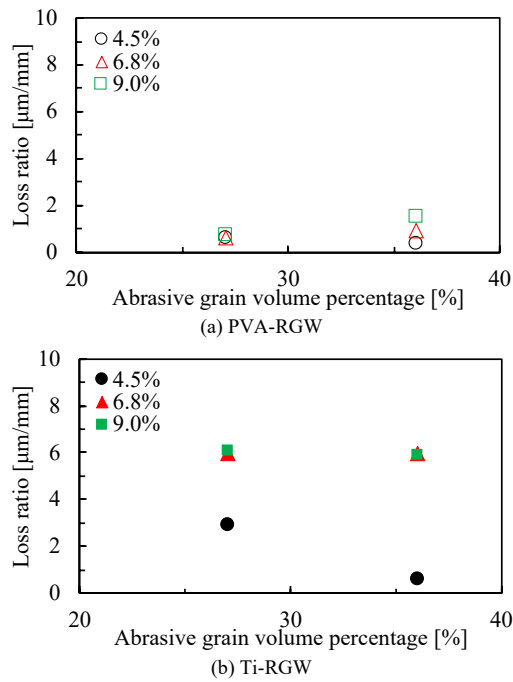Detailed processing cost calculations when using

Fig. 13. Loss ratios of steel sheets after processing using RGWs.

RGWs are underway. The polishing performance of the RGWs was almost the same as that of the SPWs. We believe that the RGWs recover a cost that is at least equivalent to that of the SPW scrap.

5. Conclusions

In this report, to reduce tool costs and reuse resources, we fabricated RGWs using scrap from SPWs and analyzed their polishing performance. An aqueous solution of PVA was used as a bonding agent for the grinding wheels, but the ease of dissolving PVA in water is a major obstacle to the wet polishing of stainless steels. Therefore, we attempted to improve the water resistance of the PVA aqueous solution by adding a cross-linking agent in the form of an organic titanium compound. The results are summarized below.

(1) The RGWs were fabricated by kneading crushed pieces of SPW scrap with a bonding agent.

(2) The maintenance of the shape of the RGWs was controlled by the concentration of the bonding agent.

(3) The RGWs with the plain PVA bonding agent were vulnerable to water. However, the RGWs in which the organic titanium compound was added to the PVA aqueous solution exhibited improved water resistance.

(4) The polishing performance of the stainless-steel sheets by the PVA-RGWs was relatively poor, but the performance of the Ti-RGWs was comparable to that of the SPWs.

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