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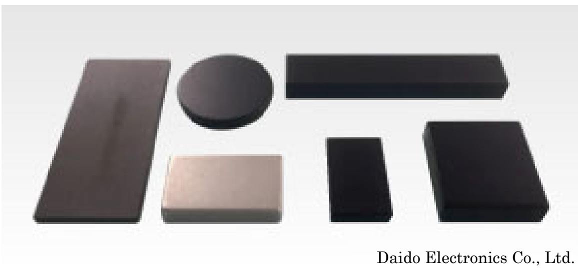
Press Release
September 29, 2023

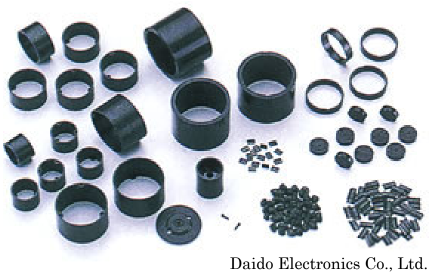
The Honda Prize 2023 Awarded to Dr. Masato Sagawa and Dr. John J. Croat

—Invention of the Neodymium (Nd-Fe-B) magnet and their contributions to its practical application—

The Honda Foundation is a public interest incorporated foundation established by Soichiro Honda and his younger brother Benjiro, and it is currently led by President Hiroto Ishida. The foundation established the Honda Prize in 1980 as Japan's first international award that acknowledges achievements contributing to "the creation of a truly humane civilization." In 2023, the 44th Honda Prize will be awarded to Dr. Masato Sagawa (an advisor to Daido Steel Co., Ltd. and the president of NDFEB Corporation) and Dr. John J. Croat (former president of John Croat Consulting, Inc.), both of whom invented the world's most powerful permanent magnet, the neodymium magnet. They established two different methods for manufacturing the magnet at approximately the same time—but completely independently.



Sintered neodymium magnet



Bonded neodymium magnet

Permanent magnets play an important role as a fundamental material in modern society and are widely used across various industries, including electronics, industrial machinery, and automobiles. When Dr. Sagawa and Dr. Croat started their research, the most powerful magnet was the samarium-cobalt (Sm-Co) magnet, developed in 1969.

In their independent research projects, both Dr. Sagawa and Dr. Croat pursued the potential of magnetic materials using iron (Fe), which is more abundant and has a greater magnetic moment*1 than cobalt. They added the rare earth element neodymium (Nd), in place of samarium, and a small amount of boron (B) to the iron-based magnet, thereby creating the Nd-Fe-B permanent magnet. In 1982, at roughly the same time, Dr. Sagawa presented a paper on the sintering process, and Dr. Croat presented his paper on the rapid solidification process as their magnet manufacturing methods.

The arrival of the neodymium magnet (Nd-Fe-B permanent magnet), which shows a high coercivity even with a piece just a few millimeters in size, enabled a significant size reduction in motors and hard disk drives, thereby advancing IT usage in society. The neodymium magnet now occupies 95% of the permanent magnet market for the use of motors in wind turbines and in electric and hybrid vehicles. This magnet accomplished the wider electrification of motor operations while improving motor efficiency, which in turn significantly contributes to reducing CO_2 emissions.

Over the years, the Honda Foundation has been promoting as its mission "ecotechnology,"[*2] which aims to contribute to the development of scientific technology and humankind, harmonizing both the human and natural environments. As the inventions are fully in accord with this mission, the Prize will be awarded to Dr. Sagawa and Dr. Croat for their inventions, which are worthy of the highest recognition.

The award ceremony will be held at the Imperial Hotel in Tokyo, Japan on November 16, 2023. In addition to the prize medals and the diplomas, the laureates will be awarded a total of 10 million yen.

*1 Magnetic moment : A measurement of the strength of attraction of a magnetic field
*2 Ecotechnology : A neologism combining an image of the natural world (ecology), technology within the context of civilization as a whole. It was advocated by the Honda Foundation in 1979 and seeks new technological concepts required by human society to further the coexistence of people and technology.

[The Honda Foundation]

The Honda Foundation was established in December 1977 with a donation from Soichiro Honda, the founder of Honda Motor Co., Ltd., and his younger brother, Benjiro. The Foundation defines approaches to resolve issues by harmonizing the human and natural environments in "ecotechnology." The Foundation focuses on the following three activities to develop and disseminate ecotechnology.

(1) Honda Prize: An international award that acknowledges significant achievements in the field of ecotechnology
(2) International symposia and colloquia: Providing opportunities for extensive discussions into various issues of modern society to search for resolutions
(3) Honda Y-E-S Program: Various programs designed to develop young talented engineers and scientists for the next generation

The Foundation aims to contribute to "the creation of a truly humane civilization" through these activities.

History of Permanent Magnet Research: Development Commenced in Response to Social Demand

A permanent magnet produces a magnetic field automatically and constantly without any external energy supply. The first permanent magnet was found in naturally occurring mineral in Magnesia, Greece, in about 600 BCE. An artificial permanent magnet was developed by Dr. Kotaro Honda in 1917, which was followed by various other types of artificial magnets. At the same time, research on a magnet that combined cobalt and a rare earth also progressed. In 1969, Dutch scientist K.H.J. Buschow and his colleagues established a compression molding process to manufacture magnets, and this process enabled the commercialization of samarium-cobalt permanent magnets.

However, both samarium and cobalt are rare earth elements, primary produced in Africa which entails associated price rise risks. As it is essential to secure stable mass production for industrial use magnets, what was really sought was a high-performance magnet made from abundant and low-priced materials.

Dr. Sagawa's Research: Invention of the Neodymium Magnet and Sintering Process

In 1975, Dr. Masato Sagawa was working on research to reinforce the mechanical strength of the samarium-cobalt magnet. In this research, he was questioning why magnets made from iron, which is abundantly available and has a high magnetic moment, does not exhibit a high coercivity. Meanwhile, he learned that the development of rare earth and iron (R-Fe) magnets had been difficult due to the small interatomic distances between the iron atoms. With this knowledge, he developed a hypothesis that adding elements with a small atomic radius between the iron atoms would expand the iron's interatomic distance. He then started making alloys of various compositions by putting different minerals into an arc furnace. He chose elements with small atomic diameters, such as carbon and boron, as additives to the R-Fe alloy, and tested various rare earth elements, including samarium and neodymium. In 1978, he eventually found that the combination of neodymium, iron, and boron produced the greatest coercivity.

Dr. Sagawa's detailed study then extended from various compositions to different manufacturing conditions, including different particle sizes of alloy powder and thermal applications. As a result, he established his own sintering process, in which the magnetic powder is compressed in a mold for shaping and then sintered to form bonds between the particles to reinforce the mechanical strength.

Sintered neodymium magnets showed a maximum energy product[*3] of 320 kJ/m^3 (the maximum energy of the samarium-cobalt magnet at that time was 240 kJ/m^3). Mass production of the magnet began only three years from the time that Dr. Sagawa applied for the patent in August 1982. This permanent magnet was originally used in automobiles and home appliances, but today it is used extensively throughout the world, for example, in EV motors and wind turbines.

Dr. Croat's Research: Invention of the Neodymium Magnet and the Rapid Solidification Process

In 1972 Dr. Croat joined the Magnetic Materials Group of the General Motors Research Laboratories whose mission was to develop high performance, low-cost permanent magnets for use in automotive components. The world economy was confronted with the 1973 OPEC oil embargo which significantly increased gasoline prices worldwide and greatly stimulated the search for lighter weight automobiles with greater fuel economy. Although $SmCo_5$ magnets had been discovered in the 1960s, all permanent magnet researchers dreamed of discovering a lower cost permanent magnet composed of the more abundant, lower cost rare earth elements Nd and Pr in combination with Fe.

In 1982 Dr. Croat discovered the ternary intermetallic phase $Nd_2Fe_{14}B$ while investigating the effect of various "glass forming elements" like silicon, carbon and boron on the properties of rapidly solidified Nd-Fe and Pr-Fe alloys. This intermetallic phase is the basis of all families of NdFeB permanent magnets currently being produced. The rapidly solidified material became the basis for a new family of magnetically isotropic bonded permanent magnets. Although the magnetic strength of these bonded magnet is lower than that of a sintered magnet, the alternate method for producing NdFeB magnets, thin-walled bonded ring magnets with high thermal stability can be rapidly produced that have found wide application in small motors for a wide range of industrial, consumer electronic and computer peripheral applications. Such thin-walled ring magnets are almost impossible to produce by the sintering process.

Dr. Croat's process was later developed into a hot-deformed process in which nanocrystalline magnetic powder made by the rapid solidification process is hot-deformed in a mold. This led to the development of a family of hot-deformed neodymium magnet that possessed an equivalent strength to that of a sintered magnet. Notably, the process was capable of producing thin-walled, axially oriented ring magnet that are currently being used in high-end servo and stepper motors.

Present and Future of Neodymium Magnets: Overcoming Challenges and Widening Applications

Neodymium magnets suffered from low thermal durability compared to samarium-cobalt magnets when applied in industrial purposes. This issue was addressed by adding dysprosium (Dy), another rare earth element, which improved the magnet's thermal durability to nearly 200°C, thereby enabling applications in motors.

The magnet requires the proportion of dysprosium to be approximately one-third of the neodymium by weight to make it thermally durable; however, the estimated global reserves of dysprosium are less than one-tenth those of neodymium. This forced the research to reduce the use of dysprosium. A solution was eventually found in the technological innovation of grain boundary diffusion,[*4] which significantly improved the coercivity at the same time.

Forty years after its invention, uses and applications of the neodymium magnet are widening. Its powerful coercivity contributes to both the downsizing and weight reduction of motors. Sintered magnets are used in a range of areas, including automobiles, air conditioners, hard disk drives, washing machines, vacuum cleaners, elevators, and industrial machinery, contributing to energy saving. The easy-to-shape bonded neodymium magnets are found to be particularly useful in small sites where compact yet high-performance magnets are required, such as spindle motors in hard disk drives, small motors in automobiles, and mobile phone speakers. The hot-deformed neodymium magnet is mainly used in driving motors and electric power steering motors for automobiles.

Demand for neodymium magnets is expected to greatly increase—particularly for motors in the next generation of electric vehicles (xEVs), wind turbines, drones, and electric airplanes. Therefore, it is necessary to improve the magnet's characteristics even further. Neodymium magnets also support the evolution of energy-saving technologies designed to reduce CO_2 emissions. This is another factor that would further increase demand for the magnet towards achieving carbon neutrality. The importance of streamlining manufacturing is also increasing, including improving resource efficiency and recycling technology.

Expectations are further rising for the continued development of magnetic materials to improve their characteristics and to resolve any issues in their manufacture.

*3 Maximum energy product : The maximum value of the energy obtained from a magnetic material.

*4 Grain boundary diffusion : A method to diffuse heavy rare-earth elements—which tend to spread over the surface of the magnet—into the intergranular spaces by applying high temperatures. The heavy rare-earth elements are dispersed through the spaces between crystal grains (grain boundaries) and concentrate on the surface of neighboring crystal grains. This improves thermal durability with a smaller amount of heavy rare-earth elements, while preventing any reduction in the coercivity due to unwanted local concentrations of the heavy rare-earth elements.

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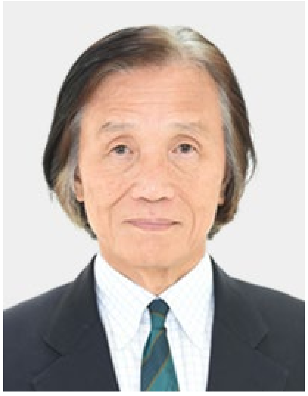
Dr. Masato Sagawa



Adviser, Daido Steel Co., Ltd.

President, NDFEB Corporation

Born

August 3, 1943, Tokushima, Japan

Education

1966	B. A., Department of Electrical Engineering, Kobe University
1968	M. A., Department of Electrical Engineering, Kobe University
1972	Dr. Eng., Metallurgical Materials Engineering, Graduate School of Engineering, Tohoku University

Employment History

1972-1982	Fujitsu Ltd.
1982-1988	Sumitomo Metal Industries, Ltd. (now Proterial, Ltd.)
1988-2012	Established Intermetallics Co., Ltd., Appointed as Representative Director
2013-present	Established NDFEB Corporation, Appointed as Representative Director
2016-present	Adviser, Daido Steel Co., Ltd.
2017-2019	Adviser, Nippon Densan Co., Ltd. (now NIDEC Corporation)
2017-2019	Specially Appointed Professor, Institute of Advanced Energy, Kyoto University
2019-present	Distinguished Invited University Professor, Tohoku University
2019-present	Guest Professor, Central Iron & Steel Research Institute, China
2022-present	Senior Fellow, Research Promotion Organization for Carbon Neutrality, Meijo University

Awards

1984	Osaka Science Prize
1985	Minister of Science and Technology Agency Award
1986	International Prize for New Materials, American Physical Society (now James C. McGroddy Prize for New Materials)
1988	The Japan Institute of Metals and Materials Meritorious Award
1990	Asahi Prize
1991	Japan Magnetics Society Award
1993	Okochi Memorial Prize
1998	Acta Metallurgica J. Hollomon Award
2003	Honda-Kinen Prize

2006 Kato-Kinen Prize

2012 Japan Prize

2016 Special Award, Nagamori Award

2018 NIMS Award 2018

2020 The Japan Institute of Metals and Materials Gold Medal Award

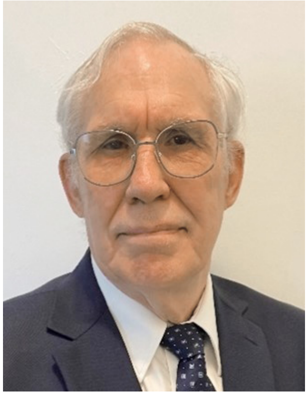
2022 Queen Elizabeth Prize for Engineering

2022 IEEE Medal for Environmental and Safety Technologies

<u>Publications</u>

- "Permanent Magnets: Materials Science and Applications", Masato Sagawa, Masaaki Hamano, Makoto Hirabayashi, AGNE Gijutsu Center Inc., ISBN 978-4-901496-38-4 (2007)
- "All About Neodymium Magnets: Protecting the Earth with Rare Earths", Masato Sagawa, AGNE Gijutsu Center Inc.,
  ISBN 978-4-901496-58-2 (2011)
- "The Work Style of the Strongest Engineer", Shuji Nakamura, Masato Sagawa, Jitsumukyoiku-Shuppan Co., Ltd.
  ISBN 978-4-788911-95-6 (2016)

Dr. John J. Croat



Former President, John Croat Consulting Inc.

Born

May 23, 1943, Iowa, U.S.A. (U.S.A. citizenship)

Education

1965 BA Degree, Simpson College, Indianola Iowa, U.S.A.

1968 MS Degree, Iowa State University, Ames Iowa, U.S.A.

1972 PhD Degree, Iowa State University, Ames Iowa, U.S.A.

Employment History

1972-1980 Research Metallurgist, General Motors Research Labs., Warren Michigan (USA).

1980-1984 Senior Research Metallurgist, GM Research Labs., Warren Michigan.

1984-1986 Asst. Chief Process Engineer, Delco Remy Div. GM Corporation

1986-1990 Chief Engineer, Magnequench, Delco Remy Div., GM Corporation

1990-1996 Managing Director, Magnequench, Delco Remy Div., GM Corporation

1996-2004 President, Advanced Magnetic Materials (AMM) Korat, Thailand

2004-2017 President, John Croat Consulting Inc.

Prizes and Honors

1985 Applications of Physics Prize, American Institute of Physics

1985 Distinguished Alumni Award, Iowa State University

1986 International Prize for New Materials, American Physical Society
(now James C. McGroddy Prize for New Materials)

1994 Outstanding Engineering Achievement Award, American Society of Metals

2022 IEEE Award for Environmental and Safety Technology

Publications

- Books

1. Rapidly Solidified NdFeB Permanent Magnets, Elsevier Published, Published 2018.
2. Modern Permanent Magnets, Elsevier Publishing, Published 2022. Co-edited with John Ormerod.

- Journal Publications

1. The Properties, Preparation and Handling of Pure Rare Earth Metals, Proc. Interamerican Conference on Material Technology, San Antonio, TX, May 20-24, 1968.
2. The Preparation and Properties of "Ultra Pure Metals", Proc. International Conference on Rare Earth Metals, Paris, France, Vol. I, Page 27 (1969).

3. Magnetic Properties of High Purity Scandium and the Effects of Impurities on These Properties, J. of Chem. Phys., 58, No. 12, 5514 (1973).
4. Magnetic Properties of High Purity Yttrium, Lanthanum and Lutetium and the Effects of Impurities on These Properties, J. Chem. Phys., 59, No. 5, 2451 (1973).
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6. Crystallization and Magnetic Properties of Melt-Spun Nd-Fe Alloys, J. Magn. and Magn. Matl., 24, 125 (1981).
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8. Observation of Large Room Temperature Coercivity in Melt-Spun Nd0.4Fe0.6, Appl. Phys. Lett. 39(4), 357 (1981).
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22. Microstructure of Rapidly Solidified Nd-Fe-Co-B Alloys, IEEE Trans. Magn., 28 (5), 2853 (1992).
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