Cold spray produces high quality coatings for a wide spectrum of applications.

Anatolii Papyrin*
Ktech Corporation
Albuquerque, New Mexico

Cold Gas-Dynamic Spray (or simply Cold Spray) is a process of applying coatings by exposing a metallic or dielectric substrate to a high velocity (300 to 1200 m/s) jet of small (1 to 50 μm) particles accelerated by a supersonic jet of compressed gas. This process is based on the selection of the combination of particle temperature, velocity, and size that allows spraying at the lowest temperature possible. In the cold spray process, powder particles are accelerated by the supersonic gas jet at a temperature that is always lower than the melting point of the material, resulting in coating formation from particles in the solid state. As a consequence, the deleterious effects of high-temperature oxidation, evaporation, melting, crystallization, residual stresses, debonding, gas release, and other common problems for traditional thermal spray methods are minimized or eliminated.

Process history
The cold spray process was originally developed in the mid-1980s at the Institute of Theoretical and Applied Mechanics of the Russian Academy of Science in Novosibirsk by A. Papyrin and colleagues. They successfully deposited a wide range of pure metals, metal alloys, and composites onto a variety of substrate materials, and demonstrated the feasibility of cold spray for various applications. A U.S. patent was issued in 1994, the European patent in 1995.

In the United States, the first research in the field was conducted in 1994-95 by A. Papyrin with a consortium formed under the auspices of the National Center for Manufacturing Sciences (NCMS) of Ann Arbor, Mich. The membership included major U.S. companies such as Ford Motor Company, General Motors, General Electric - Aircraft Engines, and Pratt & Whitney Division of United Technologies. This consortium established the first U.S. cold spray capability, and the group published property measurements for several cold-sprayed materials.

At the present time, a wide spectrum of research is being conducted at several research centers, including the Institute of Theoretical and Applied Mechanics of the Russian Academy of Science; Sandia National Laboratories; the Pennsylvania State University; ASB Industries Inc., in the United States; the University of Bundeswehr, Germany; and others.

These studies are related to jet gas dynamics, physics of high-speed particle impact, various powder materials, and development of specific technologies. All are very important for understanding the process and developing commercial applications.

Cold spray technology
Figure 1 illustrates the results of early Russian studies on the basic concept of cold spray. Its underlying principle is to apply coatings with the aid of a high-speed flow of “cold” spray particles onto a “cold” substrate. Figure 1 shows the dependence of the deposition efficiency on particle velocity for several metal powders (aluminum, copper, and nickel) under an ambient stagnation temperature of the jet. The main results of the studies were as follows:

The two characteristic ranges of deposition efficiency were found to be bounded by the critical ve-
The first range (V<V*) corresponds to the critical value V*, the coating process begins. Deposition efficiency rapidly increases to 50 - 70% as the particle velocity approaches the critical velocity. Typical values of V* for the various metals (Al, Cu, Ni) shown in Figure 1 are in the range of 500 to 700 m/s. Various metals and alloys could be sprayed even at room jet stagnation temperature (without any heating at all) if necessary particle velocity is achieved. This transition from the erosion of the substrate to the formation of viable coatings by the flow of "cold" solid particles was the physical basis for development of the cold spray method.

Based on these and the following studies conducted at the Institute of Theoretical and Applied Mechanics, the basic requirements for the coating formation from particles in solid state were formulated:

- **Jet temperature** must always be lower than the melting or heat softening temperature of the particle material.
- **Particle size** must be in the range of 1 to 50 μm.
- **Particle velocity** must be in the range of 300 to 1200 m/s depending on powder material and particle size.

In practice, particles may be cold sprayed with the aid of a supersonic gas jet at stagnation pressures between 1 and 3 MPa with nozzle Mach numbers ranging from 2 to 4. Gas jets may consist of various gases such as air, nitrogen, helium, and their mixtures, and must provide the necessary particle velocity V>V*. Gas preheating can increase the gas discharge speed and particle velocity. Figure 2 shows a schematic of the cold spray system. The propulsion gas or compressed air at an elevated pressure is introduced through a gas control module to a manifold system containing a gas heater and powder-metering vessel. The pressurized gas is heated electrically, in contrast to the thermal spray methods. The high-pressure gas is then introduced into a de Laval type nozzle with compression through a throat region, followed by expansion to nominally atmospheric pressure. This results in supersonic flow. The powder feedstock is introduced on the high-pressure side of the nozzle, and is delivered by a precision-metering device. Particles not incorporated into the coating may be continuously recycled by conventional dust collection devices and the placement of an enclosure.

Figure 3 shows the specific temperature and velocity ranges of particles for cold spray as compared with known thermal spray methods. As shown in the diagram, the distinguishing feature of cold spray is the ability to produce coatings with the jet temperature range between 0 and 700°C, which is always lower than the melting temperature for the candidate powder and substrate materials.

**Advantages and applications**

Eliminating the deleterious effects of high temperature on coatings and substrates offers significant advantages and new possibilities. These include:

- **Avoid oxidation and undesirable phases**
- **Retain** properties of initial particle materials
- **Induce** low residual stresses
- **Conduct** heat and electricity easily through the coatings
- **Provide** high density, high hardness, cold-worked microstructure
- **Spray** thermally sensitive materials
- **Spray** powders with a particle size < 5 – 10 μm
- **Work** with highly dissimilar materials

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**Table 1 — Typical range of jet parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stagnation jet pressure, MPa</td>
<td>1 - 3</td>
</tr>
<tr>
<td>Stagnation jet temperature, °C</td>
<td>0 - 700</td>
</tr>
<tr>
<td>Gas flow rate, m³/ min</td>
<td>1 - 2</td>
</tr>
<tr>
<td>Powder feed rate, kg/hour</td>
<td>5 - 15</td>
</tr>
<tr>
<td>Spray distance, mm</td>
<td>10 - 50</td>
</tr>
<tr>
<td>Power consumption, kW (for heating gas)</td>
<td>5 - 25</td>
</tr>
<tr>
<td>Particle size, μm</td>
<td>1 - 50</td>
</tr>
</tbody>
</table>

Operating gases: air, nitrogen, helium and their mixtures.
Prepare substrate minimally with surface preparation/masking, short standoff distance
Feed powder at a high rate, resulting in high productivity
Deposit many materials at high deposition rates and efficiencies
Collect and re-use particles (powder utilization up to 100% with recycling)
Heat substrate minimally
Increase operational safety because of the absence of high-temperature gas jets, radiation, explosive gases

The above advantages make cold spray promising for producing and repairing a wide range of industrial parts. Examples include turbine blades, pistons, cylinders, valves, rings, bearing components, pump parts, sleeves, shafts, and seals for many industries. Various coatings may add strengthening, hardening, wear resistance, corrosion resistance, electro-magnetic conductivity, thermal conductivity, and other properties. The process is also suitable for the production of compact powder materials and for the direct fabrication of parts.

Key features

The most important features of the cold spray process are the following:
- In the Cold Spray process, each coating is applied at a temperature as low as possible. (Why apply coatings of many materials at T = 2000 to 3000°C and higher if the same or higher quality coatings are possible at T = 0 to 700°C?)
- From a physical point of view, cold spray forms coatings from particles in the solid state.
- From a practical point of view, cold spray provides high quality coatings of many metals, alloys, and composites at temperatures ranging between 0 and 700°C, at the optimum spray temperature for each coating material.
- From a technical point of view, cold spray incorporates conventional equipment that does not require a plasma, arc, detonation, combustion, or complex equipment for heating the gas jet.

Transition to industry

Current activities are setting the stage for transition from R&D to commercial applications for industry. To successfully commercialize the technology, two issues need to be addressed. First, improvements must be made on the process and equipment performance. Second, someone must manufacture the equipment.

Sandia National Laboratories has taken the lead to address the first issue by forming a consortium of several industry leaders to develop the process and improve equipment. The consortium of eight companies has executed a Cooperative Research and Development Agreement (CRADA) to address pre-competitive issues leading to commercialization. The member companies include Sandia National Laboratories/DOE, DaimlerChrysler, Ford Motor Company, Jacobs Chuck Manufacturing Company, Ktech Corporation, Pratt & Whitney, Praxair, and Siemens-Westinghouse. Transfer of technology and intellectual property to consortium members should lead to broad commercial applications of the Cold Spray technology within three years.

R&D work will be conducted at Sandia’s Thermal Spray Research Laboratory, providing high level experimental studies as well as physical modeling of the process. Sandia will be leading research tasks to improve equipment, economics of the process, understanding of the bonding mechanisms, and nozzle spray patterns. Sandia will also make the system portable for field applications. Consortium members are to provide in-kind support to the various CRADA tasks.

The second issue is identifying a company who will manufacture the equipment. CRADA member Ktech Corporation has taken the lead in this area. Dr. Papyrin, one of the inventors of the process and the patent holder, joined Ktech in July 2000, to pursue the development of the technology and equipment. Dr. Papyrin has issued an exclusive license to Ktech to “make and sell” Cold Spray equipment in the United States and non-exclusive rights outside of the United States. He has also granted licenses to consortium member companies to develop commercial applications.

In the year 2000, Ktech began offering both the design and manufacture of cold spray systems, ranging from laboratory R&D machines to sophisticated high-volume production machines. The systems are the first commercially available, computer controlled, cold spray machines in the United States. Because of the variety of applications, these systems are configured to meet customer applications requirements. Ktech will also be providing applications research and proof-of-principle testing. This will allow customers to validate specific applications without making a large investment in equipment and research.

The transition of the cold spray technology from R&D to viable coatings for industrial and military applications is planned, organized, and moving forward for deployment between now and FY 2003. When fully developed for commercialization, the technology will have a wide range of industrial applications that span products from electronic components to satellite structures. Industries as diverse as aerospace, petrochemicals, automotive, paper and printing, electronics, computers, biomedical, military, and many others will benefit from this technology.

For more information: Dr. Anatolii Papyrin, Ktech Corporation, 2201 Buena Vista SE, Suite 400, Albuquerque, NM 87106; tel: 505/998-6004 fax: 505/998-6073; e-mail: papyrin@ktech.com; Web site: www.ktech.com.

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Not useful, Circle 279