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Research and Competition—Best Partners

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RESEARCH AND COMPETITION - BEST PARTNERS

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SUMMARY

America's high standard of living is the result of the technology, the knowledge of how to do things, that this country has developed. That technology, in turn, is the result of research.

A research expenditure is money spent in an attempt to purchase superior technology, which will produce a superior product, and thus gain for a company a competitive advantage in its markets.

NASA's Microgravity Science and Applications Program is directed toward research in the science and technology of processing materials under conditions of low gravity. The objective is to make a detailed examination of the constraints imposed by gravitational forces on Earth. The program is expected to lead, ultimately, to the development of new materials and processes in Earth-based commercial applications adding to this nation's technological base. The goals of using a microgravity environment as a laboratory are the following:

(1) To obtain an understanding of basic physical phenomena and processes.

(2) To quantify the limitations and effects imposed by gravity on those phenomena and processes.

(3) To apply the basic knowledge we gain to specific processes for applications that are unique either to space or Earth.

An important resource that U.S. researchers have readily available to them is the new Microgravity Materials Science Laboratory (MMSL) at NASA Lewis Research Center in Cleveland. A typical scenario for a microgravity materials experiment at NASA Lewis would begin by establishing 1-g baseline data in the MMSL and then proceeding, if it is indicated, to a drop tower or to simulated microgravity conditions in a research aircraft to qualify the project for space flight. A major component of NASA Lewis microgravity materials research work involves the study of metal and alloy solidification fundamentals. The role of gravity on liquid metal fluid flow and containerless processing opportunities is being evaluated. Other areas under investigation include undercooling and bulk undercooling as well as the effects of gravity on the processes of dendritic growth.

INTRODUCTION

By any reasonable standard or measure, Americans live better than anyone else in the world. Many of the things that are regarded as rare or unusual or even luxurious--even in other Western countries--are commonplace here. The reason for that enviable state of affairs is the American economic system, which is based on the notion of free enterprise, and which is possible because of the American political system, which, in the last analysis, is based on the principle of the maximum responsible freedom for the individual. But what goes on in that environment that produces this fine standard of living?

What goes on is something that comes naturally to the human spirit when it is let alone to function freely: People try to figure out new and better ways to do things so that their labors will allow them to live as well as possible.

The better way that is sought after is called "technology." And the effort that is put forth, the work that is done to find that better way, is called "research." The purpose of this paper is to examine a type of research that would be useful to the foundry industry, and more particularly than that, to explore what foundrymen can hope to gain from research conducted in the microgravity environment of low Earth orbit, which is about 150 miles above the surface of the Earth--about where the space shuttle operates and about where the space station will be.

SPACE MANUFACTURING

First, a matter that has received a lot of attention and has been the subject of a lot of speculation must be addressed: manufacturing in space. At the moment, except for a handful of very high value-to-weight ratio products--certain pharmaceuticals, some biological materials, and perhaps a few specialized electronic crystals--manufacturing in space is prohibitively expensive. So unless and until something changes very drastically, there will not be any foundries in space. And that, by the way, is nothing peculiar to the foundry industry. Except for the few products mentioned, it's true of manufacturing in general.

WHAT'S THE POINT?

When it comes to microgravity research, the first question for anyone to deal with, including foundrymen, is, "What can I hope to learn that will be of any practical value to me?" The answer--and not to beg the question--is, "That's what you're going up there to find out."

And going is a "must." It will be necessary to do research and to spend money. And research does require an investment of funds, just the same as the purchase of capital equipment does. In fact, under certain circumstances, money spent on R&D is not expensed, but capitalized. But regardless of what sort of accounting procedures are used to handle R&D funds within a company, one fundamental fact remains:

> A RESEARCH EXPENDITURE IS MONEY SPENT IN AN ATTEMPT TO PURCHASE SUPERIOR TECHNOLOGY, WHICH WILL YIELD A SUPERIOR PRODUCT, AND THUS GAIN THE MANUFACTURER A COMPETITIVE ADVANTAGE IN HIS MARKETS.

Now, all of a sudden, things begin to look a little different, and the justification for an expenditure of funds is seen in a different light, and the question that must be answered becomes something like "How's my business, and how much better is my bottom line going to look if I can obtain a significant product advantage over my competition?"

The foundry industry, of course, does do research, but as George Booth said in his President's Report at the 89th Casting Congress last year, "It is discouraging that our industry spends less on research as a percent of sales than any other industry." And it is indeed most discouraging, because research is what produces the technology, the intellectual capital, without which there can not be the physical capital--the tools and the processes--that will increase productivity.

Robert R. Jones, editor of Research & Development magazine has put it this way: "There are direct, demonstrable, traceable connections in the progression from high technology to productivity to profitability. That is not a new notion, of course. It's one of those things, however, that some people never do perceive and others frequently lose sight of, so we need to remind ourselves of these key facts of economic life from time to time."

A British magazine, The Economist, makes the point quite clearly another way, saying: "The best job prospects are in those industries that improve productivity fastest." And in Britain, the ten industries that increased productivity fastest in the 1960's and 1970's raised employment by 25 percent, although employment in British manufacturing as a whole fell during that time. "In the United States," continues The Economist, "high-technology industries have increased productivity twice as fast as low-technology ones--and expanded employment nine times as fast." And of course, the one and only reason to hire anyone is that there is work to be done. In other words, business is good.

NASA'S PROGRAM

NASA's Microgravity Science and Applications Program is directed towards research in the science and technology of processing materials under conditions of low gravity. If gravity on the Earth is 1 g, then gravity in a spacecraft orbiting at an altitude of 150 miles is in the range of 10^{-4} to 10^{-6} g. It's known correctly as microgravity, but even without the complete absence of all gravitational forces, materials behave in a markedly different way. The objective of the program is to make a detailed examination of the constraints imposed by gravitational forces on Earth. The program is expected to lead, ultimately, to the development of new materials and processes in Earth-based commercial applications adding to this nation's technological base.

Current research emphasizes selected materials and processes that will best uncover limitations due to gravity and demonstrate the enhanced sensitivity of control of processes that may be provided by the weightless environment of space. Examples include growth of crystals and directional solidification of metals under conditions in which gravity-driven fluid flow is eliminated; containerless processing of reactive materials to eliminate reactions with the container (and to provide geometrical control of the product); and synthesis and separation of biological materials in weightlessness to reduce heat and mass transfer problems associated with sedimentation and buoyancy effects.

The environment of space differs from that of the surface of the Earth in two obvious and important respects: It's a pretty good vacuum, and gravity is greatly reduced. But vacuum conditions comparable to space can be pumped here on Earth. So that leaves a marked reduction in gravity as the main thing to be achieved by going into space, even in low Earth orbit. And when the force of gravitational attraction is reduced to about 10^{-4} g's, or less, or about one ten-thousandth of what it is here on Earth, things behave differently, particularly fluids, including molten materials as they begin to crystallize and solidify.

What happens in space, in very general terms, is that when not under the influence of significant gravitational forces, things just begin to do what comes naturally to them. For example, when buoyancy-driven convection is eliminated, and thermal and composition fluctuations within a fluid are suppressed, unwanted mixing due to either of these is eliminated. In microgravity, there is no sedimentation, thus making it possible to maintain heterogeneous mixtures and suspensions. Unwanted phase separation is prevented. Objects can be free-floated, and molten metal can be allowed to solidify without having to come into contact with any kind of mold material. In low Earth orbit, there will be hardly any gravitational forces to affect dendrite growth direction and morphology through convection and fluid flow.

MICROGRAVITY GOALS

The understanding of these phenomena is just part of what can be expected from research in microgravity. The goals of using a microgravity environment as a laboratory are principally the following:

(1) To obtain an understanding of basic physical phenomena and processes.

(2) To quantify the limitations and effects imposed by gravity on those phenomena and processes.

(3) To apply the basic knowledge gained to specific processes or products for applications that are either unique to space or Earth.

In addition, NASA wants to expand, centralize, and disseminate the research data as widely as possible to the U.S. private sector.

The rest of the world, by the way, is not just standing by and waiting in the wings to see what the United States is going to do. Other countries are moving forward aggressively in microgravity research. West Germany, in fact, took over the entire payload bay of the space shuttle in November 1985 for the Spacelab D-1 mission. Once America's launch capability had delivered them into orbit, West German scientists took total charge of all of the experiments in orbit from their own mission control center on the ground.

Consider also the Japanese. They are formidable worldwide competitors now, and concurrently with their preparations for space flight, they are in the process of building not one but two 5 000-ft drop tubes here on Earth. That's nearly a mile deep and will give them about 17 sec of microgravity, which is ample time to do all sorts of really serious experimentation in metal solidification.

Reference was made earlier to this nation's technological base. What exactly is that? A country's technological base simply is the amount of technology that it has, the amount of knowledge of how to do things. It has two aspects to it: how many different things it can do, and how well can it do each of them. And it's technology, the knowledge of how to do things, that makes it possible to compete in world markets as a nation and as individual producers of castings.

The reason that is important is that, difficult or easy, like it or not, the only really effective way for any company or industry to compete over the long haul is to have the kind of technology that enables it to offer a better product than the competition. America grew into the great nation it is today on the results of working and striving for a better way, because that always has been the only way to achieve any real progress or improvement in our lives.

GETTING STARTED IN MICRO-G

The Microgravity Materials Science Laboratory (MMSL) has been established at NASA Lewis as part of NASA's longstanding Microgravity Science and Applications Program. It is a national facility that is available to scientists and engineers from industry, the academic community, and other government agencies. The laboratory is equipped to make it easy to conduct research aimed at taking the first step toward developing an understanding of how gravity affects materials and processing techniques. The MMSL contains functional duplicates of research equipment that is flown on the space shuttle, enabling the visiting researcher to understand the experiment better in a 1-g environment by using equipment configured to simulate flight-type hardware.

The MMSL currently provides experimental capabilities to support research in the areas of metal and alloy solidification and crystal growth. Other areas of materials research also can be considered, and capabilities for materials research in glasses, ceramics, and polymers are being added for future use.

During the design of the MMSL, major emphasis was placed on keeping the experimental equipment used for microgravity materials research in a single location, with key support capabilities incorporated into the laboratory. The MMSL currently consists of three experimental laboratory rooms; a data analysis room; a dedicated metallography laboratory; a dedicated machine shop; an experiment build-up area; and office space for visiting researchers. The experimental equipment and the computational analysis capabilities in the data anlysis room are the core of the MMSL. The following are brief descriptions of some of the capabilities and operational aspects of the major pieces of equipment.

General purpose furnace. - The general purpose furnace (GPF) is a three-zone furnace that is used to melt and resolidify experimental specimens. It simulates the functions of one of the three furnace cavities in the GPF that is flown on the space shuttle.

Electromagnetic levitator. - The electromagnetic levitator is a 25-kW induction furnace capable of levitating and melting metal alloy samples of up to 30 g in a vacuum or in an inert atmosphere. The EML is mounted on a 1 sec drop tube for microgravity solidification. Samples also can be quenched directly below the EML without falling through the drop tube.

Instrumented drop tube. - The instrumented drop tube provides 1 sec of "containerless solidification" to study phenomena such as undercooling. Temperatures from 700 °C are measured optically, and up to ten samples a day can be dropped.

Undercooling furnace. - The undercooling furnace is designed to study the effects of undercooling on the microstructure of alloys. Prealloyed and slag-refined specimens can be melted and resolidified repeatedly under controlled conditions to achieve a desired degree of undercooling. The sample can be quenched in a silicon oil bath when recalescence is observed. Experiments can be run in a vacuum or under an inert gas cover.

Dendrite growth apparatus. - The isothermal dendrite growth apparatus observes the growth and morphology of individual free dendrites in a transparent super-cooled melt. Materials studied are organics, and they generally fall under the classification of plastic crystals--e.g., succinonitrile. The organic material serves as a model for metal and alloy dendritic growth. The apparatus also measures dendrite growth velocities, tip radii, and side-branch spacing.

Master melt furnace. - The master melt furnace is an induction-heated furnace used to melt high-purity metals and alloys in a vacuum or a controlled inert gas atmosphere. This is a general facility for preparing experimental materials.

High vacuum furnace. - The high vacuum furnace is a general purpose, resistance-heated furnace for heat treating metals and metal alloys in a vacuum or an inert gas atmosphere.

In addition, a visiting researcher will be supported by Lewis' computer capability and microstructural characterization, chemical characterization, and spectrometric analysis facilities.

The MMSL, however, is only the first step that can be taken with an experiment. A typical scenario for a microgravity materials experiment at Lewis would begin by establishing 1-g baseline data in the MMSL and then proceeding, if indicated, to a drop tower or to simulated microgravity in a research aircraft to qualify the project for space flight.

Lewis has two drop towers. The larger of the two is designed to provide 5 sec of low gravity. Experimental packages are dropped in free-fall a distance of 430 ft in a vacuum. Reducing the air pressure inside the shaft to 10^{-2} torr lowers the air drag to less than 10^{-5} g. Test packages are decelerated in a container filled with pellets of expanded polystyrene, experiencing a force of about 35 g in the process of stopping in a distance of less than 20 ft. A 195 ft drop tower can simulate microgravity for 2.2 sec. The free-falling package is isolated from aerodynamic drag by a drag shield.

Lewis also operates a Model 25 Learjet that can provide up to 22 sec of microgravity. The low gravity environment is obtained by flying the aircraft through an 8 000-ft parabolic trajectory at altitudes between 10 000 and 30 000 ft. Many materials science experiments can be performed within the limited times of low gravity provided by these facilities.

Since the space shuttle currently offers up to seven days of microgravity, it greatly broadens the types of materials science and processing experiments that can be conducted in low gravity. Indeed, the primary emphasis of the MMSL is to provide experimental capabilities for developing a microgravity materials science idea into a space shuttle experiment and/or a commercial venture in space. The coordination and management of flight experiments aboard the shuttle does not rest with the MMSL. However, the technical staff within the Materials Division and the Space Experiments Office at Lewis will assist a visiting researcher in obtaining information and making the correct contacts to facilitate application for a shuttle flight.

A SIMPLE PROCEDURE

How does one make use of this unique facility? Application to use the MMSL requires the submission of a brief proposal describing the experiment. The proposed research must be related to microgravity materials science topics. Although the work conducted in the MMSL is performed in Earth gravity (1 g), the proposed experiment must demonstrate the intent to conduct follow-on experimentation in a microgravity environment. This may include either ground-based microgravity facilities or application to NASA to fly the experiment aboard the space shuttle.

The purpose of the proposal is to demonstrate briefly the technical merit of the experiment and its potential relationship to microgravity materials science. The proposal also must indicate what MMSL capabilities are required.

CURRENT WORK

Lewis is now, and has been for years, heavily involved in microgravity materials research. Current projects include the study of metal and alloy solidification fundamentals. The role of gravity on liquid metal fluid flow and containerless processing opportunities is being evaluated. Current activities also involve the study of macrosegregation by Dr. V. Laxmanan of Case Western Reserve University and by Prof. Angus Hellawell of Michigan Technical University.

Undercooling and bulk undercooling are being examined by Dr. Laxmanan and Dr. Surendra Tewari, a National Research Council research fellow, both in residence at NASA Lewis; by Professors Merton C. Flemings and Julian Szekely of Massachusetts Institute of Technology; by Prof. Martin Glicksman of Rensselaer Polytechnic Institute (RPI); and by Prof. John H. Perepezko of the University of Wisconsin.

Prof. Glicksman and his associates have made significant progress in investigating the effects of gravity on the processes of diffusion controlled dendritic growth. They have worked extensively with pure succinonitrile (SCN), a transparent substance that is a model material for metallic solidification and is very useful for laboratory studies. This work has been extended to include dilute binary alloys--that is, SCN with small additions of either argon or acetone. The RPI researchers have shown that linear morphological stability theory successfully predicts dendritic growth behavior in both the pure and dilute binary alloy systems.

The influence of the gravitational body force on dendrite growth kinetics has been shown to be highly dependent on growth orientation and on the level of the thermal supercooling. In fact, an abrupt transition occurs at a critical supercooling, above which diffusion dominates the growth process and below which convective transport dominates. By using a different material, pivalic acid, the effect of anisotropy in the solid-liquid surface energy on the dendritic growth kinetics has been determined. Prof. Glicksman now is preparing a flight experiment to demonstrate growth behavior in SCN in a microgravity environment.

The same investigators also have studied the influence of gravity and rotation on convectively induced crystal-melt instabilities. The stability of the crystal-melt interface surrounding a vertical, coaxial melt annulus undergoing stable convective flow was studied. Heat transfer experiments with a phase change were carried out on high-aspect ratio, vertical cylinders containing an axial heat source. A novel instability, designated as a "coupled mode," was found due to the effect of convection on the deformable crystalmelt interface. This instability occurs above a critical Grashof number of about 160, which is an order of magnitude smaller than that corresponding to a rigid-wall interface. At instability, the helical crystal-melt interface was found to rotate with a period ranging from a few minutes to more than ten hours, depending on the radial gap in the melt zone. The scalings were fully characterized both in a linear stability analysis and in an experiment with general agreement between them.

DENDRITE STUDIES

During the past year, work was completed by Dr. Laxmanan on a simple model to describe dendritic growth in a binary alloy melt. This model describes satisfactorily many known features of dendritic growth. For example, it predicts that a dendritic interface will become a planar interface at both very low and very high growth rates. (When the interface becomes planar, there is no segregation whatsoever in the solid formed.) Previous models have been unable to predict a planar interface at the limit of high growth rates.

Dr. Laxmanan's model also describes how the amount of eutectic (which represents the amount of severely segregated material in the finally solidified alloy) will decrease and eventually vanish at both extremes of very low and very high growth rates. Moreover, the model is able to derive an important dimensionless parameter, which has been called the dendrite tip stability parameter, from steady-state considerations alone. In the past, it has been believed that this parameter could be obtained only by resorting to ideas coming from the marginal stability approach. The values of the tip stability parameter predicted by the new approach are remarkably in agreement with those obtained from "marginal stability" considerations. The simple model also describes the underlying reasons for the differences between the two radically different approaches, and thereby allows a coalescence of the theoretical background into a single, self-consistent framework.

Dr. Laxmanan has obtained final approval for one shuttle experiment leading toward a proposed series of three additional shuttle experiments on the Solidification in a Binary Alloy Melt. The first of these experiments is designed to simulate macrosegregation occurring in large ingots commonly produced by the steel, nonferrous, and superalloy industries and will make use of the general purpose furnace.

Prof. Flemings and his associates at MIT have conducted research in the following four related areas:

(1) Thermal measurement during undercooled solidification of droplets of nickel-based alloys.

(2) Metallographic analyses of the resulting highly undercooled metal droplets.

(3) Analytical work to model the droplet solidification process considering high undercooling.

(4) Planning and flight specimen preparation for the MIT electromagnetic levitator experiments in the space shuttle.

Specific results showed that measured undercoolings in alloy samples ranged up to about 300 K and both total solidification time and recalescence time become shorter with increasing initial undercooling. In the case of a hypoeutectic (Ni-25 wt % Sn) alloy, a range of recalescence times was observed from 500 ms for a low undercooling (T = 35 K) to 2 ms for a high undercooling (T = 230 K). Thermal profiles upon solidification of hypoeutectic composition alloys showed the existence of two distinct nucleation events. Although cooling rates before nucleation generally were low (50 K/s), fine microstructure similar to those expected in rapid solidification processing were typically observed. It also was observed that the fineness of microstructure increased with increasing undercooling and that uniform distribution of second phases was achieved by increasing undercooling.

Prof. Szekely and his associates at MIT have developed a mathematical representation for the electromagnetic force field, the fluid flow field, and the temperature field (for transport-controlled kinetics) in a levitation melted metal droplet. The technique of mutual inductances was employed for the calculation of the electromagnetic force field, and the turbulent Navier-Stokes equations and the turbulent convective transport equations were used to represent the fluid flow field, the temperature field, and the concentration field. The governing differential equations, written in spherical coordinates, were solved numerically. The computed results were found to be in good agreement with measurements reported in the literature regarding the lifting force and the average temperature of the specimen and carburization rates, which were transport controlled. The mathematical representation will be used to model the functions of the space shuttle EML in support of Prof. Flemings' shuttle experiment. Both normal gravity and microgravity situations have been modeled. Professor Szekely also is preparing for a shuttle experiment in which he will monitor the surface flow in a molten sphere that has been heated inductively.

A model binary lead-tin alloy in sample sizes of about 180 g (6.3 oz) has been chosen for these experiments. Severe segregation, typical of that found in the more massive industrial ingots, has been reproduced in small, slowly cooled lead-tin samples in ground-based experiments. The sample solidification times, which are on the order of several hours, are comparable to the solidification times encountered in large industrial ingots. That is the main reason for the severe segregation observed. It generally is believed that the underlying cause of this severe segregation is gravity-driven convection, which occurs during the solidification process. Removal of this convective disruption during solidification in the shuttle experiment will verify the gravity influence theory. The proposed follow-up shuttle experiments are to obtain fundamental information on the details of the dendritic solidification morphology in this alloy. That would verify (or refute) the previously discussed theories describing dendritic growth occurring during solidification.

Prof. Flemings and his associates have completed all ground-based experiments and specimen preparation needed to support his electromagnetic levitator flight experiments on alloy undercooling. More specifically, they have conducted numerous nickel-tin alloy undercooling experiments at MIT. The experiments proved that their theoretical concepts were valid and resulted in several published reports. In addition, they developed a technique to fabricate glass-coated nickel-tin EML flight specimens and produced the 18 required specimens.

Prof. Glicksman and his associates have completed the ground-based science needed to support their proposed flight experiment on dendritic crystal growth and have submitted their Science Requirements Document. More specifically, they have developed a bench apparatus and conducted hundreds of experiments measuring the growth rates and tip radii of succinonitrile dendrites. These experiments have verified theoretical concepts and confirmed the feasibility of the proposed space experiment. NASA Lewis is developing the flight apparatus conceptual design.

Prof. Szekely and his associates have developed a mathematical description for molten metal fluid flow with electromagnetic levitation for both normal and reduced gravity. They also have developed preliminary design criteria for a space shuttle experiment. The understanding of electromagnetically driven flows has been applied to both laboratory scale and industrial scale induction furnaces.

AN AMERICAN EDGE

The price of anything has two parts to it. It always can be stated in terms of money per product. In other words, it's a fraction with a numerator and a denominator, and there are, of course, two ways to decrease the value of a fraction: Either decrease the numerator or increase the denominator. In the case of a casting made in an American foundry, the chances of being able to decrease the numerator--that is, ask fewer dollars for the product--are extremely small. On the other hand, the research opportunities available to American foundrymen through NASA mean that the chances of being able to increase the denominator by developing better technology and offering a casting buyer greater value for his money--even the guy who has a record of buying strictly on price--are very good indeed. And recall the words of Bob Jones of Research and Development magazine: "There are direct, demonstrable, traceable connections in the progression from high technology to productivity to profitability."

The need for new and better technology, always present, is even greater now. The means to acquire that technology through microgravity research are at hand. The funds for such research can be found.

What in the world are we waiting for?

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16. Abstract

A research expenditure is money spent in an attempt to purchase superior technology, which will produce a superior product, and thus gain for a company a competitive advantage in its markets. NASA's Microgravity Science and Applications Program is directed toward research in the science and technology of processing materials under conditions of low gravity. The objective is to make a detailed examination of the constraints imposed by gravitational forces on Earth. The program is expected to lead, ultimately, to the development of new materials and processes in Earth-based commercial applications, adding to this nation's technological base. An important resource that U.S. researchers have readily available to them is the new Microgravity Materials Science Laboratory (MMSL) at NASA Lewis Research Center in Cleveland. A typical scenario for a microgravity materials experiment at Lewis would begin by establishing 1-g baseline data in the MMSL and then proceeding, if it is indicated, to a drop tower or to simulated microgravity conditions in a research aircraft to qualify the project for space flight. A major component of Lewis microgravity materials research work involves the study of metal and alloy solidification fundamentals.

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