Reversible Transverse Stress Effects on the Critical Current of an Internal Tin Nb_3Sn Strand Under Axial Strain

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***Abstract*—We have developed an apparatus to investigate the effect of transverse stress under axial strain on the critical current of superconducting strands. An internal tin Nb_3Sn wire is soldered on a C-shape ring (called Pacman) made of 2% beryllium doped copper alloy and axial strain from −0.7 to 0.7% can be applied. The actual strain on a sample was estimated from a comparison with the critical current measurement results using a Walter spiral probe. Reversible transverse stress effects on the critical current were studied in this work and the transverse pressure was applied up to 40 MPa under ±0.5% axial strain. The critical current was initially increased about 3% as transverse load was applied and then decreased almost linearly under compressive axial strain. Similar behavior is observed under tensile axial strain but the critical current decreases rather sharply at higher load. A unified description based on 3 dimensional deviatoric strain was difficult for the sample studied in this work.**

***Index Terms*—Deviatoric strain, internal tin Nb_3Sn, scaling law for flux pinning, strain dependence of the critical current, transverse stress effects.**

I. Introduction

Nb_3Sn strands in cable-in-conduit conductors for large scale superconducting magnet applications experience axial strain due to thermal contraction difference with jacket material. There is additional transverse pressure during high field operations due to the Lorentz force. It is well known that the field dependence of the critical current of a Nb_3Sn strand at various axial strain collapse into a single curve when the critical current is converted into the pining force and the field is normalized with respect to the upper critical field [1]. The critical current is reversible up to about 1% compressive axial strain [2]. A similar scaling law for flux pinning was also reported for the temperature dependence of the critical current [3]. Unified scaling laws for flux pinning in Nb_3Sn superconducting strands are actively studied for practical applications such as the ITER magnet [2], [4], [5].

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On the other hand, the effect of transverse stress on the critical current has been rarely studied even though there were reports that transverse stress can damage strands much more severely than axial strain does [6]–[9]. Axial strain not only changes the length of wire but also affects wire diameter. Recently, 3-dimensional deviatoric strain is considered in the analysis of strain effect on the critical current [10]. The influence of transverse pressure can be quite different under various applied axial strain. In this work, reversible transverse stress effects under various applied axial strain are studied for the first time. Details of measurement apparatus will be reported and preliminary results on reversible transverse stress effects under axial strain will be discussed.

II. Experimental

Usually, axial strain is applied to a superconducting strand using strain transmitting medium of various shape. The Walter spiral enables to accommodate a long length wire and has been widely used [11]. Recently, U-shaped ring has evolved into a c-shaped ring called Pacman [12]. A longer strand can be attached on a Pacman compared with the U-shaped ring. The periphery of the soldered wire forms a planar circular surface. We adopt the Pacman structure to apply both axial and transverse stress simultaneously. As shown in Fig. 1(a), a strand is soldered on the outermost part of the Pacman not at the side periphery. The strand is located in between the Pacman and the inner shaft as shown in Fig. 1(b). As the inner shaft moves up and down, transverse stress can be applied to the strand. The inner shaft also transfers a torque to the Pacman. Two pins mounted on the inner shaft tightly fit the pin holes on one side of the Pacman. The other side holes are put into the bottom pins shown in Fig. 1(d). The inner shaft is connected with a jackscrew and a worm-wheel reducer on the top.

The schematic diagram for the upper part of the developed measurement apparatus is shown in Fig. 2. The jackscrew can apply transverse load up to 40 kN. The transverse load is measured by a load cell located in between the worm-wheel reducer and the inner shaft. When we lift up, the worm-wheel reducer is hanging on the jackscrew and slides over 4 guide-rods. When it is pushed down, the worm-wheel reducer is still hanging on the jackscrew until the bottom of the inner shaft touches the wire. Then the ball bush attached on the bottom of the jackscrew pushes the worm-wheel reducer and the load cell gage level increases. The inner shaft is directly connected with the worm-wheel reducer and the rotation angle can be accurately adjusted. The backlash of the worm-wheel reducer is less

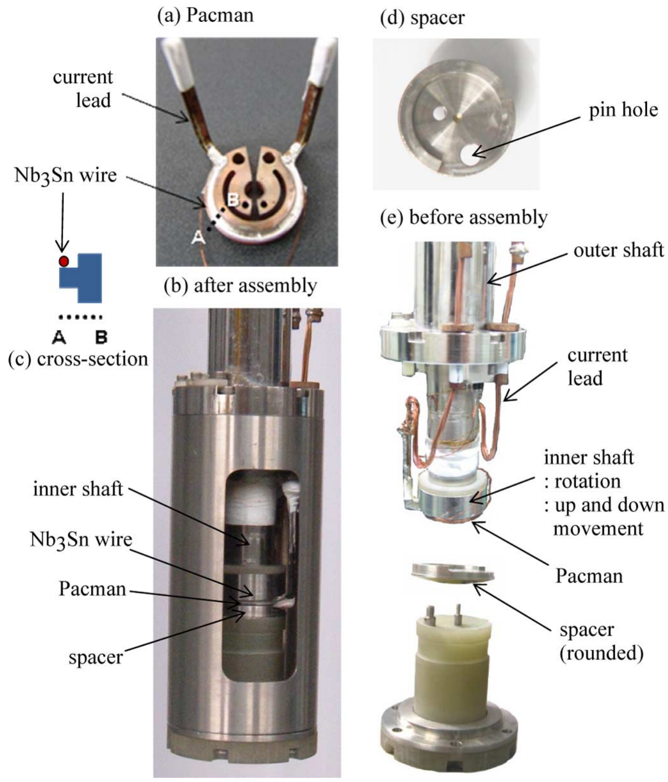

Fig. 1. The bottom part of the developed apparatus. (a) sample soldered on a Pacman, (b) a photograph after assembly, (c) a schematic cross-sectional view, (d) a spacer used for sample adjustment, and (e) a photograph before assembly. GFRP was used for electrical insulation.

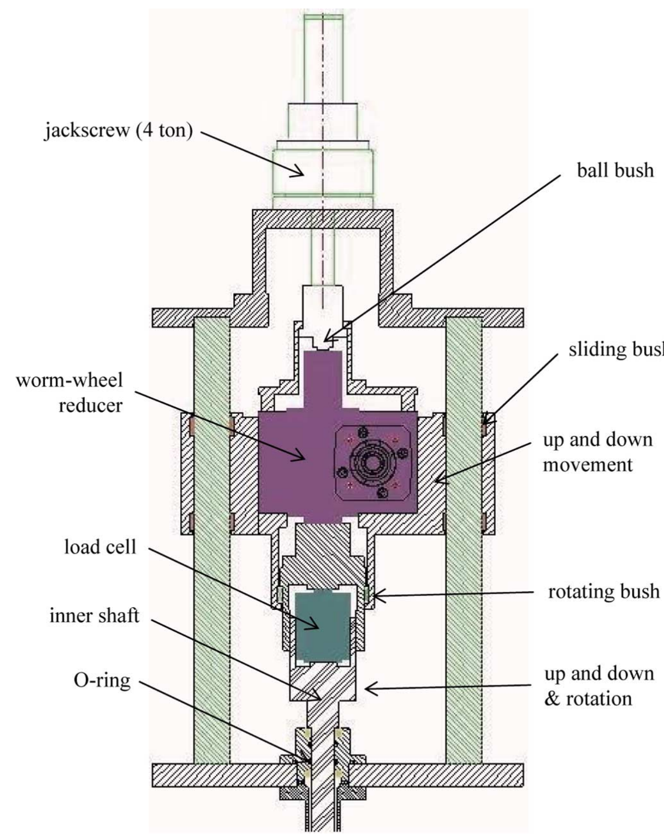

Fig. 2. A schematic diagram for the upper part of the developed apparatus. The inner shaft is attached to the worm-wheel reduce and the worm-wheel reducer is connected with the jackscrew. Both rotational and translational movement is possible.

than 0.1 deg. Even though the probe is designed and assembled carefully, there can be a slight misalignment so that the wire is not pressed uniformly. That is a reason why a spacer shown in Figs. 1(c) and 1(d) is inserted below the Pacman. The bottom of the spacer is rounded so that the Pacman can adjust itself when it is pressed.

The overall shape of the Pacman is quite similar to that of reported one [12]. Diameter was reduced to about 32 mm in order to be accommodated in our magnet. Our Pacman is made of 2% beryllium doped copper alloy and samples need to be heat treated on a Ti-6Al-4V alloy heat treatment jig. Strand length on the Pacman is about 6 cm but when the distance between voltage taps is more than 1 cm, current sharing effects [13] were observed. The n-value was defined from the slope of the log-log plot of $I - V$ curve in the range between 1 and 10 $\mu\mathrm{V/cm}$. The critical current is defined at an extrapolated onset criterion of 0.1 $\mu\mathrm{V/cm}$. A Chroma current source is used and voltage is measured with a Keithley 2182 nanovoltmeter. GFRP (Glass Fiber Reinforced Plastic) was used for an electronic isolation. All measurements were carried out at 4.2 K.

III. Results and Discussion

An internal-tin processed strand manufactured by KAT (Kiswire Advanced Technology) is studied in this work. About 2 wt.% of Ti ternary element is added. Outer diameter, the number of filaments and the average filament diameter are 0.82 mm, 3344 and 5.5 $\mu\mathrm{m}$, respectively. The sample was heat treated at 650°C for 120 hours. Details of sample characteristic are reported elsewhere [14]. Before sample soldering, six strain gages were bonded on the Pacman as shown in the inset of Fig. 3. As was reported [12], the gage reading among strain gages on the outer or inner circumference was quite similar with each other. The solid symbols in Fig. 3 are measured data at three different positions along the outer periphery (location A in the inset of Fig. 3) and the open symbols are for the inner circumference (location B) data. In our case, we found a simple polynomial expression for the rotation angle (θ) dependence of axial stain (ε). The strain on the outer circumference can be written as, $\varepsilon = -550 \cdot \theta - 0.55\theta^3$, and the inner one as, $\varepsilon = -200 \cdot \theta - 0.2\theta^3$. For comparison, the strain dependence of the critical current was also measured with a Walter spiral (WASP) probe [15] as shown in Fig. 4 as open symbols. The measurements result using the apparatus described in this work without transverse load is shown together as solid symbols. It is coincident with the WASP result when we calculate the average strain of the wire on the Pacman as, $\varepsilon = -410 \cdot \theta - 0.41\theta^3$. Almost linear relation among strain measured at different radius in the Pacman structure can be analytically calculated using Winkler's theory of initially curved beam as was reported by Godeke [12]. The dotted lines in Fig. 4 are fitting results using Ekin's strain scaling law [1],

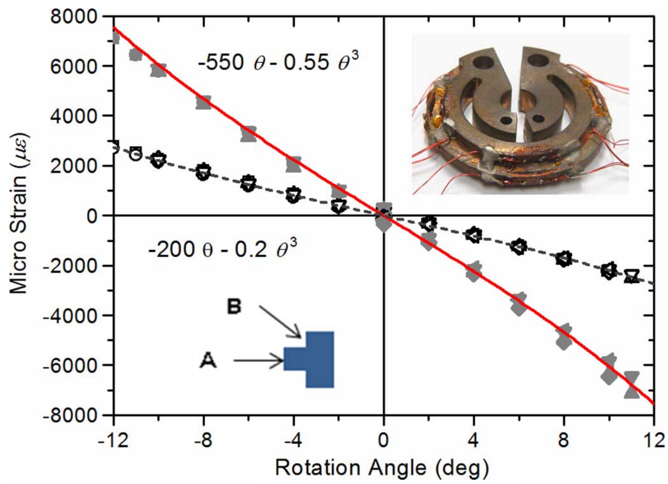

Fig. 3. Angular dependence of strain measured from the attached strain gages. (inset) A photograph after strain gage attachment.

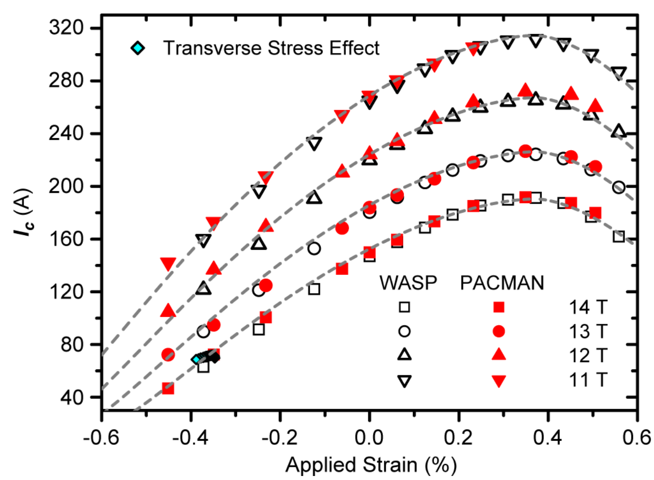

Fig. 4. The strain dependence of the critical current for the internal tin sample. Dotted lines are fitting results using strain scaling law. Solid diamond symbols are converted data from transverse stress measurements.

$$F_p(B,\varepsilon) = CB_{c2}(\varepsilon)^n f\left(B/B_{c2}(\varepsilon)\right),$$

$$\text{where,}\quad f\left(B/B_{c2}(\varepsilon)\right) = f(b) = b^p(1-b)^q,$$

$$B_{c2}(\varepsilon) = B_{c2m}\left(1 - a|\varepsilon_a - \varepsilon_m|^u\right).$$

The parameters used for the calculation are $n = 1$, $p = 0.5$, $q = 2$ and $u = 1.7$. The maximum upper critical field $(B_{\rm c2m})$ is 28.3 T. The strain coefficient (a) in the compressive region is 1100 and in the tensile region 2400.

The effects of reversible transverse stress effects under axial strain are shown in Figs. 5 and 6. First, axial stain was adjusted without transverse pressure and then transverse load was applied. In an early work, it was reported that the transverse stress effects are reversible up to about 150 MPa [6]. On the other hand, it is recently reported that it's reversible only up to about 40 MPa when a 20 mm long PIT (powder in tube) Nb_3Sn strand was pressed [16]. Or in a point contact experiment on an internal tin RRP (rod restack process) Nb_3Sn, it is reversible only up to

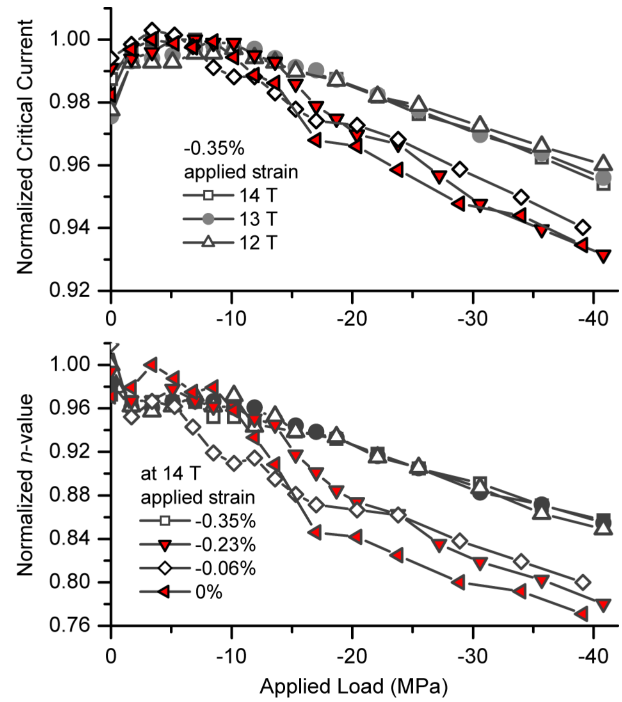

Fig. 5. Normalized critical current and n-value as a function of applied load at different axial compressive strain and applied field.

60 MPa [17]. In this work, we are focused on the reversible effects and want to study whether it is possible to apply a 3 dimensional deviatoric strain tensor approach when there is both axial strain and transverse stress. For that reason, transverse stress is limited to 40 MPa. The load was translated into pressure by dividing it with the projected area as usually done by many authors [6]–[9], [16], [17]. The deviatoric strain is defined as [10],

$$\varepsilon_{dev} = \frac{2}{3}\sqrt{(\varepsilon_x - \varepsilon_y)^2 + (\varepsilon_y - \varepsilon_z)^2 + (\varepsilon_z - \varepsilon_x)^2},$$

where, $\varepsilon_{\rm x}$, $\varepsilon_{\rm y}$ and $\varepsilon_{\rm z}$ are the principal strain component.

In the compressive axial strain region, the length of a wire is reduced but the diameter is slightly increased. When it is pressed, the length of wire will increase at first and then the effects of transverse pressure would appear. As shown in Fig. 5, the critical current slightly increased to about 3% then almost linearly decreased, which is consistent with the deviatoric strain concept. However, in the tensile strain region, we observed a similar trend as shown in Fig. 6. Actually, the reduction in the critical current was observed when higher transverse stress was applied. But above some critical transverse load, the critical current decreased sharply. These measurements carried out 3 times and were found to be reversible. A unified description on the effects of axial strain and transverse stress seems to be difficult for the sample studied in this work.

A local peak stress in actual cable-in-conduit conductors, such as ITER magnet, can be as high as 110 MPa [18]. But if the cable configuration is well organized so that a uniform distribution of load is possible, it is only about 20 MPa [19]. In such a case, it can be argued that transverse load is not a serious problem, at all axial strain condition. Using a typical elastic modulus of 100 GPa for Nb_3Sn wires [19], the effect

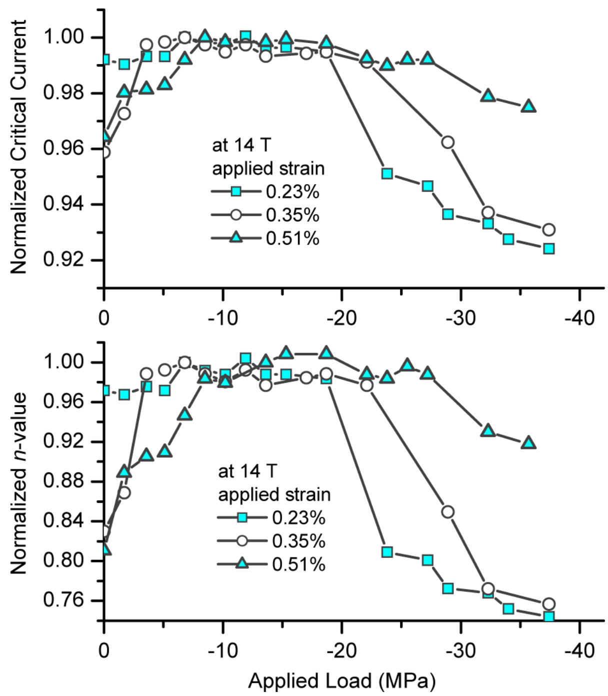

Fig. 6. Normalized critical current and n-value as a function of applied load at different axial tensile strain.

of tensile stress is converted into axial stain and is shown in Fig. 4 as solid diamond symbols. The effect of transverse stress in quite negligible compared with that of axial strain. The other feature needs to be noted is a correlation between the n-value and the critical current. Whether the transverse load is applied under compressive or tensile strain, there is a clear correlation between the n-value and the critical current as was reported for a bending experiment [18]. All these features were independent of applied field. The measurement results under -0.35% axial strain at different applied field shown together in Fig. 5 are in agreement with each other.

IV. Conclusion

A transverse stress probe under axial strain was successfully fabricated. With this probe, reversible transverse pressure effects on the critical current of an internal tin processed Nb_3Sn strand under various applied axial strain was measured for the first time. Under $\pm 0.5\%$ axial strain, up to 40 MPa transverse stress is applied. It was found that 3 dimensional deviatoric strain concept is not applicable for the sample studied in this work. Both in compressive and tensile strain region, the critical current was increased at first and then decreased as the transverse stress increased. There was a correlation between the n-value and the critical current. The measurement results were reversible and independent of applied field. It can be argued that the effects of transverse stress under $\pm 0.5\%$ axial strain do not degrade a cable-in-conduit conductor if it is designed with a local peak stress less than 40 MPa. However, further comparative studies on other types of strands are needed.

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