ELIMINATING A MAJOR CAUSE OF WIRE DRAWING BREAKAGE IN A-15 HIGH-FIELD SUPERCONDUCTORS

Final Report

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N O T I C E

Eliminating a Major Cause of Wire Drawing Breakage in A-15 High-Field Superconductors

Phase 1 Summary

Purpose of the research:

The Phase 1 goal was to make a significant improvement in the wire drawing technology used for difficult to draw superconductor precursor composites. Many ductile Nb-Al and Nb-Sn precursor wire composites have experienced the onset of wire drawing breakage at about 1.5 mm diameter. Phase 1 focused on evaluating the role that precision rigid guidance of the wire into the drawing die and the hydrostatic stress state at the die entrance played in preventing wire breakage.

Research carried out:

The research performed depended upon the construction of both a mechanical wire guide and a hydrostatic pressure stiffened wire guidance system. Innovare constructed the two wire guidance systems and tested them for their ability to reduce wire drawing breakage. One set of hardware provided rigid alignment of the wires to their wire drawing die axes within 0.35 degrees using “hydrostatic pressure stiffening” to enable the precision guidance strategy to be implemented for these highly flexible small diameter wires. This apparatus was compared to a guide arrangement that used short span mechanical guide alignment with a misalignment limit of about 0.75 degrees. Four A-15 composite wires with breakage histories were drawn to evaluate the use of these wire guiding systems to reduce and/or eliminate wire breakage.

Research findings and results:

In Phase 1, a breakthrough in wire drawing technology for A-15 superconductor composites was achieved by dramatically limiting or eliminating breakage in four different A-15 composite precursor wire designs during the drawing of these very desirable composites that previously could not be drawn to near final size. Research results showed that the proposed Phase 1 mechanical wire guides were sufficiently effective and successful in eliminating breakage when used along with other advanced wire drawing technology to justify the development of an integrated compact production type Advanced Wire Drawing Station. New insights into the formation and growth of a shear type defect that causes breakage lead to improved drawing technology and it will be the basis for further study and improvements included in a Phase 2 proposal.

Potential application of the research:

This new capability now justifies the development of an integrated compact production type Advanced Wire Drawing Station to replace the bulky, slower and research oriented equipment that currently uses four independent operations for each wire diameter reduction. In a Phase 2 proposal, the designs for each operation were to be optimized for their performance and so they could be used to integrate these individual operations into an Advanced Wire Drawing Station. This station will perform all the mechanical conditioning, cleaning, lubrication, guidance and drawing operations simultaneously and it will be tested to verify wire drawing performance targets. A portable Advanced Wire Drawing Station will be developed and constructed in the final stage of the proposed Phase 2 program and it will be used in an outside manufacturing facility for superconductor composite wire drawing field trials.

DEMONSTRATED ACHIEVEMENTS

A breakthrough in wire drawing technology for A-15 superconductor composites was achieved by dramatically limiting or eliminating breakage in four different A-15 composite wire designs during the drawing of these very desirable composites that previously could not be drawn to near final size. Research showed that the Phase 1 proposed mechanical wire guides were effective when used along with other advanced wire drawing technology. This new capability now justifies the development of an integrated compact production type Advanced Wire Drawing Station to replace the bulky, slower and research oriented equipment that currently uses four independent operations for each wire diameter reduction.

PHASE 1 PROPOSAL BACKGROUND

Problem

Statement of the Problem addressed in Phase 1:
Many ductile Nb-Al and Nb-Sn precursor wire composites have experienced the onset of wire drawing breakage at about 1.5 mm diameter. Wire drawing breakage at sizes under 1.5 mm diameter in A-15 superconductor precursor composite wire occurs frequently and results in low product yields because typically purchase orders specify multiples of kilometers in 0.6 to 0.8 mm diameter wire. This breakage results in significantly higher costs and at times prevents the successful drawing of experimental superconductor composites with desirable new designs into usable lengths for testing.

Detailed examination of some breaks showed that they resulted from the wire entering the die at an angle to the die axis. This misalignment resulted in the elongation deformation concentrated on one side of the wire that induced a tensile stress on the other side that combined with the drawing force to cause the fracture. In many cases, it was observed that the non-uniform thickness of the processing shell shifted the drawing deformation to favor the softer side of the wire and caused this misalignment. Processing shell wall thickness variations frequently occur in composites made by inserting a bundle of composite sub-elements into a round bore copper or copper alloy tube.

Analysis of the Problem:
The factors that contribute to the onset of this behavior at smaller diameters are:

- The primary factor causing this problem appears to be the wire's tendency to draw unevenly coupled with a high bending flexibility that dramatically increases as the diameter decreases and reduces the ability to mechanically guide the wire to be aligned with the die centerline axis.
- The strength differential between the faster work hardening composite core and the softer processing shell increases as the wire is reduced and thus increasing potential misalignment forces.

- The observed residual compression stress in the shell and tensile stress in the core are intensified with increasing reduction and work hardening that increases the chance of a composite core tensile failure.
- The flow strength, a measure of the resistance to drawing reduction deformation, grows more rapidly than the tensile strength of the composite wire. This condition increases the potential for a tensile failure caused by the wire drawing tension.

Solution Difficulties:
The state of the art wire drawing technology approach would be to use high back tension to straighten the wire and align it with the die. However, high back tension would add to the drawing stress that is limited by its lower tensile strength. In another approach, the use of mechanical guidance becomes very difficult to implement since the mechanical wire guide would have to be moved very close to the die due to the increasing wire bend flexibility. This configuration in turn would require unusually tight tolerances on the precision and accuracy of positioning of the mechanical guide.

Background

It has been repeatedly observed that reasonably ductile Nb-Al and Nb-Sn precursor composites have experienced the onset of wire drawing breakage at about 1.5 mm in diameter. Close examination of the fractures often showed that the breaks resulted from the wire entering the die at an angle with the die axis. This misalignment resulted in the elongation deformation taking place on one side producing a compression stress that induced a tensile stress on the other side. This tensile stress combined with the drawing force stress to cause a fracture that was always observed to be initiated on the low reduction side.

This type of fracture has been observed at much larger diameter when they were drawn on a draw bench with no mechanical guidance of the rod or wire to align it with the die axis. Typically the drawn products from a draw bench operation are curved which indicates non-uniform deformation. In the case of restack composites, straightening the rod between passes reduced breakage.

It has been observed that the non-uniform thickness of the processing shell shifts the drawing deformation to favor the softer side of the wire causing this type of misalignment. Processing shell wall thickness variations frequently occur in composites made by inserting a hexagonal bundle of composite sub-elements into a round bore copper or copper alloy tube.

Observations

The following figures illustrate the development of the misalignment in a NbTi/Nb-Sn composite wire to the drawing die axis which resulted in wire breakage.


Figure 1(a). Magnification: 6X

In Figure 1(a)&(b)., to the left, the 0.072” diameter wire was entering the die from the left so the product [which broke about 0.5” from the die] was being pulled in alignment with the die axis and the unguided wire entered the die at an angle to the die axis. The wire drawing was done at Outokumpu.


Figure 1(b). Magnification: 3X

To the right, Figure 2., is the transverse section of this composite which after close examination revealed that the right side of the relatively soft copper processing shell was about 14% thicker than the left side.

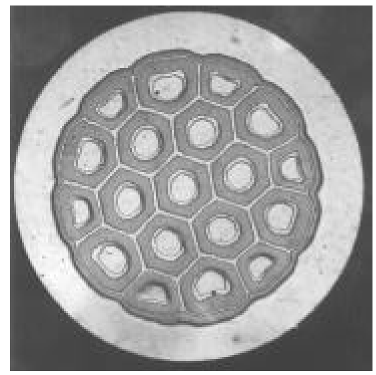


Figure 2.

This same NbTi/Nb-Sn composite wire shown above was drawn down to 0.04” diameter using an alignment guide 3” from the die. Again the wire enters the die from the left and in spite of the guide, the wire was flexible enough to develop a misalignment to the die axis which is horizontal in the picture and was in line with the pulling force. However, after breaking past the die, the drawn product curved due to the residual stress pattern resulting from the non-uniform deformation. The wire drawing was done at Innovare.

The next example illustrated the development of angular misalignment in a Nb-Al jellyroll composite made by a double “six-around-one” restack to produce a 49 jellyroll sub-element composite.

In the Figure 3. photograph below, the 0.81” diameter wire approached the die from the left at about a 6 degree angle with the die axis and exited the die on the pulling force axis. It broke shortly after leaving the die with the fracture initiation site on the side opposite the high reduction side. The wire was drawn at Otokumpu without a guide.

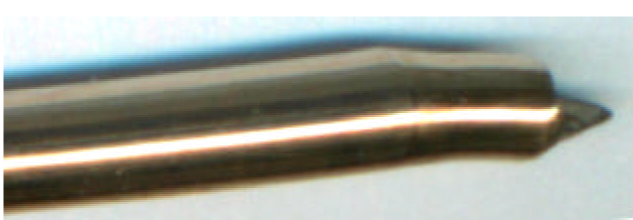


Figure 3. Magnification: 8X

The transverse section, Figure 4., to the right again shows the non uniform shell thickness [thicker on right side] which is responsible for the unguided wire developing an angled approach to the drawing die.

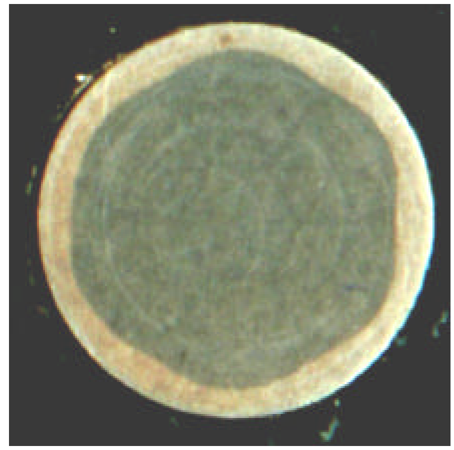


Figure 4.

Development of the Misalignment Fracture

For the case where the composite wire has a non-symmetrical feature such as a side to side cladding shell wall thickness variation, how that feature leads to a misalignment fracture offers an important insight.

An experiment was performed using the previously discussed NbTi/Nb-Sn, 19 sub-element composite wire to provide that insight. In the photograph below, Figure 5., a 0.0476” diameter wire was drawn from left to right through a 0.0446 die with a 7.5 degree semi-cone angle. A wire guide [not shown] had been placed about 9” to the left of the 1” O.D. die which guided the wire to approach the die along its axis. However, the guide did not rigidly align the wire’s approach angle to the die due to its distance from the die and the wire’s flexibility. After the first 6” of wire was drawn, the wire was still entering the die with only a slight misalignment of perhaps 1 degree. However after drawing a total of 18” of wire, the misalignment had increased to 7.5 degrees as shown in the previous photograph. Also,

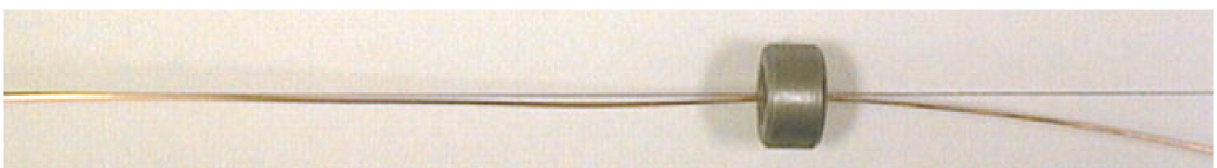


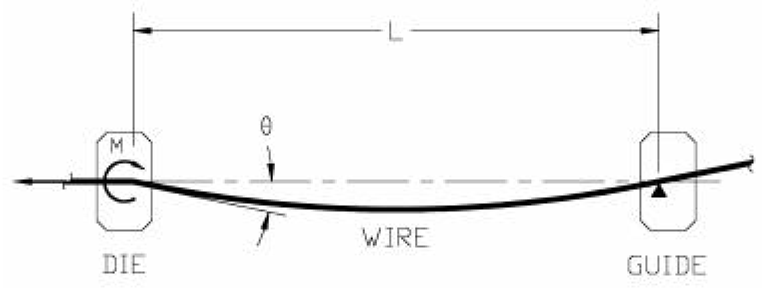
Figure 5.

when the drawing force was released, the wire bowed to indicate the residual stress that had developed from this misalignment. If the guide were placed much closer to the die, it would have more influence in reducing the misalignment. However, how much closer and how will wire diameter and flexibility control that distance? That question will be addressed next.

Wire guidance as a function of size

Since guiding the rods and large diameter wires to stay in line with their die axes was demonstrated to work, it made sense to continue that approach at smaller diameters. As a standard practice, Innovare used a guide in the form of a die that was one drawing size larger than the wire. A holder positioned it on the drawing die axis 3” or 9” before the drawing die depending on the wire diameter. As the wire got smaller the guide die was moved closer to the drawing die.

However, in some cases, as the wire diameter reached the 1 to 1.5 mm diameter range, misalignment breakage started. As we discovered, in those cases where breakage started, the cladding shell was usually non-uniform and was inducing a misalignment. If the wire was being guided to resist this misalignment, then the non-uniform flow had to produce a bending moment at the die to flex the wire between the die and the guide. This behavior can be described using a standard hand book formula for beam deflection with a bending moment applied to one end of the beam as shown below.



M = Bending moment applied to the wire at the die due to non uniform flow through the die.
θ = Angle of approach of the wire to the die
L = Distance between the guide and the die
$\theta = 1/3\ (ML / EI)$ where "E" is the elastic modulus and " I " is wire section moment of inertia such that $I = \frac{1}{4} \pi R^4$ and R = wire radius.

It can also be reasoned that the bending moment at the die will be a function of the non uniformity of the composite and the diameter of the composite so, M = k R where k is some constant that represents the non uniformity of the wire. So,

$\theta = 1/3\ [\,kRL / E\ (\frac{1}{4} \pi R^4)\,]$ By combining the constants for a given wire into K,

$\theta = K\ (L / R^3)$

A composite can tolerate some misalignment without developing stresses that break the wire. We will define the misalignment angle which causes occasional breaks as the Critical Angle, θ_C. To illustrate the use of θ_C in understanding guidance requirements, take the case where breakage just starts to occur at 1.6 mm diameter with a 3" die to guide distance. This information can be used to calculate $\theta_C / K = 91{,}552$. Now, using this information, one can calculate the maximum die to guide distance, L for a 0.8 mm diameter wire such that, $\theta_C / K = 91{,}552 = L / R^3$. Solving for L with R = 0.4 mm or 0.016", L = 0.375".

Aside from being physically difficult, bringing the guide this close (0.375") to the die will require precision axial alignment of the die and guide which may not be possible considering the clearance of the die to the guide and the commercial tolerances of the dies used for the drawing and the guide.

The values of θ_C and K will be different for each composite and may even vary from composite batch to batch or along the length of the wire. The above set of parameters used for illustration may be more severe than most, but it illustrates the sensitivity of wire guidance to changes in wire size.

Other Contributors to Misalignment and Breakage:

Adverse Residual Stress Pattern, [ARSP]: After extensive drawing, both sides of a composite rod were filed away to allow its components to relax and indicate their residual stress state by their differential movement. The outer casing elongated showing it was in compression and the Nb-Al core elements contracted indicating that they were in tension. We know that the ARSP builds with increased wire drawing because they can be reversed with hydrostatic extrusion that allows additional drawing before the ARSP starts to cause wire breaking after it builds up again. The strength differential between the faster work hardening composite core and the softer processing shell increases as the wire is reduced. The observed residual compression stress in the shell and tensile stress in the core stress are intensified with increasing reduction and work hardening.

Reduced transverse shear strength: It is the common experience that increasing the number of sub-elements reduces the ability to draw a composite. It is generally accepted that weak bonding between the sub-elements of the composite cause defects which lead to breakage. In the case of misalignment, weak bonding between the sub-elements reduces the transmission of deformation via shear stress from the high reduction side to elongate the low reduction side which intensifies side to side axial stress differences.

The flow strength, that is a measure of the resistance to die reduction deformation in the die, grows more rapidly than the tested tensile strength of the composite wire increasing the potential for a tensile failure caused by the wire drawing stress.

In summary: Of the aforementioned factors that help cause breakage and contribute to the misalignment condition in the under 1.5 mm diameter wire, guidance stands out as the one effective method for eliminating the problem at larger sizes. Therefore, it was logical to develop a new method for adapting this approach to the smaller sizes.

Overall Technical Approach

The approach to wire misalignment was to provide effective alignment of the small diameter, highly flexible wire to the die axis. Two different methods were tested and their effectiveness compared.

Method 1 – Short Span Mechanical Guide

In this design, the mechanical guide is brought as close as practically possible, about 0.5”, to the die deformation zone by stacking a guide die against the drawing die shown schematically in Figure 6. In this approach, the short guidance span compensated for the lack of wire stiffness.

Commercial drawing dies were used and they were modified to align the die cone axis within 0.25 degrees of perpendicular to the support surface and concentric with the casing outside diameter to 0.001 TIR. Using reasonable tolerances for the assembly clearances, it was estimated that the maximum misalignment of the wire to the die axis would be 0.75 degrees. It was possible that this approach would not provide the alignment precision that was sufficient for the most sensitive composites. Thus, an alignment method with greater precision and an added benefit of imposing a higher hydrostatic stress in the wire at the die entrance was also tested.

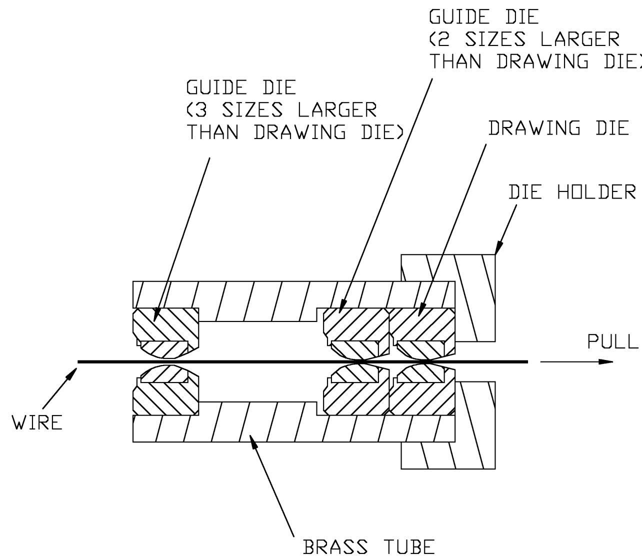
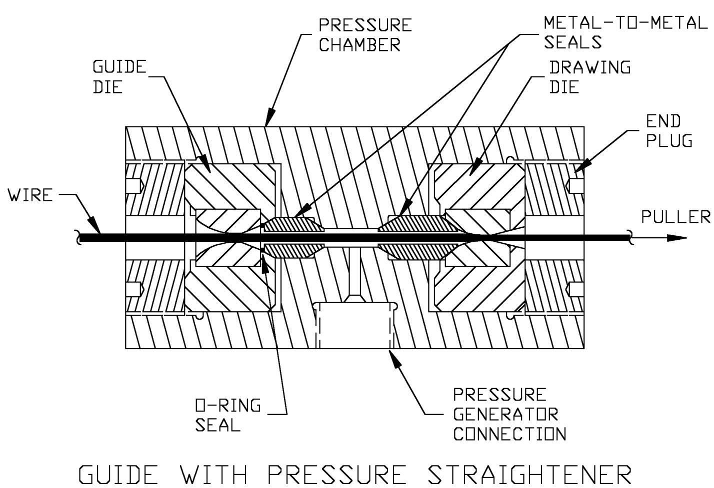


Figure 6.

Hydrostatic Pressure Stiffened Wire Guide:

In the short span guidance approach, two thirds of the allowable misalignment limit are due to the short span in combination with the component clearances. Therefore, if the wire can be sufficiently stiffened, a longer span can be used to improve the calculated maximum misalignment limit from 0.75 degrees to 0.35 degrees. To achieve this reduced misalignment, Innovare used the “hydrostatic pressure stiffening” concept to hold the wire straight by applying high fluid pressure [up to 50,000 psi] to the wire between the die and guide. This pressurization was achieved using a small bore pressure chamber that is sealed against the drawing die and guide as shown schematically in Figure 7.



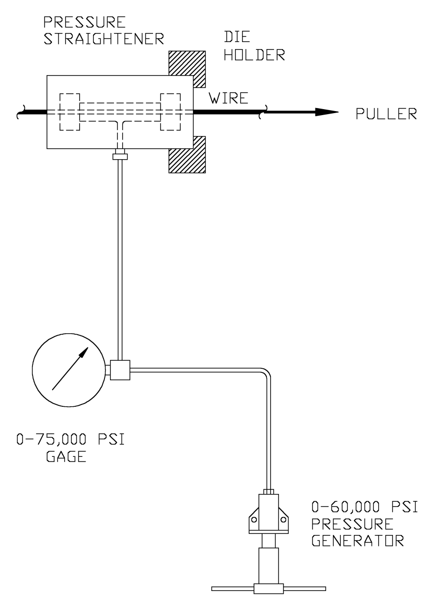


Figure 7.

The stress state in the wire was identical to that in a tensile test specimen surrounded by pressurized fluid such that the applied axial tensile stress is equal to the environmental pressure. The wire was put into in this stress state so it will be “pulled” straight [“hydrostatic pressure stiffened”] within the pressurized channel connecting the guide [sealed against leakage] and the drawing die. The only addition to the wire drawing stress at the die exit was contributed by the guide seal friction drag which may be more than compensated for by the lowering of the drawing stress due to improved drawing die lubrication. Another major benefit was the high hydrostatic stress state of the wire in the die entrance similar to that in hydrostatic extrusion which mechanically enhanced composite component bonding and ductility.

Testing these approaches to improving the wire’s alignment to the drawing die axis for composites that have shown a history of breakage below 1.5 mm demonstrated the importance of adding this processing feature to production facilities.

<u>Technical Objectives from Phase 1 proposal</u>

1) Demonstrate, for A-15 precursor composite wires below 1.5 mm in diameter, that rigid alignment of the wires to their wire drawing die axes within 0.35 degrees will dramatically reduce wire breakage and that “hydrostatic pressure stiffening” enables the precision guidance strategy to be implemented for these highly flexible small diameter wires.

2) Compare the wire drawing breakage results from the precision, 0.35 degrees misalignment limit attained using “hydrostatic pressure stiffening” to those obtained using short span mechanical guide alignment with a misalignment limit of about 0.75 degrees.

3) Determine if using the “hydrostatic pressure stiffening” concept adds a pseudo hydrostatic extrusion process benefit from the high fluid pressure at the die entrance.

The feasibility of the commercialization of this technology to substantially reducing wire drawing breakage in superconductor precursor composite wire below 1.5 mm diameter will depend upon meeting these objectives. If success is demonstrated, this technology will represent a breakthrough in understanding. The continuing development in Phase 2 will depend on engineering implementation of the wire alignment process and it will not be impeded by the need to overcome technological barriers or for large capital investments.

PHASE 1 PERFORMANCE

Purpose of Phase 1

The Phase 1 goal was to make a significant improvement in the wire drawing technology used for difficult to draw superconductor precursor composites. Phase 1 focused on the role that precision rigid guidance of the wire into the drawing die and the hydrostatic stress state at the die entrance played in preventing wire breakage. However, other techniques and process features developed earlier were used to create the best practices available.

Research Performed

Fulfilling the three previously stated Technical Objectives depended upon the construction of both a mechanical wire guide and a hydrostatic pressure stiffened guidance system. Innovare constructed the two wire guidance systems described in the proposal and tested them for their ability to reduce wire drawing breakage.

The details of the guides, their features and how they were to be used was given in the Phase 1 proposal background. However, schematic drawings of the two guides are shown below in Figures 6. and 7. in that section.

Since both systems use the same die set, a housing was designed with special components such that it could be used for both guide systems. It was mounted on top of the exit side platen of Innovare's hydrostatic extrusion press as shown in Figure 8. Figure 9. shows how the hydrostatic extrusion unit's product puller wheel was used as the puller for wire drawing. This puller is computer controlled and the wire tension was measured by a load cell in the wheel support system.

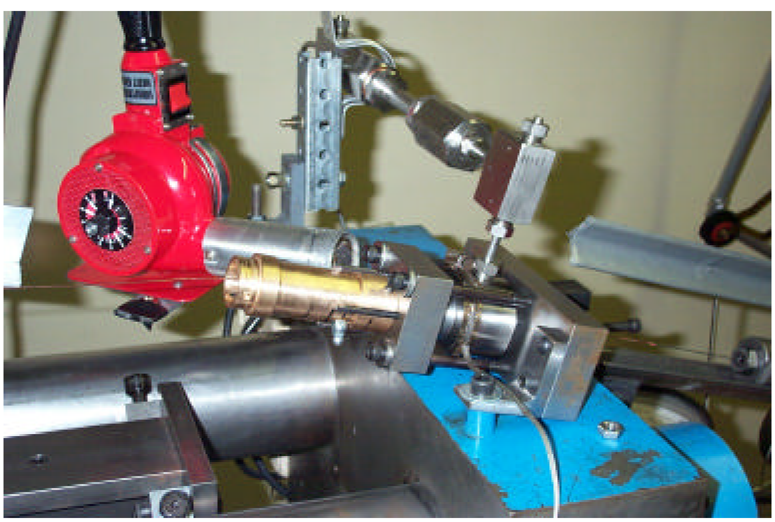


Figure 8.

Figure 9.

In Figure 9., the steel cylinder with block end closures holds the drawing die and guide dies while the brass cylinder in the wire inlet side houses the lubricant application system. When high pressure stiffening is used, pressurized lubricant enters through the fitting at the top of the wire guidance unit.

Innovare tested a number of commercial lubricants and determined that our proprietary paste lubricant performed best and we worked out handling methods for using it. The pressurizing hydraulic pump oil was separated from the paste lubricant with a floating piston inside the 4.77 mm bore of a cylinder. Also, we observed that the viscous drag of the pressurized paste lubricant was significant, due to an 80% increase in the drawing force with 50,000 psi lubricant pressure and ambient temperature. Heating the lube a modest 25C was sufficient to eliminate the pressure related viscous drag effect.

The pressure for the high pressure straightening guide was generated by a hand operated pressure generator mounted on the press platen as shown in the photograph, Figure 10. The schematic drawing, Figure 11., shows the basic components of the system. The system worked well in the 24 trials that were made with high pressure straightening.

Figure 10.

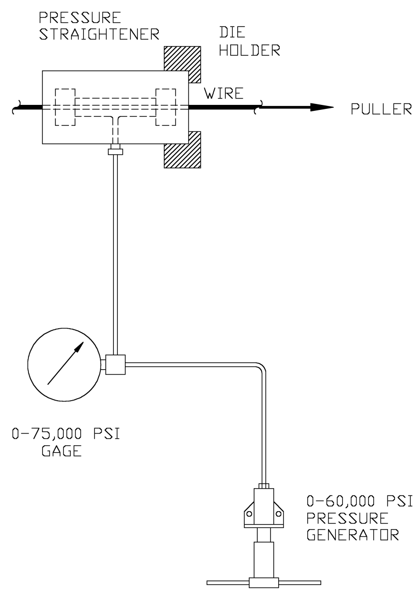


Figure 11.

Research Performed – Defect formation Study:

Typically, the defects that form and lead to breakage became evident due to external “necking” of the wire up to several drawing passes before breakage occurred and this pattern is present for the Nb/Sn composite wires that were evaluated in Phase 1. The typical cup and cone fractures suggested a tensile failure and the strong possibility that they were initiated by center burst. However, the observations made on this defect formation and growth pattern showed it to be very different in nature. It starts as a small shear crack at the outer surface of the core composite and grows progressively.

This defect study research effort was not identified as a task in the Phase 1 proposal, but as the Phase 1 work progressed, the recurrent appearance of this defect formation pattern made it important to study. The schematic drawing below, Figure 12., illustrates the observed defect formation and growth pattern that was studied by polishing open the wires at the locations where the telltale surface indentations had appeared.

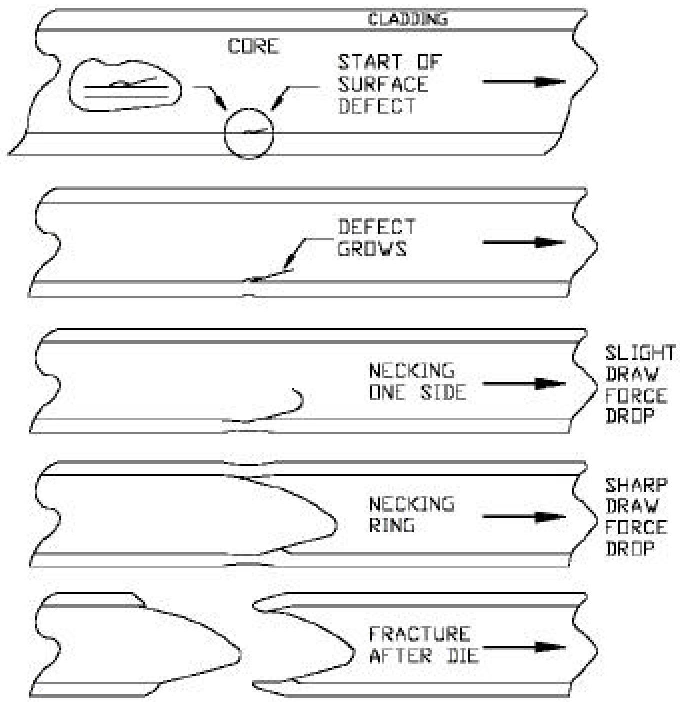


Figure 12.

- **The defect starts as a shear crack in an outer filament.**
- **The defect grows through several successive drawing reductions.**
- **When the defect reaches an intermediate size, external "necking" appears on the wire.**
- **When necking appears, there is a dip in the drawing force at the defect location.**
- **The wire fracture at the defect appears to be cup and cone.**

Other common features associated with this defect formation were:

- Defect formation typically starts at between 1.5 to 2 mm dia.
- There is a general trend such that defects start at larger diameters with more filaments.
- After the initial defect formation occurs, the distance between new forming defects reduces as the wire diameter reduces with additional drawing reduction.
- The onset of this defect formation can been eliminated by using hydrostatic extrusion.
- Innovare's most highly developed Advanced Wire Drawing Technology, (AWDT), that combines deformation geometry control, friction management and wire preconditioning substantially delays and now in most cases eliminates wire breaking defects.

- The occurrence of this defect was usually observed in conjunction with a high residual tensile stress in the core and compressive stress in the copper shell.

CONCLUSIONS

1) The defects that are the major cause of A-15 superconductor composite wire breakage start as shear failures on the outer surfaces of the core elements on one side of the wires.

2) Defect formation appears to be the result of a specific deformation mechanism that has not yet been analytically modeled and explained in terms of composite structure, residual stress patterns, drawing stress patterns and drawing parameters.

Research Performed – Residual Stress Patterns

As described in the Phase 1 proposal, the study of residual stress patterns continued as a noteworthy research activity and it became instrumental in gaining insights that lead to substantial improvements in Innovare's wire drawing capabilities. Well prior to this Phase 1 program, Innovare was aware of the existance of this adverse residual stress pattern that developed in superconductor precursor composites and its deleterious influence. Therefore, these patterns were monitored as part of our drawing trials.

The method for measuring residual stress was simple. The length of a section of wire was measured very accurately and then the outer copper casing was etched off. The change in length determined from the length of the unclad core provided the strain that was used to calculate the residual stress in the core assembly.

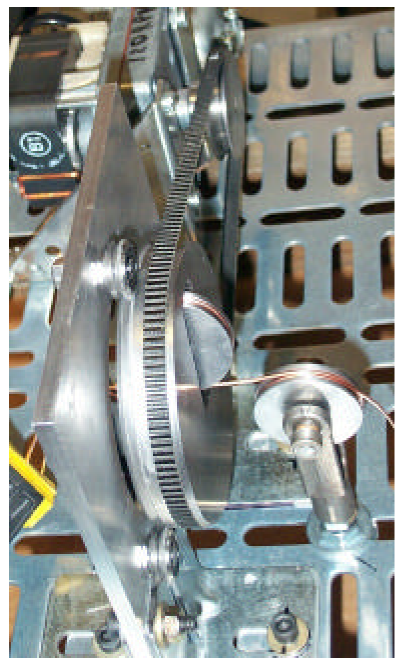


Figure13.

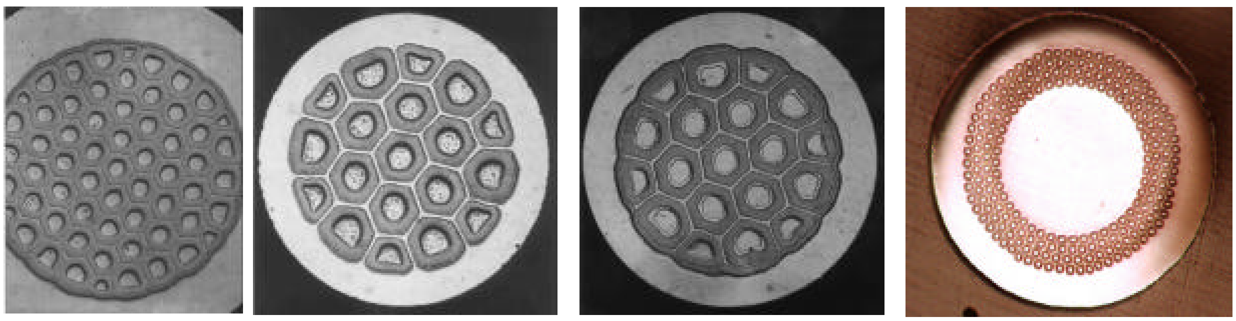
Dozens of determinations were performed and residual tensile stresses in the core assemblies of "as drawn" wires that developed defects typically ranged from 25 to 65 ksi in several different composites.

Various methods were evaluated for managing the residual stress pattern including torsional flexing of the wire using an apparatus [shown in Figure 13] that twisted and untwisted the wire as it passes through the apparatus. While this operation did reduce the residual stresses significantly, it had to be applied frequently since the residual stress pattern built up again during drawing. While it was effective in extending the drawing reductions before the onset of the defect formation, it wasn't sufficiently effective to warrant introducing it into Innovare's AWDT package. A combination of other process additions and modifications proved to be more effective and easier to implement.

Research Performed - Wire Drawing Advances

Selecting Composites for Phase 1 Trials

Innovare selected four A-15 superconductor precursor wire composites for the Phase 1 trials based on the demonstrated difficulty in drawing these wires. Also, composites with different structures as shown below were chosen to provide variations that broadened the investigation. They were also selected because of their significance as important superconductor design concepts.



(a) (b) (c) (d)

Figure 14.

(a) 61 Sub-element Nb-Sn Composite EP3-1-4* is a 61 sub-element restack Nb/Sn composite with a Nb barrier between the restacked elements and the outer copper shell.
(b) 19 Sub-element Nb-Sn Composite SP-1B1A1* is a 19 sub-element restack Nb/Sn composite with individual element barriers and no outer barrier.
(c) 19 Sub-element NbTi/Nb-Sn* Composite is a 19 sub-element restack composite wound with an outer barrier of Nb foil.
(d) 216 Nb/Al Jellyroll Sub-element is an Oxford Superconductor Technology composite
(*) Outokumpu identity

The difficulties in drawing these composites that was experienced by their manufacturers will be presented for comparison to Innovare's drawing performance.

Phase 1 Drawing Trials Results

The drawing trial results were performed in the following three stage:

Stage 1 – Draw the four program composites through the mechanical wire guide apparatus.

Stage 2 – Draw the program composites through the high hydrostatic pressure guides system for comparison to the results from stage 1

Stage 3 – Test improved drawing techniques resulting from the defect characterization and residual stress studies.

The Stage 3 drawing trials gave results that indicated we had a breakthrough in wire drawing capability. This exploratory drawing program was performed using the three difficult to draw Nb/Sn composites –(a) 19 Sub-element Individual Barrier; (b) 61 Sub-element Outer Barrier and (c) 19 Sub-element Outer Barrier NbTi/Nb-Sn.

The Stage 3 drawing trials started at the small diameter of 0.033" [0.838 mm] using a set of new dies down to the 0.023" [0.584 mm] size. This size range was chosen to provide a critical test because essentially we were not previously able to draw below this 0.033" diameter with our best technology without encountering frequent defects along the wire on the above composites.

In summary, results obtained using our most recent improvements demonstrated a breakthrough in wire drawing capability since we were able to draw the samples through multiple reductions without any defects or breaks from 0.838 mm to magnet wire sizes:

Composite Final Diameters and Sample Lengths from Stage 3 Trials

19 Sub-element Individual Barrier Nb/Sn, SP-1	0.670 mm dia. by 0.61 m long
61 Sub-element Outer Barrier Nb/Sn, EP3-1-4	**0.782 mm dia. by 0.51 m long**
19 Sub-element Outer Barrier NbTi/Nb-Sn	**0.584* mm dia. by 1.0 m long**
	(*) Innovare's Smallest Die Size

Essentially, the relatively short lengths resulted from: (1) the availability of wire samples at the 0.838 mm diameter from prior trials and (2) our decision to limit the scope of the new die set to a small range to minimize the investment in the initial exploratory effort.

Demonstrated Achievements with Phase 1 Technology

Prior to the recent breakthrough in drawing performance, the new technology introduced in Phase 1 was extensively tested in Stage 1. Innovare was able to demonstrate significant improvement in wire drawing performance using its Advanced Wire Drawing Technology that was enhanced with the precision wire guidance implemented in this Phase 1 development. To summarize this advancement, the wire drawing limits experienced by others is compared to Innovare's performance in the following table.

Table showing Innovare's AWDT improvement over other drawing attempts

Composite	Joint Comparison	Attempts by Others	Innovare Phase 1
Outokumpu Nb-Sn 61 Filament EP3-1-4	Size at 1st Break Excessive Breakage*	5.08 mm **2.03 mm**	1.15 mm **0.884 mm**
Outokumpu NbTi/Nb- Sn 19 Sub-element	Size at 1st Break Produced multiple barrel winding samples	1.83 mm **N/A**	1.15 mm **0.795 mm Test Samples**
Outokumpu SP-1 19 Sub-element w/ individual barriers and no outside barrier	Size at 1st Break Excessive Breakage*	6.35 mm **3.810mm**	2.057 mm **0.884 mm**
Oxford 216 Nb/Al jellyroll sub-element composite	Size at 1st Break Produced multiple barrel winding samples	3.98 mm **Failed Defects at 2.03 mm**	No breaks **No defects at 0.762 mm, 9.34 m**

(*****) Prevented drawing sufficient length for a barrel winding sample

High Hydrostatic Pressure Guidance System:

The high hydrostatic pressure precision guidance system was used in two dozen Stage 2 trials on the three Nb/Sn composite wires and did not show any advantage over the mechanical guidance system.

However, wire drawing with up to 50,000 psi fluid pressure on the entrance side of the die using the copper clad Mg2B mixed powder core and found no substantial change in density – that is, no more that a couple of percent at most.

We measured the density using the wire dimensions and weight which gave a resolution of about +/- 0.5% on overall density or perhaps up to +/- 1.5% on core density. We reduced the wire from 0.0404 to 0.0375 [1.16:1 total AR] in a few passes without any wire drawing breakage.

We also cut off nose and tail sections of ~12" that had been drawn with different pressures but found that we couldn't compare density changes accurately because the density along the wire varied by ~1.3% which represents about 4% in core material variation.

It was suspected that the flow strength of the mixture of Mg and B particles was well above 50,000 psi which would account for why we could not cause any increase in density.

How Well Were the Phase 1 Objectives Met?

The primary objective on the Phase 1 proposal was to demonstrate, for A-15 precursor composite wires below 1.5 mm in diameter, that rigid alignment of the wires to their wire drawing die axes would dramatically reduce wire breakage. This objective was met with overwhelming success as shown by the substantial improvement in wire drawing reduction presented in the above summary table. This success brought the wire drawing capabilities at Innovare to the brink of a breakthrough which was made using insights from other Phase 1 studies on defect initiation and growth plus residual stress patterns. The major Phase 1 achievement is that now Innovare has the technology to apply it's Advanced Wire Drawing Technology (AWDT) system commercially and has proposed that goal as part of this Phase 2 proposal.

Other technical objectives were aimed at determining if the use of the more complex hydrostatic pressure straightening in the wire guidance system would enhance performance due to potentially better guidance and/or the high hydrostatic stress state at the die entrance. Wire drawing trials were successfully made on the three Nb/Sn composites and none showed significantly enhanced drawing performance experienced with mechanical guidance when the hydrostatic pressure straightening was used.

THE PROPOSED PHASE 2 PROJECT

In Phase 2, first, the compact versions of hardware that perform the functions of the existing four individual process operations will be designed, built and operated to optimize their performances along with continuing efforts to further improve the wire drawing technology. Then the optimized performance designs will be used to integrate these individual operations into an Advanced Wire Drawing Station that will perform all the mechanical conditioning, cleaning, lubrication, guidance and drawing operations simultaneously and it will be tested to verify wire drawing performance targets. A portable Advanced Wire Drawing Station will be developed and constructed in the final stage of the Phase 2 program and it will be used in an outside manufacturing facility for superconductor composite wire drawing field trials.

Technical Objectives

The major Technical Objectives for the Phase 2 proposal were stated as:

1) Establish a complete, production type wire processing line to implement Innovare's unique Advanced Wire Drawing Technology to replace Innovare's bulky, slow and multiple operation R&D wire drawing capability and demonstrate its performance on A-15 composite wire under 1.5 mm diameter.

2) Continue to analyze the formation of shear defects that cause breakage with respect to: (a) relative core to casing strength; (b) residual stress patterns and (c)

processing parameters and use the insights to continue to make incremental performance improvements to Innovare's Advance Wire Drawing Technology.

3) Design, construct and test operate a portable Advanced Wire Drawing Technology Station at Innovare and then use it in demonstration wire drawing trials in a superconductor manufacturing facility.