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A Nickel Coating Removal Process for ITER Superconducting Cables*

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Abstract A new method is developed for removing the nickel coating on ITER superconducting cables by mechanical polishing. The obvious advantage of the mechanical method, which uses a nylon brush, is that there is no chemical residual left in the cable, which would otherwise result in passive effects on the joint resistance. The coating resistance test results of this newly developed method are compared with those of the two other methods that can meet the requirements of ITER. An automatic polishing machine is designed and manufactured for the procedure to provide quality under precise control. This new technique can replace the conventional manual method due to its improved efficiency.

Keywords: ITER superconducting cable, nickel layer removal, polishing, spectra, coating resistance, automatic polishing machine

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(Some figures may appear in colour only in the online journal)

1 Introduction

A feeder system consisting of a set of tubes, superconducting cables and wires is used to supply power, cooling fluid and diagnosis for a total of 31 sets of the TF, PF, CS, and CC coils of the ITER (International Thermonuclear Experimental Reactor) magnets system. The TF feeder contains one pair of superconducting busbars, two pairs of low-temperature cooling pipes and two instrumentation lines. The superconducting joints combine the current leads with the magnet coils. According to the ITER feeder functional specification requirements [1], the resistance of the single joint should be less than 2 nΩ at a temperature of 4.2 K under an operating current of 68 kA with the background magnetic field not taken into consideration.

The nickel coating of the cable not only prevents further soldering, but also badly impacts the resistance of the joints, which is the reason why the nickel coating should be removed before soldering. There are usually two traditional coating stripping technologies. One is the chemical method and the other the electrochemical method. The former method is commonly performed using nitric acid and sodium chloride, and the latter using sulfuric acid and glycerol.

The chemical method is fast and low cost, but will exhaust many harmful gases such as nitrogen monoxide. For the electrochemical polishing process, as the coating dissolves the metal coating ions are accumulated in the solution. As a result, the solvency of the solution will eventually deteriorate [2]. On the other hand, mechanical polishing is very simple, and easy to understand and control. There are many benefits, such as mass production, a stable quality, high efficiency and no environmental pollution.

In order to find an appropriate nickel coating removal method, three different technologies are used, respectively, to remove the nickel coating of a superconducting cable: the mechanical method, chemical method and reverse electrolysis method. The mechanical method, using a nylon brush wheel on an automatic polishing machine, can uniformly remove the nickel coating without any chemical residual left on the surface of the cable. This newly developed method may replace the other two methods, as suggested by analysis of the coating resistance test results.

2 The nickel coating removal experiment

2.1 The technological process and features of the three different methods

2.1.1 The mechanical method

The processes of the mechanical method include the following steps: degreasing, alcohol scrubbing, setting of operational parameters, mechanical polishing, visual inspection and note taking. The parameters should be properly set up, including the drive motor speed, travel times and polishing motor speed. Automatic polishing is characterized by simple operation and batch processing, and the polishing and running speeds are adjustable in wide ranges. The quality can be quantitatively controlled compared to manual polishing.

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2.1.2 The chemical method

The processes of the chemical method consist of degreasing, water washing, pickling, water washing, chemical polishing, water washing, film stripping, passivation, water washing, alcohol rinsing and drying. The procedure and conditions are presented as follows: nitric acid 500 mL/L, sulfuric acid 300 mL/L, phosphoric acid 200 mL/L, thiourea 10-20 g/L, room temperature, and time 3-5 min. The thiourea is used as a corrosion inhibitor to avoid the corrosion phenomenon described in Refs. [3,4], and is used to enhance the effect of the chemical polishing solution and to extend the application scope of the polishing solution [3,5].

2.1.3 The reverse electrolysis method

The processes for the reverse electrolysis method consist of degreasing, water washing, electrochemical polishing, water washing, dipping, chemical polishing, water washing, film stripping, passivation, water washing and drying. The procedure and conditions are given as follows: citric acid 10 g/L, sodium chloride 100 g/L, PH value 1.0-1.5, current density 30 A/dm^2, temperature 21°C-27°C, and time 1-3 min [6,7]. The citric acid can improve the polishing quality and reduce nickel erosion. The main salt, sodium chloride, is mentioned in Ref. [3]. It is used to prevent the dissolution of the copper wire and improve the conductivity of the electrolysis solution [3].

2.2 Specification of test samples [8,9]

Certain samples taken from the main busbar (MB) of the ITER superconducting cable are used to perform the nickel coating removal experiments. The sample consists of an ITER superconducting cable and a stainless steel tube with an outside diameter of 44.5 mm and thickness of 2 mm. The ITER superconducting cable is made of twisted Cu/superconducting wires, and the main component of the superconducting wire is NbTi. Table 1 describes the parameters of the ITER MB superconducting cable, including the strand form, strand direction, pitch and winding direction assigned to the columns, respectively. The fourth column gives the pitch of the MB cable. It is difficult to polish the cable surface because of the many distributed valleys between the strands.

The specifications of the test samples are shown in Table 2. The real size of the mechanical polishing sample is 40.5 mm in the outside diameter. However, small sub-cables are used to perform the other two polishing experiments to reduce the expense in the R&D stage. In addition, the small sub-cables are easy to operate on-site.

2.3 Testing process

The nickel removal tests were carried out with three different polishing methods. Then, the temperature, time and other parameters of each sample were recorded. The mechanical polishing experiments were carried out with three different polishing brushes, individually, as shown in Table 2. These brushes were installed on an automatic polishing machine. The wheel speed, driving motor speed, travel times and the time taken to polish one whole cable are listed in Table 3.

Table 1. The structure and parameters of the main busbar of the ITER [2]

Type	Cable pattern	Twist direction	Cable twist (mm)	Wrapping direction
MB cable	(2 sc+1Cu)×3 × 5 ×(5 +1C0)× (6+1C1)	Right-hand	First: 80 ±5 Second: 140±5 Third: 190±5 The fourth: 300±5 The fifth: 420±5	Left-hand

Table 2. The specification of the nickel removal test samples

Polishing method	Specification OD (mm)	Length L (mm)	Quantiy N (piece)
Nylon brush	40.5	1000	3
Brass brush	40.5	1000	3
Stainless steel brush	40.5	1000	3
Chemical method	10	120	5
Reverse eletrolysis method	10	120	5

Table 3. The SEM spectrum of the mechanically polished surface with three different brushes

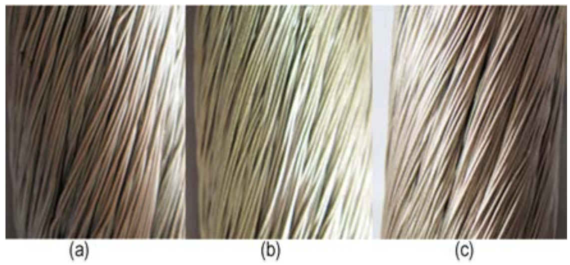
ID No.	Type	Ni (%)	Cu (%)	Zn (%)	Fe (%)	Polishing wheel speed V_{P} (r/hour)	Drive motor speed V_{D} (r/min)	Duration T (min)
NL-01	Nylon	0	100	0	0	75	50	25
NL-02	brush	0	100	0	0	75	50	25
NL-03	wheel	0	100	0	0	75	50	25
HT-01	Brass	6.27	60.82	32.91	0	75	50	25
HT-02	brush	2.5	61.93	35.57	0	75	50	25
HT-03	wheel	5.63	59.82	34.55	0	75	50	25
SS-01	S.S.	5.07	94.01	0	0.92	75	50	20
SS-02	brush	6.13	93.87	0	0	75	50	20
SS-03	wheel	7.38	90.9	0	1.72	75	50	20

Finally, the nickel residual, if any, would be checked by visual inspection with a magnifying glass. If there are nickel residuals in the valleys, this area must be polished by hand with fine grit sandpapers so that the superconducting wires aren't harmed.

2.4 Test results

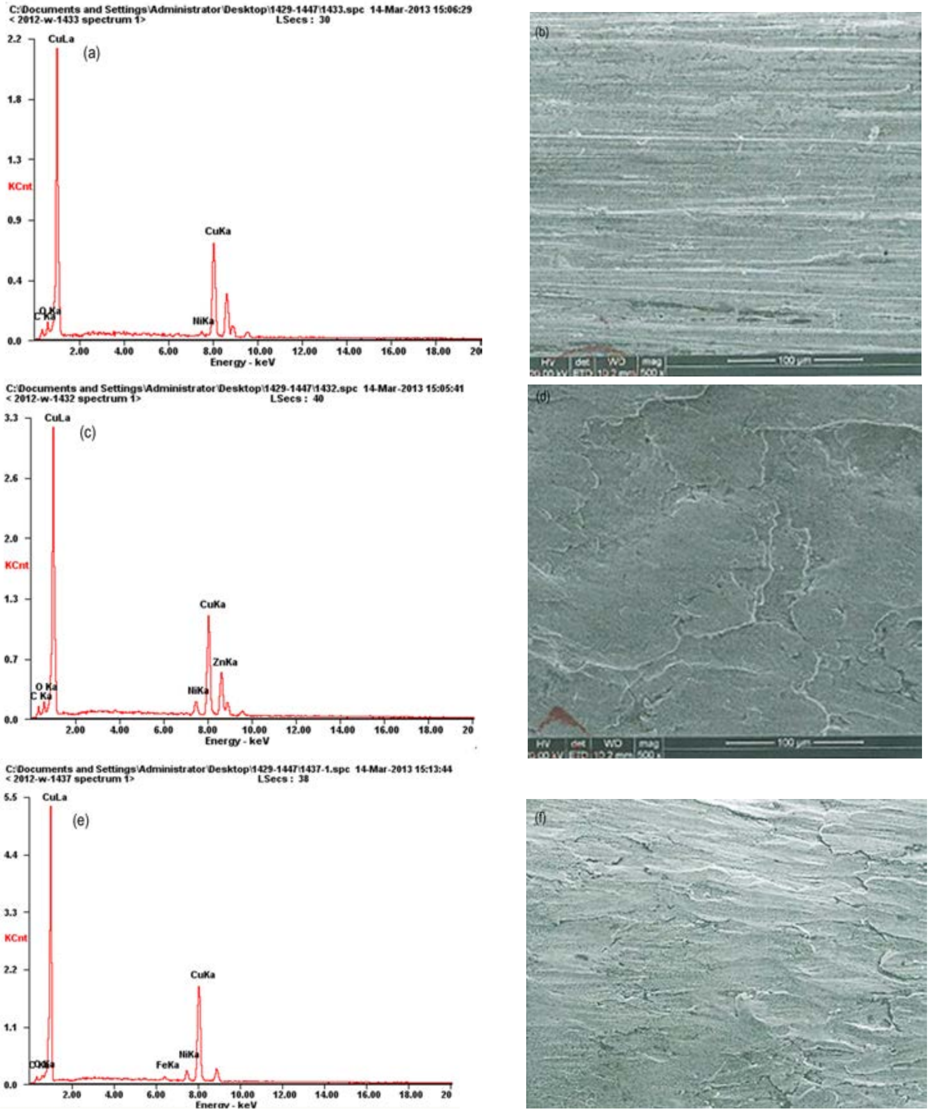
The test results are presented in Fig. 1. The visual inspection results are shown in Fig. 1. Fig. 1(a) is the nylon brush polished surface, and the copper appears obviously. Fig. 1(b) is the brass brush polished surface, and the color appears yellow. The final one was polished by the stainless steel (S.S) brush as the brush hardness is very high and many scratches can be seen on the cable surface (Fig. 1(c)).

All the test samples were analyzed both qualitatively and semi-quantitatively using energy dispersive X-ray (EDX) microanalysis in the testing center of the Shanghai Research Institute of Materials. For each sample, tests were performed on three different test points randomly chosen on the polished surface. The surface morphology of the nickel coating removal surface was observed with scanning electron microscopy (SEM) [10]. Fig. 2 shows the EDX spectra and SEM micrographs of the superconducting cable surface polished using the mechanical method.



(a) Nylon brush polished surface, (b) Brass brush polished surface, (c) S.S brush polished surface

Fig.1 The polished surface by three kinds of brushes

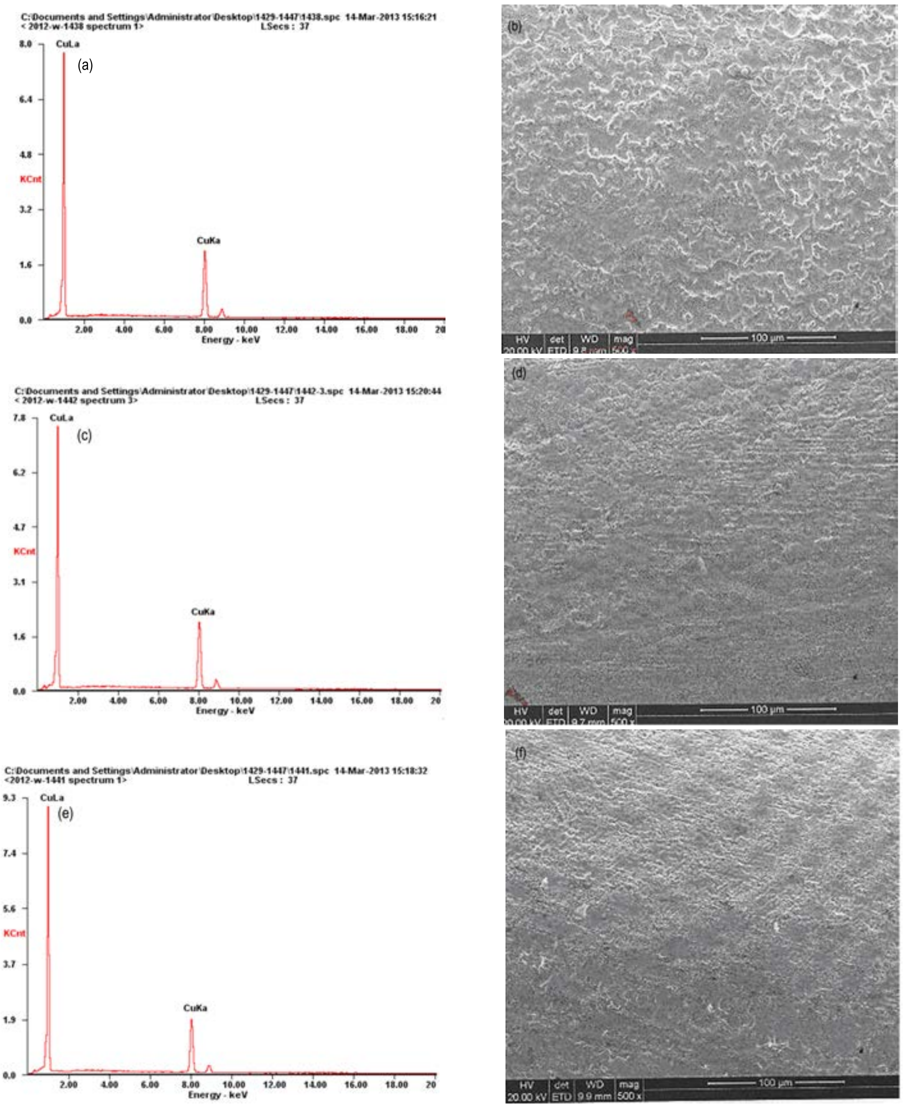


(a) The EDAX spectrum of the surface polished by nylon brush, (b) SEM micrograph of the surface polished by a nylon brush, (c) The EDAX spectrum of the surface polished by a brass brush, (d) SEM micrograph of the surface polished by a brass brush, (e) The EDAX spectrum of the surface polished by an S.S brush, (f) SEM micrograph of the surface polished by an S.S brush

Fig.2 The surface morphology of the mechanical polishing cable (amplification 500)

Table 3 describes the elemental composition percentage of each superconducting cable surface polished with three different brushes. The first column is the ID number of the experiments. Nine trial runs of the experiments are needed for each sample, and each trial run is indicated in the array. The second column is for the three kinds of brushes used in the mechanical polishing. It also lists the polishing wheel speed, driving motor speed and the time for finishing one whole cable.

Fig. 3 presents the EDX spectra and SEM micrographs of three sub-cable samples polished using the chemical method. In Table 4, five trial runs with the chemical method are listed in the columns for different chemical compositions and temperatures. According to the spectra surface morphology of five trial runs, the second group is the best due to the smooth surface (Fig. 3(d)) and resistance test results (Fig. 6(a)). A white fog mark appears on the first sample surface (Fig. 3(b)), and a red color appears on the fourth sample surface (Fig. 3(f)). It was found that the surfaces of the other three samples are smooth.



(a) The DEAX spectra of the 'HY-01' surface, (b) SEM micrograph of the 'HY-01' surface, (c) The EDAX spectra of the 'Hy-02' surface, (d) SEM micrograph of the 'HY-02' surface, (e) The EDAX spectra of the 'HY-04' surface, (f) SEM micrograph of the 'HY-04' surface

Fig.3 The surface morphology of the chemically polished cable (amplification 500) [11,12]

Table 4. The SEM spectrum of the chemically polished samples

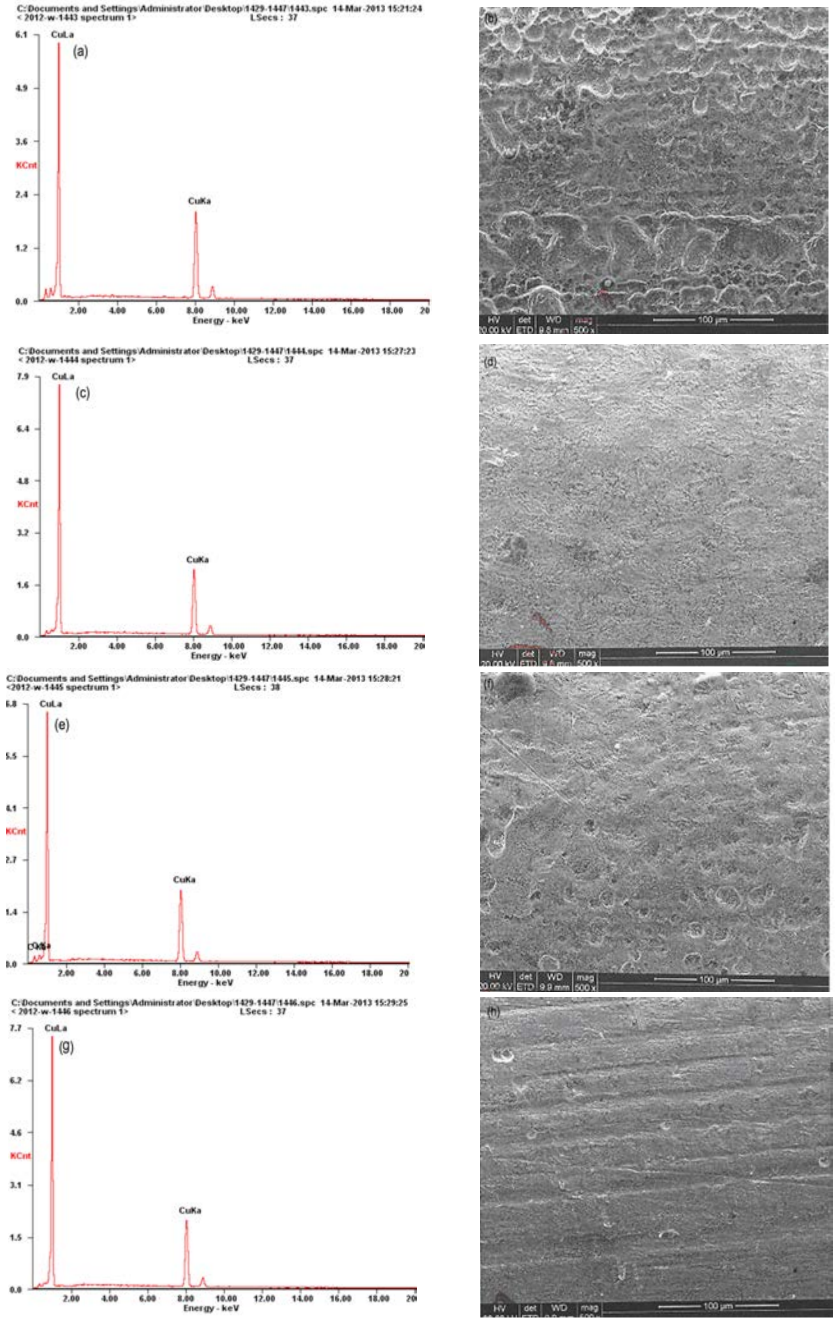
ID No.	HNO_3 (mL)	H_2SO_4 (mL)	HPO_4 (g/L)	$CS(NH_2)_2$ (g/L)	Temperature T (°C)	Element (%)	Duration T (min)
HY-01	500	500	0	10	20	100	64
HY-02	500	300	200	10	20	100	64
HY-03	500	300	200	15	20	100	64
HY-04	400	300	200	10	40	100	64
HY-05	500	300	200	20	20	100	64

Fig. 4 shows the EDX spectra and SEM micrographs of three sub-cable samples polished with the reverse electrolysis method.

Table 5 presents the different temperatures, current densities and durations for another five trial runs using the reverse electrolysis method. Although the EDX spectra of the five trial runs look almost the same, the second group is the best due to the EDX spectra (Fig. 4(c)) and smooth surface (Fig. 4(d)). The first sample shows the spot-corrosion phenomenon (Fig. 4(b)), a part spot-corrosion phenomenon is indicated in (Fig. 4(f)), and some scratched lines can be observed, as shown in (Fig. 4(h)). The surface of the final sample is smooth under visual observation, the same as the second one.

Table 5. The SEM spectrum of samples polished by the reverse electrolysis method

ID No.	Temperature T (°C)	Current density I (A/m^2)	Element Cu (%)	Duration T (min)
FDJ-01	18	10	100	30
FDJ-02	25	10	100	20
FDJ-03	20	8	100	30
FDJ-04	25	10	100	15
FDJ-05	25	10	100	25



(a) The EDAX spectra of the 'FDJ-01' surface, (b) SEM micrograph of the 'FDJ-01' surface, (c) The EDAX spectra of the 'FDJ-02' surface, (d) SEM micrograph of the 'FDJ-02' surface, (e) The EDAX spectra of the 'FDJ-03' surface, (f) SEM micrograph of the 'FDJ-03' surface, (g) The EDAX spectra of the 'FDJ-04' surface, (h) SEM micrograph of the 'DF-04' surface

Fig.4 The surface morphology of cables polished with the reverse electrolysis method (amplification 500)

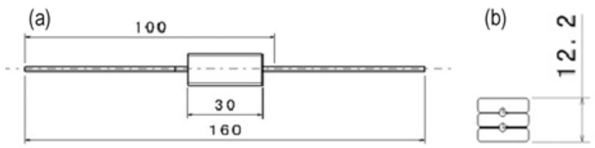
3 Sub-cable coating resistance tests

3.1 Purpose

The purpose of the coating resistance tests on the sub-cable samples treated with three different polishing methods is to detect whether the coating resistance value can meet the requirements of the ITER PA document or not. In the R&D stage, sub-cable sample tests are usually used to replace all the superconducting cable tests to reduce the cost. Furthermore, the sub-cable coating resistance tests are easy to conduct in contrast with the test on the whole cable.

3.2 Test procedure [11,13]

The sub-cable samples were twisted by special tools with seven NbTi superconducting wires of 0.726 mm diameter. The pitch is 20 mm. After tinning, the sub-cable was soldered with small copper blocks, as shown in Fig. 5.



(a) Top view, (b) Left view

Fig.5 Sketch of the sub-cable samples

Fifteen samples polished with three different methods had been tested individually by soaking in a Dewar vessel filled with 200 L liquid helium. After a few minutes, the temperature values of the sub-cable samples approached a steady value 4.2 K. Then the continuous load current was smoothly increased from 0 A to 100 A, and the rate was 0.5 A/s [14]. During the process, every voltage drop of each sub-cable sample was recorded individually.

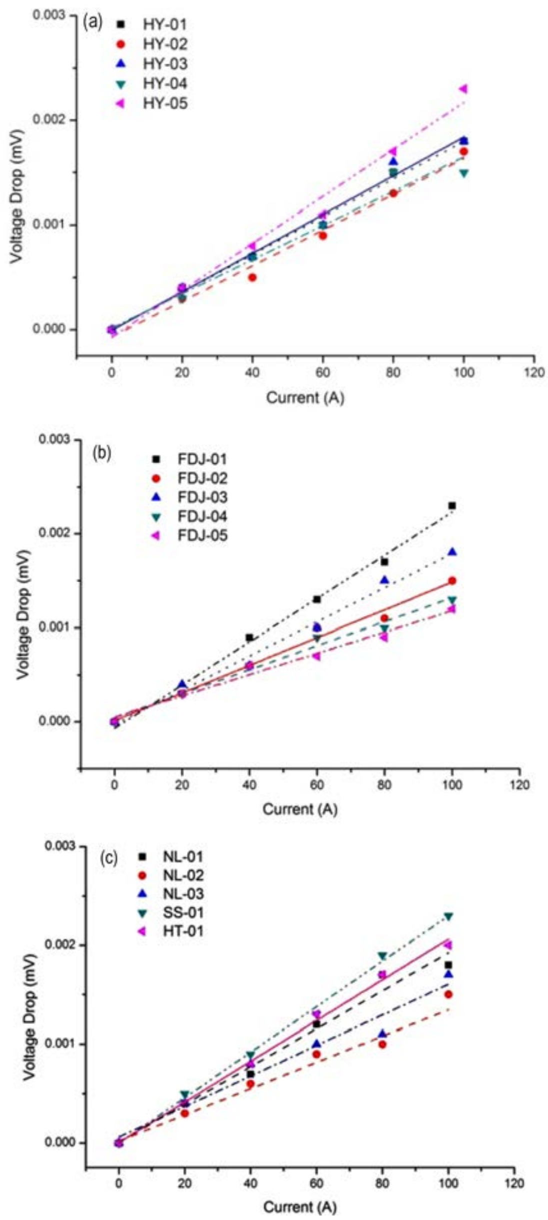
3.3 Results

After curve fitting, the coating resistance values of the 15 sub-cable samples polished with three different methods are shown in Fig. 6.

Fig. 7 indicates that the mechanical method results in a coating resistance value of about 19 nΩ, almost the same as the results of the other two polishing methods. The coating resistance value of the chemical method is 18 nΩ, the same as that of the reverse electrolysis method.

4 Analysis of test results and influencing factors

From Table 3, it can be found that all of the three polishing wheels used in the mechanical method can remove the nickel coating of the ITER cable surface,



(a) Chemical method, (b) Reverse electrolysis method, (c) Mechanical method

Fig.6 The V-I characteristic curves for the three different methods

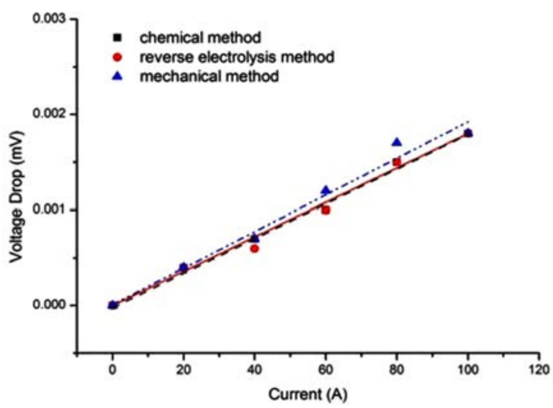


Fig.7 Comparison of the V-I characteristic curves for the three different polishing methods

but the brass brush brings in the impurity element Zn, as seen in Fig. 2(c). The average content of the copper element is 60.86%. The stainless steel brush wheel contains the element Fe, as shown in Fig. 2(e), so it cannot be used for the polishing wheel because it will influence the magnetic permeability of the coils. The average content of the copper element with the S.S brush is 92.93%. Compared with the other two brushes, the nylon brush does not bring in any other element during the polishing process (Fig. 2(a)). The nickel coating on the superconducting cable surface was removed completely, as shown in Table 3.

The polishing mark of the nylon wheel is straight, uniform and along the cutting direction, as shown in Fig. 2(b). The mark of the brass brush and S.S. brush is flaky and unevenly distributed, as shown in Fig. 2(d) and (f). The only shortcoming of the mechanical method is that it can only remove the nickel coating of the cable surface, but it will not influence the coating resistance, as shown in Fig. 7.

The effect of nickel coating removal is closely related to the speed of the polishing wheel. Experiments show that when the speed of the polishing wheel is between 46.67 r/hour and 75 r/hour, the surface can be polished very well. Below 46.67 r/hour, the motor cannot drive the polishing wheel well. Over 75 r/hour, the superconducting cable will be over-polished.

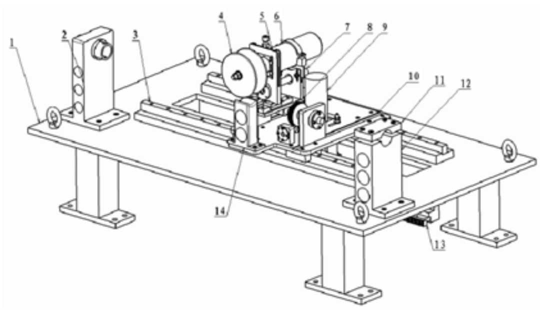
The nickel coating surface polished by the chemical method shows good uniformity, as can be seen in Fig. 3(d). A white fog mark appears on the surface of the 'HY-01' sample because of too much sulfuric acid. A red color appears on the surface of the 'HY-04' sample due to a lack of oxidant. During operation, the cable should be held in a vertical manner to avoid the pickling solution from flowing into the jacket. This cannot be done for cables with a complex space size, irregular shape or large weight. The pickling time and immersion depth need to be strictly controlled. If the pickling solution flows into the jacket, it will affect the future service life of the superconducting cable. In addition, the chemical solution needs to be mixed on-site. The disadvantages of the chemical method are a short life, large consumption and unrecyclable resource. The pungent gas and acid mist discharged from the pickling process are also harmful to people and the environment.

The effect of nickel removal by the reverse electrolysis method is as good as that of the chemical method. From scanning electron microscopy with an amplification of 500, the surface of the 'FDJ-02' sample is smooth, as shown in Fig. 4(d). The 'FDJ-01' sample shows the spot-corrosion phenomenon because of the low temperature of the electrolyte. The 'FDJ-03' sample indicates part spot-corrosion, which is caused by low current density. For this method, the polishing time and immersion depth need to be controlled strictly. Some scratched lines can be observed, as shown in Fig. 4(h), because of the short time. During the polishing process, the cable should be held in a vertical status to prevent the citric acid solution from flowing into the jacket of the cable. Apart from this problem, the reverse electrolysis method needs direct-current power. The pungent gas generated from the polishing process is harmful to the operators and environment, and the electrolysis solution must be disposed after purification and filter treatment [15]. This will greatly increase the costs involved.

Compared with the chemical method and reverse electrolysis polishing method, the coating resistance value of the mechanical polishing method is nearly the same (Fig. 7), so the mechanical method can be used to remove the nickel coating instead of the other two methods. Furthermore, the mechanical method has other advantages, such as high efficiency, easy operation and less pollution to the environment.

5 The mechanical polishing machine

The automatic polishing machine was self-designed according to the mechanical polishing principle by the R&D center at the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP). It is composed of a support plate, locking support, linear guiderail, polishing wheel and others, as shown in Fig. 8.



1 Support plate, 2 Locking support, 3 Linear guide rail, 4 Polishing wheel, 5 Height-adjustable mechanism, 6 Servo motor, 7 Horizontal feed-adjustment screw, 8 Worm and worm-wheel mechanism, 9 Drive motor, 10 Polishing bracket, 11 Plate, 12 Fixed support, 13 Rack and gear mechanism, 14 Support block

Fig.8 Sketch of the automatic polishing machine

The polishing wheel can move along the axial direction of the superconducting cables. The rotating direction is in the tangential direction of the polishing wheel to prevent the cable from loosening during polishing.

The transmission mechanism is combined with a servo motor by elastic coupling. The gear's rotary movement in the circumferential direction is used to drive the polishing wheel in the horizontal direction. Fig. 9 shows that the polishing wheel can be adjusted in the horizontal position by a screw rod. The center distance between the polishing wheel and the superconducting cable can be adjusted by certain bolts so as to meet the different specification requirements of the ITER superconducting cables. The polishing wheel can be moved around the cable's center axis by adjusting the worm and worm wheel transmission so that the 127 degree circumferential surface of the cable can be polished, with no need to rotate the cable.

The automatic polishing machine is equipped with a digital display control system. The operation interface is shown in Fig. 10. Information on the polishing wheel's rotation speed and polishing times can be displayed. There is also a vacuum cleaner and dust cover, which is not shown in Fig. 11. So the solid particles, dust and metal particles generated in the polishing process can be collected to protect the environment and the operators.

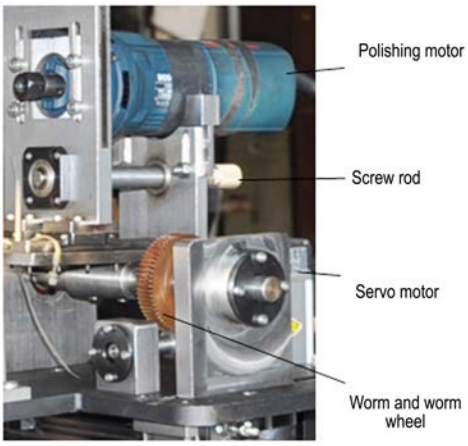


Fig.9 The worm and worm wheel transmission

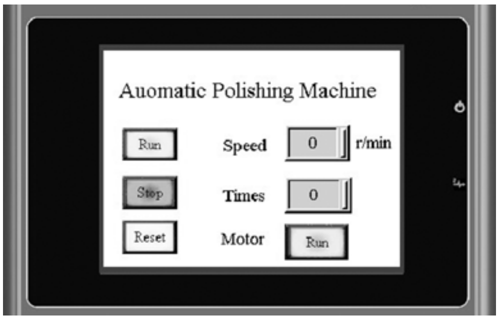


Fig.10 The digital display system of the automatic polishing machine

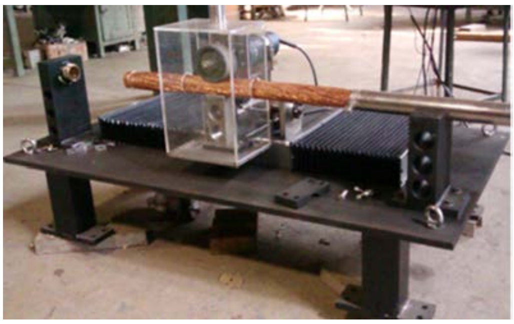


Fig.11 The mechanical polishing machine

6 Conclusion

After many comparisons between the newly developed method and the traditional methods for nickel coating removal, the advantages of the proposed mechanical method with automatic polishing machine have been validated. Compared with the traditional methods, the surface polished with the new method is smooth and free of chemical residual, as shown in the analyses of the EDX spectra and the SEM micrographs. The coating resistance of the new method can also meet the ITER requirements, as verified by the test analysis results. It can be foreseen that the newly developed mechanical polishing method will have wide applications in the nickel coating removal of ITER superconducting cables.

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