Dr. Ralph Delmdahl and Dr. Alexander Usoskin

Superconductors for everyone

Extremely thin superconducting tapes can transfer more than 100-times the electrical current compared to conventional copper wiring in the same conductor cross-section — and without any losses. Cooling with liquid nitrogen is sufficient for this purpose. Now these wonder tapes can be produced for the first time on an industrial scale — with the laser.

The ceramic high-temperature superconductor (HTS), for which Georg Bednorz and Alexander Müller were awarded the Nobel Prize in 1987, immediately awakened the hope for a revolution in energy technology. Unlike the superconductors known up to that time, the HTS loses its resistance above the boiling temperature for nitrogen (-196C°), which means it becomes superconductive and permits loss-free conduction of electricity. Cooling using environmentally-friendly liquid nitrogen is feasible both from a technical as well as from a economic perspective. However, commercial use has not occurred because it proved to be extremely difficult to produce new ceramic coated conductors in suitable quantities with sufficient quality. The conductor's superconducting thin layer of only one-thousandth of a millimeter is made up of tiny crystals consisting of yttrium-barium-copper oxide ($YBa_2Cu_3O_x$ or YBCO, for short). To maintain the superconducting properties across the entire length of the conductor, the electrical current must overcome the boundaries from crystal to crystal as easily as possible. The conductivity along these so-called grain boundaries is highly dependent on the orientation of the crystals. To achieve the highest possible current-carrying capacity along the entire tape, the superconducting YBCO layer must have an almost perfect biaxial texture — just as if the superconductive YBCO in the conductor were made out of layers of identical Lego blocks.

Micrometer sandwich

The completed conductor is built like a sandwich. It consists of several functional layers that are applied in consecutive process stages. First, on a polished and cleaned 100-micrometer thick stainless steel tape, which is typically 5 millimeters wide and lends tensile strength and flexibility to the finished conductor, a 1.5 micrometer-thin texture made of yttrium-stabilized zircon (YSZ) is separated by means of patented ion beam deposition from the company HTS Bruker. An additional metal oxide layer (CeO_2) only 0.05 micrometers thin functions as the diffusion block between the YSZ texture and the quasi-monocrystalline superconducting YBCO substrate. Finally, the conductor with a thin stainless metal layer is protected against external influences and is coated with copper or silver for contacting purposes.

Lab procedure for the plant

The critical processing point for the performance of the tape is the application of YBCO. This is done by pulsed laser deposition or PLD. This process involves evaporating the YBCO powder in a high-energy, ultra-violet (UV) laser pulse and transferring it to the supporting substrate. There, it grows atom layer by atom layer and forms a crystal grid structure. The PLD process is a method that has been proven in scientific material research for the production of high-quality thin layers over the last 25 years; however, the deposition speed is slow and the substrate size is limited. That's why no one took it seriously for production on an industrial scale. But there has now been a breakthrough. Today, by upscaling the PLD process, conductors up to two kilometers long can be produced with feed speeds of more than 75 meters per hour — without sacrificing layer quality. This advance has been made possible by innovations in the field of excimer lasers, extremely short-wave gas lasers with power outputs of up to one kilowatt and more than one joule per laser pulse of energy. Modern high-performance machines can be operated in continuous three-shift operation over a period of one year with more than 6 billion pulses at full capacity and a high level of stability for industrial mass production. However, upscaling the PLD process for industrial production required additional innovations in the beam guidance and deposition architecture because the material transfer per laser pulse cannot be increased as desired. In order for the current laser output to provide a correspondingly high volume deposition, the original laser beam is divided up into beamlets. Beam homogenization and scan algorithms that calculate the relative movement of the beamlets on the material to be ablated make it possible to increase the deposition speed almost in line with the laser pulse frequency and the number of beamlets. In addition, a suitable machine configuration had to be found. For the PLD coating of substrate tapes over two kilometers long with a quasi-monocrystalline quality, a roll-to-roll method was developed in which the substrate tape is wound in the deposition chamber using a rotating cylinder that moves on a longitudinal axis to achieve a uniform coating.

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What next

As a result, using the machines currently available on the market and depending on the substrate width, up to 500 kilometers of conductors can be produced annually. Like copper, the new HTS-coated conductors can be wound onto spools or power cables. However, products based on the new conductors are considerably smaller and lighter as well as far more powerful and energy-saving than those that use copper as a conductive material. For example, in the area of energy transfer, inherently safe, conductor-based HTS fault current limiters restrict short-circuit currents a thousand times faster, i.e. in a few milliseconds, and thus recover on their own within just a few seconds.

This means that expensive power failures can be avoided and safety reserves can be set aside for power grids that are under increasing loads. Power cables from HTS-coated conductors can replace conventional copper cables in existing cable ducts. Although they can be laid using dielectric material, cryostats and diverse reinforcements, much more power can be transported through the same cable duct on the end. In energy-producing systems such as engines and generators, HTS-coated conductors can cut net losses in half — including cooling losses — compared to copper. The higher magnetic fields of the superconducting rotor spools make it possible to produce engines or generators that can be configured using the same output with up to one-third of the conventional volume or weight. Superconducting cables and current limiters, engines and generators have been successfully tested in numerous projects worldwide over the last few years, but their long-desired market launch was considerably delayed due to the lack of availability of the HTS-coated conductor materials. This problem has been solved with the successful mass production of the HTS-coated conductor using the laser.

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__Dr. Ralph Delmdahl__ (left) and __Dr. Alexander Usoskin__ (right) together with Dr. Kai Schmidt and Rainer Pätzel received the Berthold Leibinger Innovation Award in 2010. Dr. Delmdahl works for Coherent in Göttingen on high-performance excimer lasers for industrial thin layer applications. At Bruker HTS in Alzenau, Dr. Usoskin is promoting the pulsed laser deposition of superconducting copper oxide layers for commercial use.

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