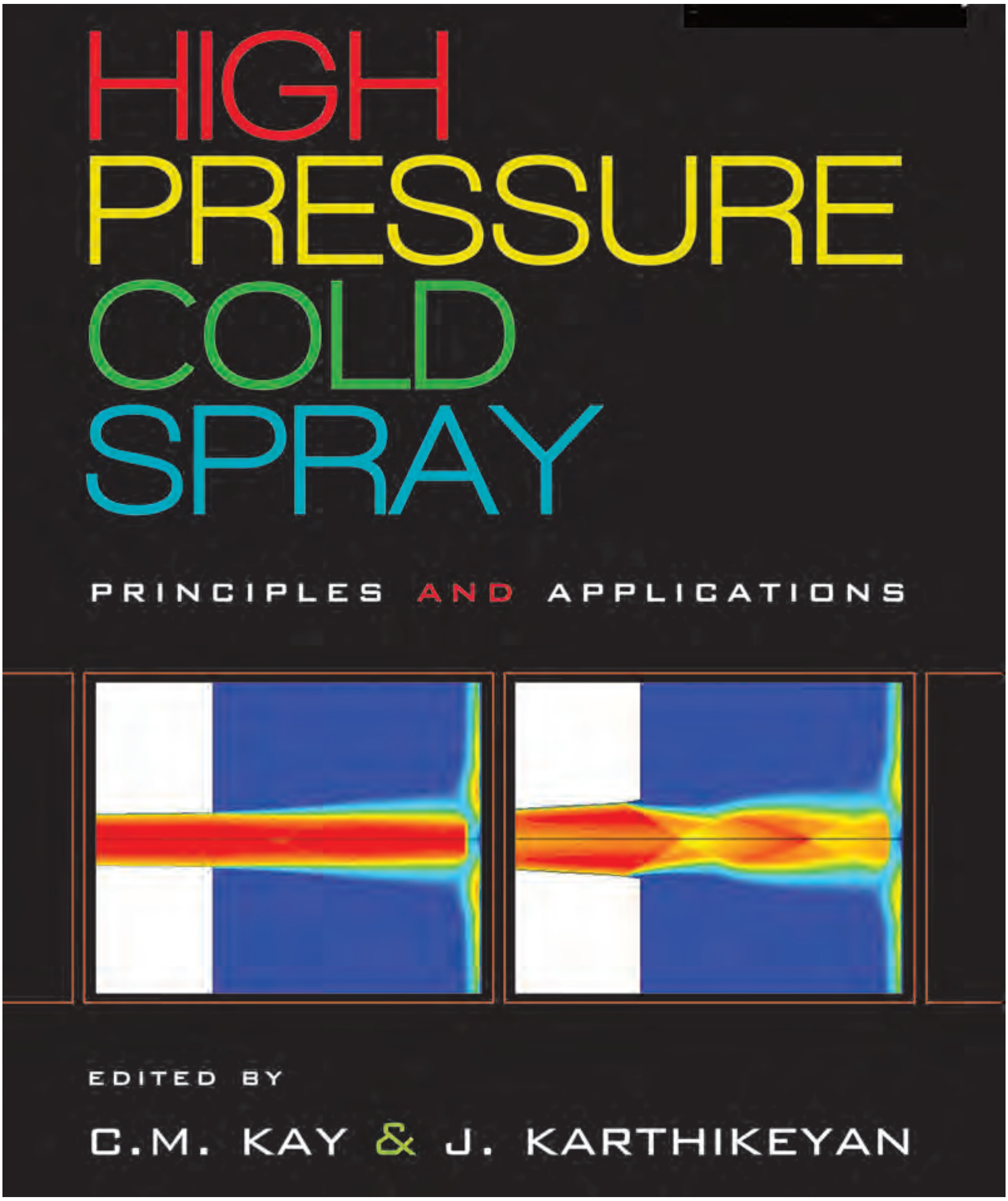

HIGH PRESSURE COLD SPRAY

PRINCIPLES AND APPLICATIONS

EDITED BY

C.M. KAY & J. KARTHIKEYAN

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Foreword

Cold Spray Technology Development at ASB Industries, Inc.

When I became a certified public accountant, the last thing on my mind was a career in manufacturing. However, when a client decided to sell ASB Industries in 1981, I could not resist the challenge; after all, I was quite familiar with the financial aspect of the operation. I bought the company, then modernized the plant and vowed to keep up with new technologies. The very next year, we bought a high-velocity oxygen fuel system, the first company in the United States to do so. ASB Industries was also the first to use natural gas, which is cheaper and safer than using high-pressure tanks. The compressor equipment may seem expensive, but natural gas is so much less expensive that we recovered the cost in just two years.

In February 1995, I read an article in the *NCTPC News* (National Center for Tooling and Precision Components) about Dr. Anatolii Papyrin, one of a group of Russian scientists who had developed cold spray in the mid-1980s at the Russian Academy of Sciences in Novosibirsk.

The article announced that Dr. Papyrin was to demonstrate the cold spray process in Toledo, OH. By that time, we were well acquainted with thermal spray but had never heard of cold spray. I wondered how it could work and if, in fact, it did work. To find out for myself, I went to the demonstration in Toledo and watched as Dr. Papyrin sprayed cold copper particles onto a substrate. To my surprise, the particles had good adherence, and the coating had good properties. The technology appealed to us because of its potential to produce coatings that retained their original properties and also to use low-melting-point powders.

We could see that the process needed improvement in many areas, but we believed that it could ultimately produce high-quality coatings without flame and with less pollution at a reasonable cost.

At the time, Dr. Papyrin was under contract with the National Center for Manufacturing Sciences, but he joined ASB Industries in 1996 as a consultant, after his contract had ended. He did a great deal of development work on the technology for us but ultimately could not do everything himself.

By 1998, we needed help with nozzle development and controls. Dr. Christopher Berndt, who was at State University of New York at Stony Brook at the time, told us about Dr. Jeganathan Karthikeyan ("Karthi"), a young engineer who was working with him on nozzle development for plasma spray. Karthi had built nozzles for the thermal spray of liquids, had also developed various controls for temperature and pressure, and had worked on development of powder materials.

In addition to his experience, I soon learned that he was as enthusiastic as I was about the possibilities of cold spray technology. My vision was to develop the technology by improving nozzle design, controlling spray parameters, and improving coating materials. In Karthi, I was sure that we had found the dedicated engineer who could actually design and build the system. We hired him.

When Karthi first saw the system we had built, he began to realize the large nature of the project he had taken on. He told me that every component of the system had to be brought up to date. The nozzle was primitive, the temperature could be set but not controlled, the powder flow was erratic, and the pressure varied too much. In addition to the equipment, the powder particles had too much variability in size, shape, and chemistry. I told him he should do whatever was necessary. Little did I know that this was the beginning of a long and difficult journey but one that would ultimately become worth all the effort and expense.

To make our vision a reality, Karthi would need to develop a reliable system with controls and feedback loops. Such a system needed a specially designed nozzle, reliable temperature and pressure controls, a dependable powder-feed system, and powder feedstock that was consistent in chemistry, size, and shape. For the system to work, all these complex components had to work smoothly together. Despite these innumerable challenges, Karthi and ASB personnel set out to design and build all facets of the technology.

To have an idea of the challenges involved, here is a brief description of the process. In the cold spray system, powder is kept in the hopper, then fed through a hose into the nozzle. Conventional thermal spray processes operate at 100 psi pressure, but in the first cold spray systems, the operating pressure was three times that, at 300 psi. Unfortunately, no powder feeder existed at that pressure. How could we proceed if this vital component did not exist?

We overcame that roadblock by working with a hopper manufacturer to develop a high-pressure powder-feed system, and we ended up with two different 300-psi powder feeders. In fact, today (2015) the cold spray systems operate at even higher pressures, up to 850 psi.

At the same time that we were discussing and deliberating over the high-pressure powder feeder, Karthi was busy inventing the first one-piece cold spray nozzle, for which we acquired a patent. He then installed temperature controllers, pressure regulators, flowmeters, feedback loops, and other controls. He and the ASB team built the rest of the system even as we waited for the first powder feeder to be delivered.

Then there was the fundamental problem with the Russian design. In the Russian system, the spray gun was mounted onto the large heater box. Carrier gas was heated in this large box and then entered the gun, where it was mixed with the powder and ejected through the nozzle onto the substrate. Because of this design, the substrate had to be moved across the nozzle, which remained stationary on the heavy box. Karthi and I agreed that this was not practical for spraying large surfaces and that we needed a flexible hose that could connect the heater with the gun, so that only the gun had to move. The hose would have to be made of materials that could withstand both high temperatures and high pressures yet be flexible enough to be easily manipulated by an operator.

Unfortunately, such hoses did not exist. Some were designed to function at high pressure but none at both high temperature and high pressure. Undaunted, we called on several hose manufacturers and told them what we needed: insulation to keep the heat in, strength for high pressure, and flexibility to allow ease of movement. They were ultimately successful in this development, and we then had an insulated hose 1 in. in diameter and flexible enough to spray large areas.

We also had to change the design of the gun, for which we received another patent. After two years of development, we thought we had made enough progress to announce the new technology at the 2000 International Thermal Spray Conference. I encouraged the audience to take on some research and design (R&D) projects, to join us in a vision of the future where everyone contributed to the success of the industry. I reasoned that if enough people took on R&D projects, the equipment and powders would improve and the number of applications would grow. However, to most of them the risks outweighed the potential benefits, and no one else was willing to take up the gauntlet.

Mark Smith of Sandia National Laboratories came to our plant and examined our system. We were happy to explain everything to him, and he went back to Sandia and built a system there.

We kept the vision, and in 2001 ASB Industries joined in a Cooperative Research and Development Agreement (CRADA) at Sandia National Laboratories that also included Pratt & Whitney, Alcoa, Ford Motor Company, Siemens Westinghouse Power Corporation, Praxair Surface Technologies, and Ktech Corporation.

This CRADA was formed to expedite the development and commercialization of cold spray technology for Sandia/ U.S. Department of Energy and the industrial partners. This collaboration allowed the partners and Sandia to pool technical expertise, funding, and other resources to jointly address some key issues related to process, equipment, and coating material characteristics. The work would provide Sandia and its partners with an improved fundamental understanding of the chemistry and physics of cold spray. This was an opportunity to jointly resolve critical technical and manufacturing challenges that needed to be addressed for successful commercialization.

Nozzle improvements were crucial to improving the economies of the cold spray process. The CRADA goals related to nozzle design were to produce the highest-possible particle velocity with the lowest-possible gas flow; greatly reduce helium use; minimize nozzle fouling with certain powders, such as aluminum; and acquire a more thorough understanding of nozzle modeling and particle velocity measurements.

To improve the quality of cold spray deposits, we needed to achieve a better understanding of the underlying process fundamentals. In other words, we needed a model that would allow us to predict coating properties from input parameters such as gas pressure and temperature. Work included determining critical velocities, investigating substrate-preparation effects, modeling deposit properties, establishing spray parameters and postspray treatments, and determining bonding mechanisms.

We contributed $20,000 per year over the three-year span of the CRADA and were the smallest of the companies involved. We were willing to share what we had learned. During the program, Karthi improved a nozzle design that enabled the process to work much better.

The nozzle is the most important component in the system. It is where everything comes together: the process gas, the carrier gas, and the powder. It is sensitive to variations in particle size and shape and to temperature. When the temperature rose too high, sometimes particles would adhere to the sides and clog the nozzle. This was the problem Karthi tackled and solved by making the nozzle out of a polymer material. This new design and new material extended the life of the nozzle and allowed us to spray some high-melting-point materials that were not possible before.

Of course, this also increased the range of possible applications, which increased the potential for growth of the entire thermal spray industry! This has always been our vision.

It was at that point that research groups and companies from around the world began to take notice of us. They knew that we would be willing partners, as I had never been reticent about expressing my belief that there should be no secrets. The way to grow the industry is to work continually to advance the technology. When that happens, applications will grow and the industry will grow, helping everyone in the business.

The Armed Forces University in Munich sent representatives to visit us. After learning all they could about our system, they returned home and built their own. The first commercially available cold spray system was built by the Germans, based on our system. Then the university initiated a program in which students joined researchers who were developing cold spray. Students learned the technology, and now they are engineers working in the field. All of this R&D work in Germany is now coming to fruition. Over the years, this university has developed knowledgeable and experienced engineers who are doing work with excellent results. In one widespread application, a company in Germany produces induction-heated pots and pans coated by cold spray with an iron-base material.

Today (2015), we work with students from various universities, such as Michigan State University and State University of New York at Stony Brook. They come for various amounts of time, from one week to six months. They learn about cold spray, the challenges involved with the technology, and the physics-based models we use to find answers.

We work with customers to develop new technologies, which they can then patent. Thus, new technology can get into the marketplace, even if it is in a limited way. Our approach is that our customers fund us to do research, then they patent it. Some share these patents with us, and others keep the patents within their companies. In that way, we can attract high-tech companies such as Pratt & Whitney, Exxon Mobil, Siemens, and others. We develop the expertise, then they get and use the patent.

For example, metal foams for insulation were developed by Exxon. A cold spray process was developed by Pratt & Whitney for refurbishment of a rocket engine chamber. BMW uses cold spray for battery components in hybrid engines. Around the globe, cold spray has found many applications, but in this country, although there are some applications, they are secret. We need an open, mass-produced application. When cold spray becomes accepted as a standard coating method, I am convinced that the scope of its applications will rapidly expand.

What could these be? Well, for one thing, three-dimensional manufacturing. The future is going to be in additive manufacturing. At the 2014 AeroMat Conference, many presentations focused on additive manufacturing. Cold spray is ideal for this technology, because the powders retain their original microstructure.

As our experience at ASB Industries has shown, a vision that is based on R&D and the future can enable progress across the industry and, indeed, across the world. We invite the readers of this book to join us.

Albert Kay
ASB Industries

Preface

Cold spray refers to a material-deposition technique that uses a supersonic particle jet. In the high-pressure cold spray (HPCS) process, gas and powder are mixed upstream and expanded via de Laval nozzle to produce a supersonic particle jet, which produces coatings based on a wide selection of materials with superior characteristics and high deposition efficiency. Although some systems (low-pressure cold spray) use subsonic particles laden with a peening agent to process ductile materials with acceptable properties, these systems are not covered in this book.

In a short span of approximately 20 to 25 years, cold spray has moved from a scientific curiosity carried out in a few research establishments to an established and integral manufacturing process, adopted in multiple high-tech industries. Homemade spray systems have been replaced with a selection of vendor-supplied commercial systems. Special powders with specific characteristics, required for cold spray processing, are readily available.

Around the globe, scientists and engineers have taken up both basic and application research and development (R&D) activities in universities, national laboratories, and industries. These activities have resulted in advancements in all aspects of the technology, including basic science of gas/particle interaction, particle impact and coating generation, parameters/processing/properties relationships, and performance of coatings in various industrial environments. These advancements have led to a multitude of applications, from protective and performance-enhancing layers to repair and refurbishing of parts to fabrication of components by near-net shaping or additive manufacturing techniques. The number of industries adapting to cold spray technology is growing rapidly, from automobile to aerospace to turbine and power to defense to sputter targets and others.

Enormous growth in R&D activities has led to a huge databank in the form of publications in peer-reviewed journals and conference proceedings. However, consolidated information on all aspects of cold spray technology in book form is hard to find. This book covers the need for consolidated information, with focus on applications in specific industries. Experts around the globe have contributed in their specific areas of specialties.

The basic science and modeling of the cold spray process are discussed in the first few chapters, which are followed by details of equipment and powder supply. The second half of the book concentrates on cold spray applications in various industries. Experts from each industry have written about applications in their specific industries.

We have tried to eliminate repetition of specific applications in multiple chapters. However, some applications present themselves in many industries. For instance, the defense, aerospace, and power-generation industries require repair/refurbishment of turbine components and are treated by industry experts in their respective chapters from their perspectives.

We offer our deepest thanks to all those who have contributed to this publication. The time, effort, and professionalism represented by the commitment to authoring these chapters is the culmination of relationships developed out of a shared passion for cold spray technology—relationships built at airports and conferences, via emails, in hotel lobbies, and through many joint development initiatives. It is both a professional and personal honor for us to work with those who are held in the highest regard for their expertise, sincerity, and time to contribute.

The reader will find this book a useful assembly of information. The substantial information provided by the authors will serve as a resource that may lead the reader in many directions, both in the principles of HPCS and in applications in which the unique properties of cold spray have developed by providing both exceptional surfacing solutions and additive manufacturing applications.

Our authors have focused on cold spray, a field in which their work has reached all corners of the world as a result of their knowledge and working relationships. Included within these chapters are references showing a cross section of true scientific research, from materials development to practical applications.

We acknowledge that these authors, in making their contributions to this book, have spent substantial amounts of time persevering in the task of documenting their knowledge. We believe the chapters contained within this book will easily demonstrate the truth of our acknowledgment and greatly add to the reader’s knowledge of cold spray.

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Charles Kay is currently vice president of ASB Industries, Barberton, Ohio, and has been with ASB for over 29 years. ASB focuses on expanding the reach of thermal spray technology in new areas. Charles specializes in identifying new application areas in various industries such as steel, paper, power, etc. He has co-authored many technical articles on cold spray technology that have been published in various peer-reviewed journals and conference proceedings. He has served as president of the ASM Thermal Spray Society and is an active member of various ASM Thermal Spray Society committees.

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He served as the conference chairman of ASM-sponsored Cold Spray 2004, Cold Spray 2007 and Cold Spray 2010 meetings in Akron, Ohio. He also organizes special symposiums on cold spray technology at international thermal spray conferences every year. He is a Fellow of ASM International and has served as a member of the ASM Thermal Spray Society Board (2008-11). He is a member of the International Board of Review of many prestigious journals such as *Journal of Thermal Spray Technology*.