STUDIES ON INNOVATIVE PRODUCTION METHODS OF HOM COUPLER FOR SRF 9-CELL CAVITY

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Abstract

Pure Nb for SRF cavity bears hard workability. In addition, HOM coupler composed of cup (outer conductor) and antenna (inner conductor), a primary device of end group components, is complicated in the shape, implying much harder formability. That is why current production methods so far show serious issues in cost-effectiveness and mass-productivity. The authors have created advanced press forming methods of HOM cup and HOM antenna aiming to solve the above issues, almost resulting in satisfied quality, cost and productivity. The innovative procedures are described, remaining a bit problems to be sorted out, and further R&D works are still ongoing.

INTRODUCTION AND TARGET

HOM coupler attached at both ends of cavity is one of indispensable devices to eliminate high order mode radio wave generated during the operation of machines to prevent lowering of accelerating voltage.

HOM coupler in Fig. 1 shows a cylindrical cup of an extremely tall body to diameter with protrusion on the flat bottom and off-center perforation followed by burring plus oblong hole on the side wall, and also an antenna demonstrating kind of unique view with a thick body, sharp corner and a large void. They are subject to EBW for assembling of HOM coupler.
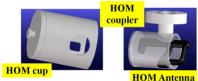

Figure 1: Schematic view of HOM coupler with cup and antenna.

From the shape and size of components, effective production methods sound quite difficult in parallel with making use of hard workable pure Nb. Now, several production methods have been implemented. However, there might be serious issues of cost-effectiveness and mass-productivity in particular.

Our final target is to invent advanced sheet plastic press-forming methods for HOM coupler i.e. HOM cup and HOM antenna aiming at realizing its satisfied function, prominent mass-productivity and drastic cost-effectiveness [1][2].

HARD WORKABLE PURE NB MATERIAL

There are close relation between material and forming, even more in tough workable pure Nb. Then, pure Nb annealed sheet (t2.8) was subject to uni-axial tension test together with commercial pure Fe sheet (t1.0) to examine both materials related to "sheet press forming" that should be most desirable due to applying plastic deformation which could make the shortest production time and extensive cost reduction available.

The diagram showing relations between applied force and

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displacement reveals large total elongation (λ_t) in Nb. However, the notable point is that λ_t is expressed as follows,

$$\lambda_t = \lambda_u + \lambda_\ell \qquad (1)$$

where indicated are uniform and local elongation each. It should be noted that λ_u and λ_ℓ correspond to plastic stable region (basically free from necking) and plastic unstable region (necking generation due to stress concentration), respectively. And the test results show the following relations,

$$\lambda_t(Nb) > \lambda_t(Fe) \ ; \ \lambda_u(Nb) < \lambda_u(Fe) \ ; \ \lambda_\ell(Nb) > \lambda_\ell(Fe) \qquad (2)$$

As the "ductility" is roughly equivalent to λ_u in case of press forming to avoid fracture in unstable plastic deformation, the experimental result (equation (2)) is important, namely Nb is hard workable compared with Fe. Adding, the last term of equation (2) gives rather an advantage to Nb when burring is applied. The following Ludwick's relation was proved [3],

$$\sigma = \varepsilon^n \qquad (3)$$

where σ and ε are true stress and true strain, and n is called work hardening coefficient showing hardenability of metals and alloys.

For the purpose of the conversion from the current methods to the whole plastic press forming, mechanical properties from pure Nb tensile test, and additionally observed data of Lankford's plastic strain ratio, r, at RT (Fig. 2 ; closely related to press drawability) together with popular pure Fe are useful. Further, we propose a new parametric index, ζ, which is defined and shown below using r, $\bar{r}$ (averaged r value in different directions) and Δr (indicating anisotropy of the material) [4],

$$r \equiv |\, r_w / r_t\,|, \qquad (4)$$

$$\bar{r} = \{\, (r_o + r_{90}) + 2\, r_{45}\, \} \,/\, 4, \ \ \Delta r = \{\, (r_o + r_{90})\,/\,2\, \} - r_{45} \qquad (5)$$

$$\zeta \equiv \Delta r \,/\, \bar{r} \qquad (6)$$

where pure Nb is featured by much smaller n and ζ than pure Fe in addition to small ε_u and s_u (ultimate tensile strength). The facts are unfavorable and tough to accomplish the target [5][6].
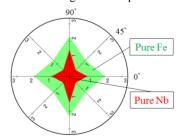

Figure 2: Plastic strain ratio, r , in different directions.

NEW PRESS DRAWING OF HOM CUP

One of points for the realization of a single process ultra-deep drawing is to strengthen the weak position of cylindrical body

because pure Nb sheet is so mild but lacks strength in the vicinity of punch shoulder. In this regard, critical fracture true stress σ_{cr} around punch shoulder where severe plane strain deformation is imposed, is significant and formulated applying mechanics of plasticity as shown below,

$$\sigma_{cr} = \left(\frac{2}{\sqrt{3}}\right)^{(1+n)} \cdot \left\{\frac{(1+\bar{r})/2}{\sqrt{(1+\bar{r})/3}}\right\}^{(1+n)} \cdot \sigma_u \cdot \frac{t_0}{t} \qquad (7)$$

where σ_u is true ultimate stress, and t_0 and t are thickness before and after drawing. It is found that a diagram between σ_{cr} and $\bar{r}$ shows a large positive effect of $\bar{r}$ upon σ_{cr} ; n has smaller positive influence. Therefore, it is easily speculated that pure Nb is poor at press drawing due to small σ_u, λ_u, n, $\bar{r}$, Δr as well as ζ .

Then the following forming methods have been tried in R&D works so far : 1) full machining ; 2) backward-extrusion + machining + recrystallization annealing ; 3) multi-processes press forming + intermediate annealing ; 4) others (pipe drawing + cutting + welding ; fine blanking + polishing, etc.). Any method has problems concerning preparation of tools, mass-production and cost performance to be hardly sorted out.

The authors have originated a newly creative single process press drawing without either heat treatment or machining. The essential points are : a) the temperature distribution control of the material sheet through tools to expect the rise of σ_{cr} ; b) the velocity control by servo-system to lower deformation resistance on the flange ; c) use of non-circular anisotropic blank ; d) use of newly developed solid state lubrication.

Figure 3 is a schematic illustration relating to the above ideas of a) and b) where the expression is made by three zones for understanding of a drastic improvement in drawability (LDR) (supposing isotropic material and circle blank [7]). Non-circular anisotropic blank (c)) is shown in Fig. 4 where the blank is calculated by observed r values in multiple directions followed by the data approximation using three dimensional spline procedure, then the following hypothetical power equation to derive D_Θ (diameter at angle θ from rolling direction) is employed with correction term R in case of BCC polycrystalline structure,

$$D_\Theta = R \cdot D_0 \left(r_{45} / r_\Theta \right)^J \qquad (8)$$

$$R = 1.0 + \{ (R_0 - 1.0) / 45 \} \cdot |\theta - 45| = f(\zeta) \qquad (9)$$

where D_0 is a diameter of circle blank, namely equivalent to a diameter of direction $45°(= D_{45})$. R could be optimized by ζ [8].
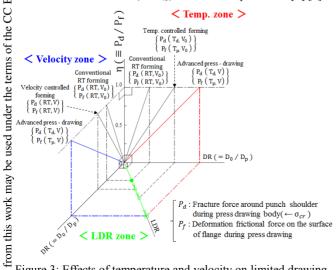

Figure 3: Effects of temperature and velocity on limited drawing ratio, LDR, based on isotropic materials.
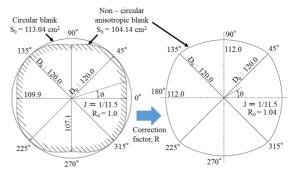

Figure 4: Example of non-circular anisotropic blank obtained from equations (8) and (9).

The overall results applying the advanced method are shown in Fig. 5. The differences among conventional drawing (using circular blank ; RT) , advanced drawing (with circular blank) and advanced drawing (with non-circular blank) are obviously seen in the light of drawn-through height and earing. The delayed fracture at lower earing position can be perfectly avoided by the advanced method with non-circular blank because of much less concentration of residual stress there [9].

In addition, the secondary forming of protrusion on the flat bottom and off-center perforation followed by burring after deep drawing are markedly available without heat treatment. This suggests the presence of enough margin for further deformation even after ultra-deep drawing due to rather uniform micro-deformation, stress-strain status and proper crystal-rotation [10].

Still there is an issue at the current R&D works of HOM cup press drawing. It is the seizure occasionally taken place during the restriking process after extremely deep drawing to obtain accurate shape and size fixation consistent with the design. The solution is expected in ongoing research works.
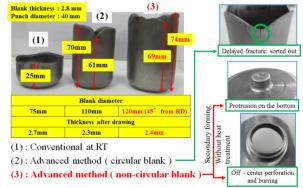

(1) : Conventional at RT
(2) : Advanced method (circular blank)
(3) : Advanced method (non-circular blank)

Figure 5: Overall results applying the advanced press drawing methods to HOM cup.
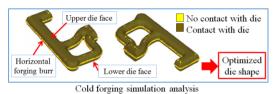
TRIAL FORMING OF HOM ANTENNA

The current manufacturing of HOM antenna is conducted by full machining. It takes time (ten hours or so per piece) to cause serious problems of productivity and cost. We tentatively tried a new method by separating the process to two stages for near net shape (NNS) semi-products and the final fabrication [11].

Alternative production method replacing full machining has been studied according to the above idea : as the first step, water jet (WJ) cutting was applied to manufacture NNS semi-products of HOM antenna, then as the second step, sheet cold forging was given to make the product almost equivalent to the designed component which is completed by subjecting to just the final machining.

Figure 6 shows the view of the WJ machine and cold forging tool used. The latter was made on the basis of sheet forging simulation using compression test data whose results are depicted in the figure, and was optimized specially in the way of the extent of contact between NNS and the forging tool, and also the generation of horizontal burr. Shown in Fig. 7 are a NNS and a cold forged products. The trial method is apparently available for mass-production because WJ can enjoy far short time handling, probably one tenth for instance, compared with machining. The same thing can be said in the cold forging. The innovation brings about much reduction in production cost.

We can see, however, a couple of defects associated with the experimentally advanced method [12]. First, small oxide particles which are necessary for WJ cutting remain as foreign objects on the surface of NNS semi-product, partly being penetrated from the surface. Basically this might be not desired to obtain satisfied acceleration voltage with SRF cavity.

Second, the necking on the surface of the product during sheet cold forging is found with small probability. As it is generally speculated that the remarkably smooth surface of HOM coupler should be prepared even by applying buffered chemical polishing (BCP) and electrolytic polishing (EP), necking as well as the presence of oxide particles on the material surface shall be fundamentally avoided. That is why further R&D is still ongoing to realize more innovative press stamping followed by new sheet forging [13][14].

Figure 6: New method of water jet cutting for near net shape product and cold forging after simulation for final product.
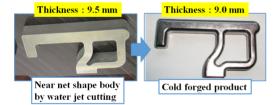

Figure 7: View of near net shape and cold forged products.

VERTICAL TEST OF HOM COUPLER

Both HOM cup and antenna produced at SPS were subjected to EBW to be HOM coupler, then attached to both ends of KEK#01 type 9-cell cavity at KEK. The cavity was cooled down to 2K for subjecting to the vertical test to obtain the experimental data of, mainly the relation between Q_0 and E_{acc} (Fig. 8). The test results judging from the correlation are revealed to be as follows (the details were reported in the proceedings of IPAC 2014 [15]):

Initial rise: 37.0 MV / m when $Q_o = 6.0 \times 10^9$ (10 - 1)
Final rise: 35.9 MV / m when $Q_o = 6.1 \times 10^9$ (10 - 2)

The value of the final rise experimentally obtained here satisfactorily exceeds the qualified value recommended by the ILC organization, meaning possible attainment of field gradient required when fundamentally press formed HOM couplers are used for 9-cell cavity. Further, it should be carried out that the probability of successful yield and applied cases of the whole press forming production methods are to be studied more in the ongoing R&D works [16][17].
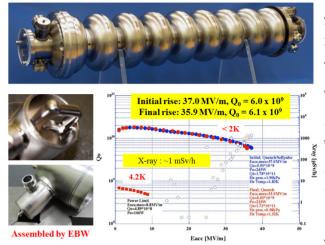

Figure 8: Vertical test results at 2K (Q_0 v.s. E_{acc}) on assembled 9-cell cavity using HOM couplers prepared by the advanced deep drawn-through cup and water jet cutting followed by cold forging of antenna to satisfy the qualified value.

CONCLUSION

(1) Material properties of pure Nb were displayed to be hard workable as a result of uni-axial tensile test and the measurement of plastic strain ratio, r, closely related to press drawability . We have proposed a new parameter, ζ, that depends on drawability and anisotropy of the material.

(2) An advanced press drawing method (a single process without dominant machining and intermediate heat treatment) for HOM cup has been invented in consideration of the comprehension of temperature distribution control through tools, velocity control on servo system, and application of non-circular anisotropic blank obtained from the actual observation of strain ratio followed by spline approximation plus calculation using hypothetical power formulation.

(3) An innovative production method of HOM antenna has been carried out by a couple of processes of near net shape (NNS) semi-products using water jet cutting first, then cold forging of the NNS to manufacture the final product based on the forging simulation including pure Nb compression testing data.

(4) HOM cups and antennas produced by the above new methods were assembled, then installed to KEK#01 cavity to subject to vertical test. Acceleration voltage indicated 35.9 MV/m at Q_o of 6.1×10^9 that satisfies the requirement.

(5) Further R&D work is still ongoing in order to improve and sort out adhesion / abrasion / seizure at ristriking etc. in the method described in (2), and also to convert the method (3) to the whole press forming by innovating a new press-stamping of the NNS and a newly improved forging metods. Resultantly, mass-productivity and cost-effectiveness could be favorably materialized.

REFERENCES

[1] A. Yamamoto, "Technical Developments in Japan for preparing the International Linear Collider", AWLC14, Fermilab, Batavia, USA, (2014).

[2] H. Hayano, "Progress of High Gradient Performance in STF 9-cell Cavities at KEK", WEPPC013, IPAC'12, New Orleans, USA, (2012).

[3] S. Kohda, "Metallurgical Physics", Corona Publishing Co. Ltd., (1967).

[4] Japan Institute of Metals, "Lattice Defects and Mechanical Properties of Metals", Maruzen Company, Ltd., (1967).

[5] K. Nohara et al., Proc. of the First International Conference on New Manufacturing Technology, "Warm Press Forming of Stainless Steel", Chiba, Japan, (1990).

[6] Kawasaki Steel Corporation (now, JFE Steel), Patent Document, JP2003-088922.

[7] K. Nohara et al., International Symposium of SAMPE, "Dependence of Forming Temperature upon Press Drawability", Tokyo, Japan, (1997).

[8] SPS and KEK, Patent Document WO2013/115401 A9.

[9] K. Nohara et al., "Basic and following Experimental Studies on Advanced Press Forming of End Group Components with pure Nb Material of rolled sheets for Superconducting Accelerator Cavity", Proc. of the 14th KEK Mechanical Engineering Workshop, P.81, Tsukuba, Japan, (2013).

[10] K. Nohara et al., "R&D of advanced fabrication method for HOM coupler", TTCmeeting, Tsukuba, Japan, (2014).

[11] N. Kawabata et al., "Research and Development Work on New Fabrication Process of End-group Component with pure Nb of Rolled Plate for Superconducting Accelerator Cavity: 'Advanced Press Forming Method' ", Proc. of the 15th KEK Mechanical Engineering Workshop, P.64, Tsukuba, Japan, (2014).

[12] K. Nohara et al., "Studies on material properties regarding plastic deformation of niobium product for superconducting accelerator cavity", The 15th KEK Mechanical Engineering Workshop, Tsukuba, Japan, (2015), to be published.

[13] K. Hanaki et al., "Speed Effects in Deep Drawing", ISIJ International, 9 (1987), P.761.

[14] A. Ujihara, "Forming of Automobile Panels by the Control of Blank Holding Force", Technology of Plasticity, 33 P.373, (1992).

[15] T. Saeki et al., "Studies of Fabrication Procedure of 9-cell SRF Cavity for ILC Mass-production at KEK", WEPRI025, IPAC'14, Dresden, Germany, (2014).

[16] M. Yamanaka, "Production of evaluation of Nb sliced from the ingot", The second SRF Material Symposium, Tsukuba, Japan, (2015), to be published.

[17] S. Kato, "Electron excited X-ray spectroscopical analysis and Electron backscatter diffraction process", The second SRF Material Symposium, Tsukuba, Japan, (2015), to be published.