Heat Resistivity of Stainless Steel Fiber Produced by Coiled Sheet Shaving

KANEKO Masao^{*}, LEE Junjae, IMAMURA Masato, and
YANAGISAWA Akira

*Faculty of Engineering, Nippon Institute of Technology,
4-1 Gakuendai, Miyashiro-machi,
Minami Saitama-gun, Saitama 345-8501, Japan*

Based on Journal of the Textile Machinery Society of Japan, Vol.53, No.6, T147-T153(2000-6)

Abstract

In order to improve the efficiency of automobiles, energy equipment, and various combustion equipment, it is necessary to raise their operating temperatures. Heat resistance to high temperature is thus strongly required in the filters that are used for these machines. In answer to such demands, the 20Cr-5Al stainless steel was developed for the metal honeycomb of automobiles. Use of fibers produced from 20Cr-5Al stainless steel at low costs by coiled sheet shaving methods for high temperature filters is expected. In this study, the heat resistance of the 20Cr-5Al stainless steel fiber was compared with that of normal stainless steel fibers. The results show that while normal stainless steel fiber becomes powdery when maintained at 1173K, 21.6ks, the 20Cr-5Al stainless steel fiber retains flexible features even at 1373K, 360 ks.

Keywords: Metal fiber, Shaved fibers, Stainless steel, Heat resistivity, Filter

1. Introduction

In the recent years, the operating temperatures of automobiles, energy equipment, and various combustion equipment are being raised to improve their efficiency, resulting in growing demands for heat resistance to high temperature of the filters used for automobiles and equipments. Fiber materials are mainly used in the manufacture of filters, and consequently demands for heat resistance to high temperature are growing for these fiber materials. One typical example of fibers with heat resistance to high temperature is the ceramics fiber. Many problems are however encountered in the use of ceramic fiber because it is brittle and hard-to-machine. Compared to ceramic fibers, metal fibers offer many advantages such as good bending, sintering, and welding properties, but one of its drawbacks is poor heat resistance to high temperature.

Recently, 20Cr-5Al stainless steel was developed as a metal material with excellent heat resistance to high temperature. Currently, there are two general ways of producing fibers from metal; one is the bundle-drawing method^[1] and the other is the wire cut method^[2]. When fibers are obtained from this material using the former method, the material yield in post-processes is poor owing to the low chemical resistance of the material. This results in high costs of the metal fiber, and consequently the purpose of use the material is restricted. In the case of the wire cut method, high quality fibers which are

suitable for the above mentioned applications are difficult to manufacture. However with the hot water soluble resin coated coil shaving method^[3,4], fibers can be produced at low costs from thin sheets about 50 μ m thick mass-produced for metal honeycomb. Though heat resistance for a sheet of 20Cr-5Al stainless steel sheet has been investigated in several studies^[5,6,7], heat resistance has not been confirmed for 20Cr-5Al stainless steel fibers with considerably different specific surface areas. In this study, we obtained fibers from six types of stainless steel: normal SUS304, SUS316L, and SUS430, and three types of 20Cr-5Al stainless steel containing different types of rare earth elements, and investigated the tensile strength of the fibers after heat resistance tests to compare their heat resistances.

2. Experimental Conditions

Figure 1 shows how the metal fiber is produced by the coiled sheet shaving method. With this method, thin metal of about 0.01 mm to 0.15 mm thick is coiled around the spindle of a shaving machine. As the sample material, we used three types of 20Cr-5Al stainless steel materials containing different types of rare earth elements in small amounts. The three types were type A containing La (0.08%), type B containing Y (0.1%), and type C containing Ce (0.081%). For comparison purpose, we also used the normal stainless steel SUS304, SUS316L, and SUS430. The sheet thickness (t) of A, B, and C was

^{*} Corresponding author Fax:0480-33-7645,E-mail:mkaneko@nit.ac.jp

Fig.1 Schematic illustration of coiled sheet shaving method

Table 1 Experimental conditions

Cutting tool	Sintered carbide tool (P20)
Cutting conditions	Rake angle γ : $20 \sim 38^\circ$ Back clearance angle α : 10° Approach angle ϕ : 2° Cutting speed v : 80m/min Feed rate S : $20 \mu\text{ m/rev}$ Width of cut W : 20mm Water soluble coolant (Castrol SUPERDGE B7)
Heat treatment	Temperature T_t : 298, 473, 673, 873, 1073, 1173, 1273, 1373K Holding time H_t : 3.6, 10.8, 21.6, 36, 180, 360ks
Work material (Stainless steel)	SUS304, SUS316L, SUS430 20Cr-5Al A (La), B (Y), C (Ce)
Sheet thickness	$t=0.05, 0.135, 0.15\text{ mm}$

set at 0.05 mm, 0.135 mm, and 0.15 mm, respectively. Fibers were produced from these samples under the conditions shown in Table 1.

Figure 2 shows the external view and cross section of fibers produced by cutting the edges of sheet metal using the coiled sheet shaving method. The length of the rectangular cross section is equivalent to the sheet thickness of the coil, while the width is equal to the thickness of the fiber, which depends on the feed rate of the tool. Both sides of this fiber cross section were rolled surfaces, where the lower surface is the cut surface and the upper surface is the freely generated surface during cutting. As metal fibers have non-circular cross section, the area of this rectangular cross section was normally converted to the cross section of a circle and the diameter of the circle was taken as the equivalent diameter of the fiber (d). When the feed rate of the tool was set at $20 \mu\text{ m/rev}$, the equivalent diameter of the fiber obtained from the respective sheet thickness was $d=35 \mu\text{ m}$ at a sheet thickness t of 0.05 mm, $85 \mu\text{ m}$ at a sheet thickness of $t=0.135\text{ mm}$, and $90 \mu\text{ m}$ at a sheet thickness of $t=0.15\text{ mm}$. In the experiments, metal fibers of these equivalent diameters were used to evaluate the dependence of heat resistance on fiber diameter. The rake angle of the tool

SUS304, $t=0.1\text{ mm}$, $V=80\text{ m/min}$, $S=20 \mu\text{ m/rev}$, $\gamma=32^\circ$

Fig.2 Enlarged surface and cross section of fiber produced by coiled sheet shaving

was set at 32 degrees at a sheet thickness of $t=0.05\text{ mm}$, and 30 degrees at sheet thicknesses $t=0.135$ and 0.15 mm . This is the rake angle at which fibers obtained were most round and had excellent and flexible properties at the tool feed rate of $20 \mu\text{ m/rev}$.

The fibers obtained were processed using an electrical furnace in the atmospheric environment at the following temperatures; room temperature, 473K, 673K, 873K, 1073K, 1173K, 1273K, 1373K, and the holding time was varied from 3.6ks, 10.8 ks, 21.6 ks, 36 ks, 180 ks to 360 ks. After cooling in the furnace, the tensile strength of the fibers were measured using the TCM-200 tension tester of Shinko Tsushin at the tensile speed of 5 mm/min. To investigate the breaking strength when used in high temperature environment, the heat resistance of the fibers was evaluated by a tensile test. Furthermore, after the heat resistance test, the fiber surface was observed by SEM, and the oxidized state of the fiber surface was checked by X-ray diffractometer.

3. Experimental Results and Discussion

3.1 Heat Resistance of Normal Stainless Steel Fibers

First, experiments were carried out on the heat resistance of normal stainless steel fibers obtained using the coiled sheet shaving method. The experiments were carried out at the above processing temperatures and held for 3.6 ks, 10.8 ks, and 21.6 ks. The fibers were then cooled in the furnace to the atmospheric temperature, and measured the fiber tensile strength. Figures 3, 4, and 5

Fig.3 Relation between tensile strength and temperature at different equivalent diameters and holding times (SUS304)

Fig.4 Relation between tensile strength and temperature at different equivalent diameters and holding times (SUS316L)

Fig.5 Relation between tensile strength and temperature at different equivalent diameters and holding times (SUS430)

show the measurement results of processing temperature vs. tensile strength. The tensile strength was found to decrease suddenly at processing temperatures higher than 873K for the SUS304, SUS316L, and SUS430 stainless steels, and SUS304 and SUS430 became completely powdery at 1173K, and SUS316L at 1273K. For these normal stainless steel fibers, tensile strength was found to decrease because they become brittle at high temperature, owing to the formation of large crystal particles, oxidation of the external layer, or peeling off of the oxidized film [8]. Furthermore, oxidation was found to spread to the center of the fiber, and result in the powdery state shown in Figs. 6(a) and (b). No significant difference was seen in the relation between tensile strength and temperature between the three stainless steels at different holding times. At holding times above 3.6 ks in this experiment, the same drop in tensile strength was seen at each processing temperature. Furthermore, in low temperature ranges below 873K, the smaller the equivalent diameter, in other words, the smaller the sheet thickness, the greater the tensile strength. In areas with little effect of the oxidization, a small sheet thickness caused a large draft in the rolling process during the manufacture of sheet metal. The difference in the work hardening of the material itself was believed to manifest as the difference in fiber strength.

3.2 Heat Resistance of 20Cr-5Al Stainless Steel Fiber

Next, an experiment was carried out on the heat resistance of the type A 20Cr-5Al stainless steel sample containing the La under the same conditions as the normal stainless steels. Figure 7 shows the experiment results. Like the normal stainless steels, the fiber strength was found to decrease with a rise in the processing temperature. At 1373K and a holding time of 21.6ks, the fiber strength was about 350 MPa, and no breakage of the fiber was seen as shown in Fig. 6 (c). The tensile strength

(a),(b): Temperature 1173K, Holding time 3.6ks
(c): Temperature 1373K, Holding time 21.6ks

Fig.6 Appearance of fiber after heat durability test

Fig.7 Relation between tensile strength and temperature

Fig.9 Relation between tensile strength and holding time for different rare earth elements

Fig.8 Relation between tensile strength and holding time for different rare earth elements

test showed a 5 to 10% elongation and confirmed that the type A stainless steel can be stretched and repeatedly bent by about several times. At the temperatures below 1173K, when the equivalent diameter is small, the fiber strength is large and depends on the machining hardness obtained by rolling. However when the temperature was above 1173K, no difference due to the equivalent diameter was found.

Next, the heat resistances of the type A (La), type B (Y), and type C (Ce) stainless steels were compared. Figures 8 and 9 show the changes in the tensile strength when the holding time was varied up to 360 ks at a fixed processing temperature of 1373K. When the equivalent diameter was small ($35\ \mu\text{m}$), the type A stainless steel containing La showed the greatest heat resistance. At the holding time of 360 ks, the tensile strength was 150 MPa. The type B stainless steel containing Y showed a tensile strength of 120 MPa, but the type C stainless steel containing Ce showed a sudden decrease in the fiber tensile strength at the holding time of 180 ks to 50 MPa. It was very brittle at the holding time of 360 ks, confirming that the fiber strength and shape required

Temperature 1373K, Holding time 360ks, $d=35\ \mu\text{m}$

Fig.10 Appearance of fiber after heat durability test

Temperature 1373K, Holding time 360ks, d=35 μm

Fig.11 Morphology of Al₂O₃ layer

film, and fibers containing La were especially found to have good film adhesion. However, fibers containing Ce (Fig. 10c) have a very rough oxidized film surface, and the cross section area was also found to decrease. Figure 11 shows the further enlargement of the fiber containing Ce. The oxidized film peeled off at many areas, and type C exhibited poorer film adhesion than the other two types of stainless steel. These results suggest that compared to the fibers containing La and Y, the peeling off and regeneration of the Al₂O₃ film and formation of voids progress more quickly with the fibers containing Ce owing to its poor film adhesion.

Furthermore, X-ray diffraction of the fiber surface was performed to investigate the oxides generated in the oxidized surface film of stainless steel fibers processed at high temperature. Figure 12 shows the results. For the SUS304 stainless steel fibers, the oxidized surface film consists mainly of Fe and Cr oxides, which causes the oxidized film to peel off easily and oxidation to

Top: SUS304, Temperature 1173K, Holding time 21.6ks, Bottom: 20Cr-5Al, Temperature 1373K, Holding time 360ks
Fig.12 X-ray diffraction pattern of fiber after heat durability test

could not be obtained. When the equivalent diameter was large, 85 μm, the fiber strength decreased with holding time similarly to the equivalent diameter of 35 μm, but at the holding time of 360 ks, type A showed a fiber strength of 200 MPa while type C showed a fiber strength of 60 MPa, confirming that these two types of stainless steels have heat resistance which continues for a long period of time.

This is apparently because the fiber diameter of these stainless steels is large, and the advance of oxidized film inside is slowed down. Figure 10 shows the enlargement of the external view of the fiber under the conditions; equivalent diameter of 35 μm, processing temperature of 1373K, and holding time of 360 ks. The fibers containing La (Fig. 10a) and Y (Fig. 10b) were coated by oxidized

progress inside, resulting in the powdery state. For the 20Cr-5Al stainless steel fiber containing a minute amount of rare earth elements, it was confirmed that the Al₂O₃ film was mainly generated on the fiber surface at the processing temperature and holding time of 1373K and 360 ks, respectively, and this film helped control the generation of the Fe and Cr oxides. Although, small amounts of rare earth elements is known to affect the tightness and adhesion of the generated Al₂O₃ film^[9], the surface of the Al₂O₃ film did not show any significant dependence on the equivalent diameter as shown in Fig. 13. For the 20Cr-5Al stainless steel containing small amounts of La and Y the surface showed fine needle-like structures. On the other hand, the 20Cr-5Al stainless steel containing small amounts of Ce showed only a few

needle-like structures, but numerous particle type structures causing poor tightness of the fiber. The voids observed, lack of tightness and adhesion, and progress of oxidation into the inside through the voids explain an abrupt decrease in the heat resistance of the type C 20Cr-5Al stainless steel.

Temperature 1373K, Holding time 360ks

Fig.13 Morphology of oxidized layer surface

4. Conclusions

The following summarizes the results of the heat resistance against high temperatures for various stainless steel fibers produced by the hot water soluble resin coated coil shaving method.

(1)The normal SUS304, SUS316L, and SUS430 stainless steel fibers became brittle and powdery owing to the oxidation at the processing temperature of 1173K and holding time of 21.6 ks.

(2)For fibers with equivalent diameter of $35\text{ }\mu\text{m}$, the 20Cr-5Al stainless steels containing La and Y showed fiber tensile strength of about 150 MPa even at a processing temperature of 1373K and holding time of 360 ks, demonstrating the flexibility of fibers. However, the 20Cr-5Al stainless steel containing small amounts of Ce showed progress oxidation due to the peeling of the oxidized film, which caused the fiber to become brittle, and lose its shape.

(3)When the equivalent diameter was large ($85\text{ }\mu\text{m}$), flexibility of the fiber was seen even at the processing temperature of 1373K and holding time of 360 ks. It was also confirmed that outstanding heat resistance at high temperatures can be obtained.

(4)For the 20Cr-5Al stainless steel, it was confirmed that Al_2O_3 film mainly forms on the fiber surface owing to the controlled generation of Fe and Cr oxides.

(5)Tightness of the Al_2O_3 film arises from the types of rare earth elements contained. Compared to stainless steel fibers containing Ce, those containing La and Y show outstanding tightness and as a result higher heat resistance.

References

- [1]Hirai O.; Metal and Technology, 50,P.19 (1980)
- [2]Nakagawa T., Yanagisawa A., and Suzuki K.; Journal of the Society Fiber and Technology Japan, 39, P.121 (1983)
- [3]Kaneko M., Yanagisawa A., and Nakagawa T.; The Japan Society for Precision Engineering, 62, P.110 (1996)
- [4]Kaneko M., Yanagisawa A., and Suzuki T.; Journal of the Textile Machinery Society of Japan, 49, T260 (1996)
- [5]Ohoshi T., et.al.; Proceedings of 1993 Powder Metallurgy World Congress, P.1133 (1993)
- [6]Kawano M., Ishii K., and Sato S.; The Japan Institute of Metals, Fall Meeting, P.1045 (1994)
- [7]Hiramatsu N., and Uematsu Y.; Tetsu-to-Hagane, 81, P.1001 (1995)
- [8]Nakamura S., Hiramatsu N., Shimizu I., and Uematsu Y.; Nisshin Steel Technical Report, 62, P.128 (1990)
- [9]Hiramatsu N., and Stott F.H.; CAMP-ISIJ, 11, P.467 (1998)