

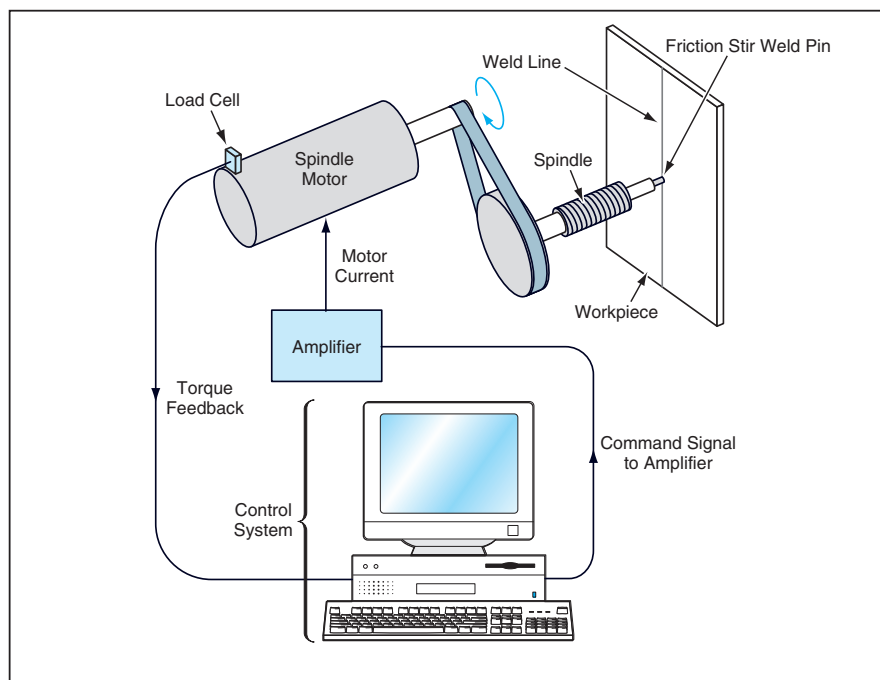
## Heat Control via Torque Control in Friction Stir Welding

Torque would be controlled and rotation measured to measure and control heat input.

Marshall Space Flight Center, Alabama

In a proposed advance in friction stir welding, the torque exerted on the workpiece by the friction stir pin would be measured and controlled in an effort to measure and control the total heat input to the workpiece. The total heat input to the workpiece is an important parameter of any welding process (fusion or friction stir welding). In fusion welding, measurement and control of heat input is a difficult problem. However, in friction stir welding, the basic principle of operation affords the potential of a straightforward solution: Neglecting thermal losses through the pin and the spindle that supports it, the rate of heat input to the workpiece is the product of the torque and the speed of rotation of the friction stir weld pin and, hence, of the spindle. Therefore, if one acquires and suitably processes data on torque and rotation and controls the torque, the rotation, or both, one should be able to control the heat input into the workpiece.

In conventional practice in friction stir welding, one uses feedback control of the spindle motor to maintain a constant speed of rotation. According to the proposal, one would not maintain a constant speed of rotation: Instead, one would use feedback control to maintain a constant torque and would measure the speed of rotation while allowing it to vary. The torque exerted on the



The Motor Current Would Be Regulated to maintain constant torque, as part of a scheme to measure and/or control the total heat imparted to the motion of the friction stir weld pin.

workpiece would be estimated as the product of (1) the torque-multiplication ratio of the spindle belt and/or gear drive, (2) the force measured by a load cell mechanically coupled to the spindle motor, and (3) the moment arm of the load cell. Hence, the output of the load cell would be used as a feed-

back signal for controlling the torque (see figure).

*This work was done by Richard Venable, Kevin Colligan, and Alan Knapp of Lockheed Martin Corp. for Marshall Space Flight Center. For further information, contact the New Technology Representative, Gary Willett at (504) 257-4786. MFS-31834*

## Manufacturing High-Quality Carbon Nanotubes at Lower Cost

The cost is about 1/20 of that of other processes.

Goddard Space Flight Center, Greenbelt, Maryland

A modified electric-arc welding process has been developed for manufacturing high-quality batches of carbon nanotubes at relatively low cost. Unlike in some other processes for making carbon nanotubes, metal catalysts are not used and, consequently, it is not necessary to perform extensive cleaning and purification. Also, unlike some other processes, this process is carried out at

atmospheric pressure under a hood instead of in a closed, pressurized chamber; as a result, the present process can be implemented more easily.

Although the present welding-based process includes an electric arc, it differs from a prior electric-arc nanotube-production process. The welding equipment used in this process includes an AC/DC welding power

source with an integral helium-gas delivery system and circulating water for cooling an assembly that holds one of the welding electrodes (in this case, the anode).

The cathode is a hollow carbon (optionally, graphite) rod having an outside diameter of 2 in. ( $\approx 5.1$  cm) and an inside diameter of 5/8 in. ( $\approx 1.6$  cm). The cathode is partly immersed in a water

bath, such that it protrudes about 2 in. (about 5.1 cm) above the surface of the water. The bottom end of the cathode is held underwater by a clamp, to which is connected the grounding cable of the welding power source.

The anode is a carbon rod 1/8 in. ( $\approx 0.3$  cm) in diameter. The assembly that holds the anode includes a thumb-knob-driven mechanism for controlling the height of the anode. A small hood is placed over the anode to direct a flow of helium downward from the anode to the cathode during the welding process. A bell-shaped exhaust hood collects the helium and other gases from the process. During the process, as the anode is consumed, the height of the

anode is adjusted to maintain an anode-to-cathode gap of 1 mm.

The arc-welding process is continued until the upper end of the anode has been lowered to a specified height above the surface of the water bath. The process causes carbon nanotubes to form in the lowest 2.5 cm of the anode. It also causes a deposit reminiscent of a sandcastle to form on the cathode. The nanotube-containing material is harvested. The cathode and anode can then be cleaned (or the anode is replaced, if necessary) and the process repeated to produce more nanotubes.

Tests have shown that the process results in  $\approx 50$ -percent yield of carbon nanotubes (mostly of the single-wall

type) of various sizes. Whereas the unit cost of purified single-wall carbon nanotubes produced by other process is about \$1,000/g in the year 2000, it has been estimated that for the present process, the corresponding cost would be about \$10/g.

*This work was done by Jeanette M. Benavides and Henning Lidecker of **Goddard Space Flight Center**. Further information is contained in a TSP (see page 1).*

*This invention has been patented by NASA (U.S. Patent No. 6,114,995). Inquiries concerning nonexclusive or exclusive license for its commercial development should be addressed to the Patent Counsel, Goddard Space Flight Center; (301) 286-7351. Refer to GSC-14601.*

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## Setup for Visual Observation of Carbon-Nanotube Arc Process

*Lyndon B. Johnson Space Center, Houston, Texas*

A simple optical setup has been devised to enable safe viewing of the arc and measurement of the interelectrode gap in a process in which carbon nanotubes are produced in an arc between a catalyst-filled carbon anode and a graphite cathode. This setup can be used for visually guided manual positioning of the anode to maintain the interelectrode gap at a desired constant value, possibly as a low-technology alternative to the automatic position/voltage

control described in "Automatic Control of Arc Process for Making Carbon Nanotubes" (MSC-23134), *NASA Tech Briefs*, Vol. 28, No. 3 (March 2004), page 51. The optical setup consists mainly of lenses for projecting an image of the arc onto a wall, plus a calibrated grid that is mounted on the wall so that one can measure the superimposed image of the arc. To facilitate determination of the end point of the process, the anode is notched, by use of a file, at the end of

the filled portion that is meant to be consumed in the process. As the anode is consumed and the notch comes into view in the scene projected onto the wall, the process operator switches off the arc current.

*This work was done by Carl D. Scott of **Johnson Space Center** and Sivaram Arepalli of GB Tech Inc. For further information, contact the Johnson Commercial Technology Office at (281) 483-3809. MSC-23131*