

Spinning process using robot technology

— Field-based bricolage of manufacturing technology —

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Metal spinning is a plastic forming method in which a rotating metal material is pushed by a roller to form a product. It is suitable for the production of a wide variety of products in small quantities owing to the low cost of forming dies. We have achieved the fabrication of noncircular shapes by using robot technology, which is difficult to realize by conventional methods. A prototype of a practical spinning machine has been developed in collaboration with a spinning machinery manufacturer. In this research, we have basically set our preference for commercial realization over academic contribution. This research was carried out in a bottom-up and trial-and-error manner, and the targets of this research were frequently modified depending on the situation. Bricolage, utilizing the combination of available and limited resources at hand, played a key role in the research activity. Decision-making reflected three-actuals theory, which values the actual field site, actual object, and actual situation. We included increased customer satisfaction in the criteria of value and carried out sales activities as a part of the research.

Keywords : Metal spinning, robot, metal forming, bottom-up, bricolage, san-gen-shugi

1 Outline of the developed technology

Metal spinning is a plastic forming method in which a metal blank such as a sheet or pipe is rotated by a motor and formed into a desired shape by pressing a roller tool against the material (Fig. 1).^[1] This method can be applied to various metal materials, including aluminum, iron, and stainless steel, as a method of creating hollow metal products. It is used widely in various industries including lighting equipment, cooking utensils, automobiles, electrical appliances, chemical plants, pressure vessels, aerospace parts, and architectural decorations. Manual metal spinning is called *hera shibori* in Japanese, and it is known as one of the most advanced craftsman's skills in manufacturing. The advantages of spinning are as follows: 1) the tooling cost is low since only a male die is necessary, 2) the yield rate of the material is better than that of a cutting process, and 3) the equipment is small and does not make much noise or vibration because the force required in processing is small.

The author has been attempting to introduce robot control technology to metal spinning to enable processing with high additional value.^{[2]-[6]} In particular, we have developed spinning machines and methods that enable the forming of noncircular shapes such as elliptical, polygonal, and eccentric shapes. Other than circular objects, which can be formed by regular metal spinning, conventionally hollow metal products have to be manufactured by sheet bending and welding, which is a complicated procedure, or drawing, which requires expensive dies. In the new process, in general,

only one die (= mandrel) is necessary, or in some cases a mandrel is unnecessary, meaning that the cost of tooling can be kept low compared with that of the pressed products and the production process can be set up quickly. Currently, the processing time necessary per product is several tens of seconds to several minutes, making it unsuitable for mass production. However, it is expected to be very useful in high-mix low-volume production, one-time special orders, and prototype fabrication.

To form noncircular shapes, two methods, force-controlled spinning and synchronized spinning, are used. These enable the forming of noncircular shapes that cannot be made by a conventional spinning machine for circular products or by manual metal spinning by a skilled worker. In force-controlled spinning, a mandrel of the same shape as the desired noncircular shape is used to form the product.^[3] By controlling the pushing force of the roller at an appropriate

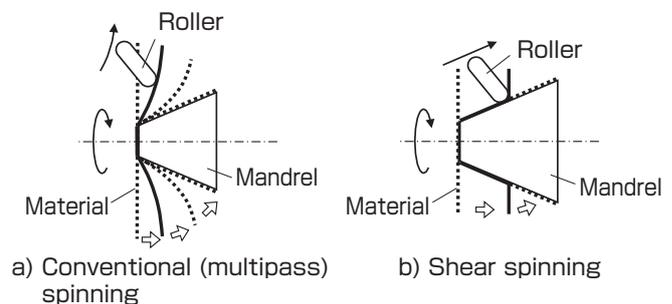


Fig. 1 Metal spinning (sheet)

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value, the material is pressed onto the rotating mandrel. Meanwhile, the roller is controlled by feeding at a constant speed in the direction parallel to the rotation axis of the mandrel. The roller moves along the mandrel to press the material firmly against the mandrel. As a result, a product that has the same noncircular shape as the mandrel can be fabricated (Fig. 2).

Initially, the roller was driven by ball screws in the spinning machine shown in Fig. 3 in our experiment. However, in forming the noncircular shape, it was necessary to move the roller in the radial direction very quickly along the surface of the mandrel. Therefore, we developed a new spinning machine where the roller was driven directly by linear motors (Fig. 4).^[4] Since the responsivity to force control is high and the roller follows the mandrel shape quickly, the time required for forming can be greatly reduced. Also, shapes with noncircular cross sections can be formed by open-loop force control without using a force sensor.

In synchronized spinning,^[5] the forming roller is numerically controlled by synchronizing the roller with the rotational angle of the workpiece. The spindle is driven by a servo motor in which the rotational angle can be controlled. The

spinning roller is moved back and forth in the radial direction according to the rotational angle of the workpiece, and the roller is moved so that the contact point between the roller and the workpiece tracks the desired cross-sectional form. The cross-sectional form is changed along the axial direction to form the entire workpiece into the desired shape. In this method, a noncircular cross-sectional shape can be formed without using a mandrel. This is particularly effective in forming a hollow tube with a noncircular cross section that is difficult to remove from the mandrel after forming. A prototype of a two-roller machine (Fig. 6) suitable for pipe forming by synchronized spinning was also developed.

A prototype of the practical spinning machine for noncircular shapes was jointly developed with Daitoh Spinning Co., Ltd., a specialist manufacturer of spinning machines (Fig. 7, Table 1).^[6] Both force-controlled spinning and synchronized spinning can be performed with this machine. Balanced-attraction linear motors, which cancel the magnetic attraction force between the iron-core coil and two magnetic track components, were employed to realize both increased propulsion and reduced friction. Steel sheets of 2 mm thickness and workpieces with diameters of 400 mm could be formed. Since its development, the machine

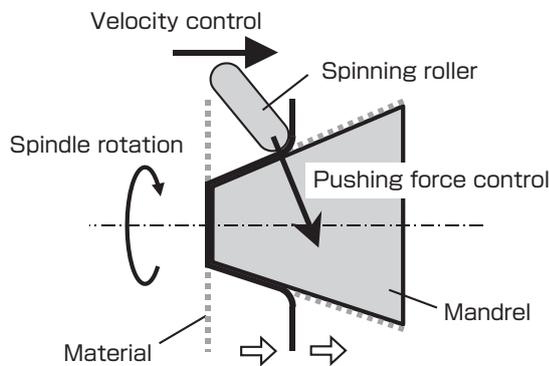


Fig. 2 Forming of non-circular shape by force-controlled spinning

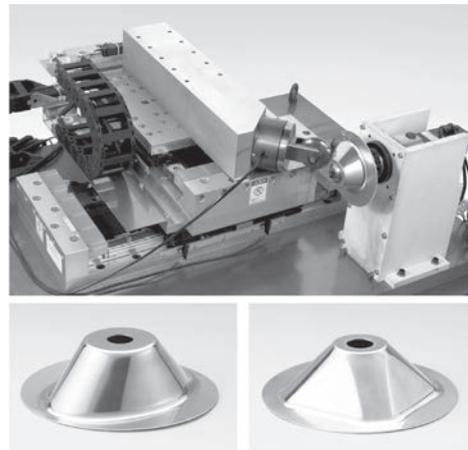


Fig. 4 Linear motor driven spinning machine (experimental) and product samples

http://staff.aist.go.jp/h.arai/linspin_j.html

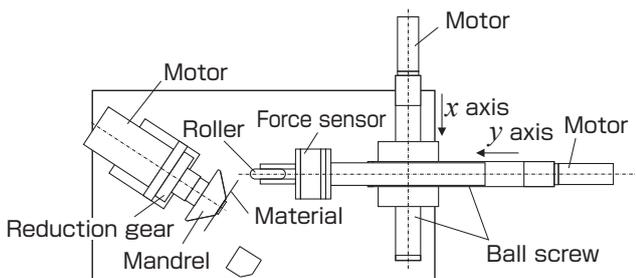


Fig. 3 Experimental spinning machine

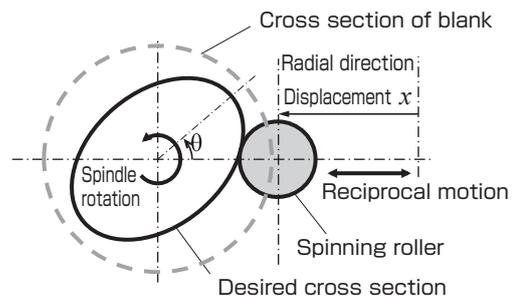


Fig. 5 Forming of non-circular shape by synchronized spinning

has been presented at various exhibitions such as the Japan International Machine Tool Fair and Ohta Industrial Fair, where the noncircular shape spinning was demonstrated. Daitoh Spinning started taking orders for machines based on this prototype. Only one order has been shipped so far, which was delivered to a sheet metal fabrication company called Papas Co., Ltd. (Fig. 8).

2 Background and motivation

2.1 Reflection of excessive emphasis on academism

This study was started around 2001 when AIST became an independent administrative agency. The beginning was a reflection of research in the robotics field (or the excessive emphasis on academism) that the author conducted during his time at the Agency of Industrial Science and Technology. For example, looking back at what we did, when explaining the objective of our research in the introduction of an academic paper, the goals set were impossible to realize in the near future and were fictions created to justify the academic research. Although the research objective of

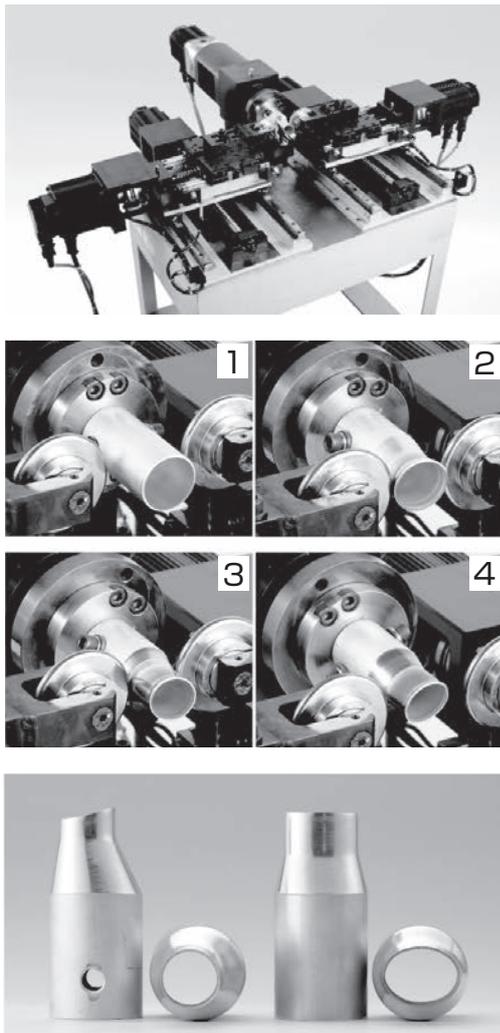


Fig. 6 Synchronized spinning using two-roller spinning machine

Table 1 Specifications of prototype machine

Dimension	Width 2875 mm × Depth 1820 mm × Height 1895 mm
X axis (radial direction)	Balanced-attraction linear motor, rated thrust 4000 N
Z axis (spindle direction)	Servomotor + ball screw, rated thrust 10000 N
Spindle	Servomotor + planetary gear, rated power 7.5 kW, rated speed 375 rpm
Workpiece	Maximum diameter 400 mm, maximum height 350 mm

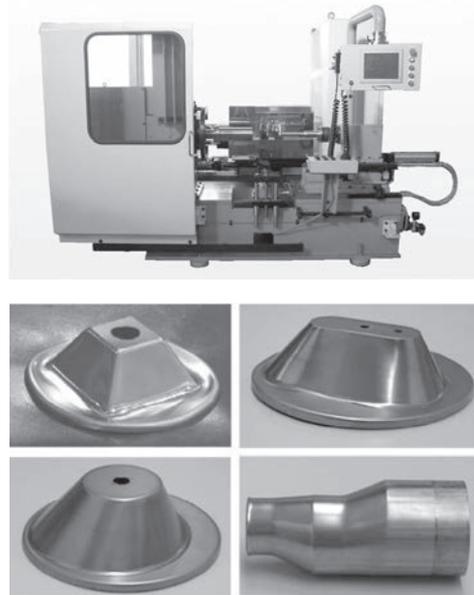


Fig. 7 Prototype of practical spinning machine for non-circular shapes



Fig. 8 Spinning machine for non-circular shapes introduced to a company

a paper is required to be somewhat plausible, stringent verification of its feasibility is not required, and this does not necessarily influence the judgment in the peer review process. On the other hand, once the paper is accepted for publication, the entire content of the research, including the research objective, which may be mere fiction, is authorized. Such a made-up research objective is useful for affirming the reason for the existence of the research, and the same reason is often carried over to the following research. The existence of a previous study may justify a subsequent study. As the citation of a research objective is repeated and spread among several researchers, the fiction turns into a verified truth and may exist on its own. I myself became apprehensive when a research objective that I wrote with full awareness that it was fiction was cited by other researchers.

When this research was started, industry and academia were separated in the robotics field. Although there have been many academic studies, the practical application of research results has been rare. A contributing factor might have been the problem of the fictionalization of research objectives. Until then, we had not been interested in industrial robots and manufacturing was not considered as an application target, which might have been the reason for not being able to do research on practical use. With this awareness, we started to seek topics of practical robot research in manufacturing.

2.2 Encounter with metal spinning

In August 2001, the first H2A rocket was launched successfully. As the nose cone of the rocket was fabricated by manual metal spinning, this procedure was broadcast repeatedly on television. There was a monozukuri or manufacturing boom at the time. The author became aware of metal spinning during this time, and because of what can only be explained as intuition, embarked on this research.

At first, the image was metal spinning carried out by a robot arm that consisted of a roller at the tip as an application of an industrial robot (Fig. 9), and it was considered as an

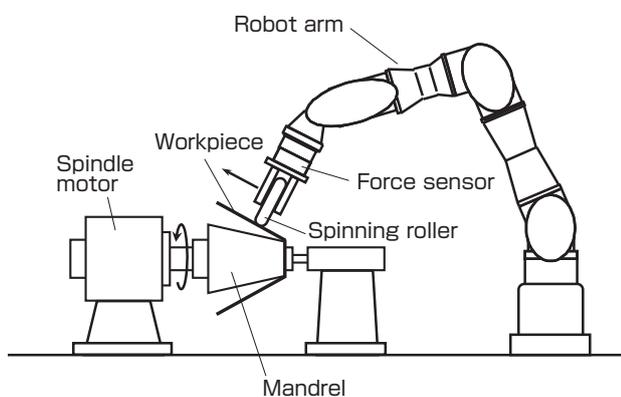


Fig. 9 Initial research concept (metal spinning robot)

example of engineering the artificial replication of skilled human labor. In robotics, force control of a robot arm has been studied for a long time, and considerable theoretical and technical know-how has been accumulated. However, since robot researchers were separate from the manufacturing industry, force control had been realized in only a few procedures such as assembly and grinding, and its effective application with high added value was still in the exploratory stage. In manual metal spinning, the sensory perception of the craftsman, particularly the perception of the force transmitted through the roller, plays a significant role. Also, since metal spinning involves incremental forming by partial deformation, the forming force is much smaller than that of other plastic forming processes. It was considered suitable for robots because of the many control parameters and the high degree of freedom. Since manual production was established as a business, it has been a high-mix low-production method with high added value, and we estimated that the profitability would be high if robot technology was introduced. Also in this research, there was a secondary intention of sending a message to other robot researchers. By presenting a specific case study of an excellent field of application where the advantages and potentials of robot technology could be utilized, we wished to arouse robot researchers' interest in manufacturing.

3 Research style and action principle

3.1 Bottom-up research style

For the author, this research was an outreach from the robotics field to the unfamiliar field of metal forming. Since we started with no preliminary knowledge, the research was commenced without preconceptions and progress took place in the dark. Therefore, we did not believe that the research goal would initially be set correctly, as mentioned in the previous section, and we took the stance that the goal was provisional. Therefore, we did not select a plan-driven method where a specific scenario for realizing a goal is set in a top-down style, and then the breaking down of the problem to the elemental technologies to be developed is carried out.

Instead, the strategy taken was to stay with a vague research goal and temporary scenario, go ahead and make something, and carry out revisions as needed, under the loose direction of "realizing a technology that may be useful for metal spinning by applying robotics technology." By operating an actual machine, the changes in the situation such as the progress of research, new inspirations, changes in awareness, and accidental external factors came into play. The research goal and scenario were changed frequently. For the elemental technology, whatever was available at the time was used, and the primary standard for the selection of elemental technology was that it was available and usable immediately. The technology developed was newly added to the inventory of elemental technologies. This was a bottom-up-style

exploratory approach, and rather than preliminary rationality through analytic planning, emphasis was placed on post facto rationality obtained by feedback of the results.^[7]

3.2 Direction of the research and action principle

The basic direction was to prioritize practical use with efficacy considered first rather than academic interest, and as mentioned earlier, effort was spent to eliminate the fictional element in the research objectives as much as possible. The action principle was characterized by 1) bricolage, 2) three-actuals theory, and 3) a focus on sales.

Bricolage is a concept introduced in *La Pensée Sauvage* (The Savage Mind) by the anthropologist Claude Lévi-Strauss^[8] as a primitive form of creative mental activity. Bricolage is a French word for “handiwork” and it means construction with whatever tools and materials are available. Although this concept is used frequently in the fields of art and education, recently, the practical value of bricolage in entrepreneurship and innovation has been discussed from the standpoint of technology management, knowledge management, and organization theories in the field of business administration.^{[9]-[14]} In the literature that discusses the role of bricolage in entrepreneurship under limited management resources,^[13] it is redefined as a “making do by applying combinations of the resources at hand to new problems and opportunities.” Here, resources are extended to a wider meaning including technology and people, not just physical resources such as tools and materials. The three main elements of bricolage are as follows: 1) to utilize the resources available at hand regardless of their originally intended use, 2) to generate new value from existing resources through combinations including usage outside the intended usage, and 3) to take action to resolve an issue without accepting the limitations. Although this research was carried out without consciously engaging in bricolage, it matches the above three elements.

Sangen shugi, or the three actuals, is a way of thinking that emphasizes the three *gen* (actuals) of *genba* (actual site), *genbutsu* (actual object), and *genjitsu* (actual situation). It is the basic stance that whenever a problem arises, rather than depending on theories, one should actually go to the site, take the actual object in one’s hands and look at it, and understand the reality of the situation. It is widely accepted as a code of conduct in Japanese companies including Honda and Toyota. This way of thinking is not unique to Japan and similar thoughts can be seen in Eugene S. Ferguson’s *Engineering and the Mind’s Eye*.^[15] In the success story of bricolage described in Reference,^[11] the development of wind turbine industry in Denmark was conducted with on-site emphasis. The three-actuals point of view is not merely about mentality, but it is effective in shortening the route from the final result to feedback and quickening the cycle of correction, and hence eliminating the noise and bias that may be added in the process. In this research, there were many cases where decision-making was based on the site, object, and situation

during the exploratory stage. However, AIST does not have a site of production where the developed result can actually be used. Therefore, several methods were devised to move as close as possible to such sites.

The researcher ultimately belongs to the service industry in the sense that the researcher engages in work to provide intangible assets. A service becomes meaningful and valuable only when it reaches the customer. Therefore, increased customer satisfaction was added to the value of the research, and we consciously made effort to gain awareness that sales activities were part of our research.

4 Progress of research

4.1 Start from handmade machine

We started by assembling a simple machine for actual metal spinning (Fig. 3). As an alternative to an expensive force sensor and servo drivers, junk parts from old machines were recycled, and the material cost was about one million yen. An old PC that was handed down from another researcher was used as the control PC. ISA bus I/O interface board was installed, and programming was done by using Turbo C++ in the DOS mode of Windows 98. Programs and control laws from past robotic research were used to drive the device. Although this configuration was outdated even at that time, real-time control with a 1 msec sampling interval was successfully achieved, and basic experiments on spinning using force control were conducted using this system.

4.2 Setback in robot arm application

On the other hand, the technological concept of realizing skilled techniques using an industrial robot failed at a relatively early stage. Metal spinning by a robot arm failed owing to the vibrations that occurred from the lack of rigidity, and although it was again attempted later,^[16] practical results have not yet been obtained. Another problem was that it was unclear who would be the customer for this technology. We were unable to decide on whether the customer would be manufacturers of industrial robots, user companies that process products using robots, or spinning machine manufacturers who would use the robot arm. Later we focused on adding higher functions to conventional machines with emphasis on the metal spinning lathe, rather than application to industrial robots. By doing so, the target of technology provision clearly became machine manufacturers.

4.3 Change in direction due to change in view of skills

As we learned about manufacturing in small factories from the books by Tomohiro Koseki, who is a former lathe worker,^{[17][18]} we became aware that the essence of skilled work is not the physical skills gained through repeated training but is in the creative thought process. There are skills best performed by humans and skills best performed

by machines, and it is meaningless to simply transfer human skills to a robot. Since the added value of a product obtained by skills is important rather than the skills themselves, the benefit of the machine should be explored rather than trying to copy human skills.

Since humans use machines on site, new skills required to master new technologies are born. In force-controlled spinning, the pressing force to be set is ultimately decided by the human personnel on site. Skill learning in manufacturing always includes a creative process.

Metal spinning started from making pots and pans, and the advanced skills required to create complex and precise products did not exist from the beginning. Even if muscles and hands are replaced by mechanical devices, the replicated skills are fixed ones. Human beings, who learn by trial-and-error and improve their skills on site, are still necessary. Therefore, rather than aiming to replace skilled workers, we aimed to develop a machine that would be an advanced tool and become effective only when utilized by a person.

4.4 Concentration on noncircular shape formation

On the other hand, the machine described in 4.1 was successful in forming noncircular shapes by the application of force-controlled spinning, and this became the selling point of the outcome of this research from then on. At that time, regular exchanges with companies started through the Collaboration Promotion Division. While we presented AIST's potential at meetings in which several companies in metal-spinning-related fields participated, the development target was narrowed down by listening to the companies' demands. Daitoh Spinning, a spinning machine manufacturer, participated in these meetings, and expressed their desire to carry out joint research as they became strongly interested in the forming of noncircular shapes. On the basis of this proposal, we obtained a joint research fund from the Small and Medium Enterprise Agency, and thus the prototype of the synchronized spinning machine was fabricated (Fig. 6).

In noncircular shape forming by force-controlled spinning, the important issue was shortening the spinning time. At that time, the author happened to visit the International Robot Exhibition and saw linear motors there. This generated the idea of using them in the spinning machine. In this study, effort was placed on patent application rather than academic publication. As a result of the patent application for the spinning machine using linear motors, we obtained funding for strengthening the patent from the Intellectual Property Division and were able to build the prototype of the linear motor machine (Fig. 4).

4.5 For the diffusion of the working machine

After repeated trial runs and metal spinning demonstrations

at exhibitions, we received a request for intellectual property licensing from Daitoh Spinning. Joint development of the prototype of the practical machine was conducted through the patent-related funding (Fig. 7). Meanwhile, the author moved to the Advanced Manufacturing Research Institute in 2009, and shifted his research from pioneering robot applications to actual processing technology. Daitoh Spinning started taking orders for the spinning machines that could handle noncircular shapes, but orders slowed down owing to the economic uncertainty after the Lehman Shock, and the company is now seeking ways to improve the situation.

4.6 Research and development that does not depend on a scenario

Looking back at the progress of research, it can be seen that there was no consistent scenario and that the research goal changed greatly owing to external and coincidental factors. As part of the positive external factors such as obtaining funding, exchange with companies, and participation in exhibitions, there were many instances where we were encouraged by the Collaboration Promotion Division and the Intellectual Property Division of AIST, and the roles played by such research-supporting sections in advancing the research were significant. Also in this research, the fact that the laboratories for the robotics and manufacturing fields were at neighboring locations, a legacy from the Agency of Industrial Science and Technology, worked positively, and this was particularly useful in gaining knowledge of the metal forming field.

5 Characteristic research activities

5.1 Synthesis by bricolage – bottom-up integration of elemental technologies

The construction of the experimental spinning machine described in the beginning of the previous section was typical bricolage, and bricolage at various levels was used in several parts of the research. Most elemental technologies can be organized as a hierarchical structure, and a function to be realized as seen from below becomes an elemental technology when seen from above. For example, we had the force control and position control technologies available as elemental technologies at the beginning of the research. These were combined to realize force-controlled spinning and synchronized spinning as functions of the spinning machine. In the next stage, these were combined as elemental technologies to conduct sheet and pipe spinning in actual parts. By building up the technologies from below, we filled our toolbox with an inventory of technologies (Fig. 10). The control laws that were the basic elements were derived from research done in the robotics field. For example, the impedance control used in the force-controlled spinning was modified from the control law used in a cooperative task between humans and robots.^[19]

While the linear motor that was employed to reduce the spinning time was a readily available, existing component, it was used in a slightly different way from the intended use. A linear motor stage is often used as a high-speed, high-precision positioning device, but in our research, it was used as a force control actuator with excellent backdrivability (the property of being pushed back flexibly in accordance with the applied force). The characteristic of bricolage where an attribute of a resource is utilized to realize novel functions can be seen here. Also, using the fact that a linear motor has no loss due to the transfer mechanism, for example, a ball screw, the force control was accomplished by open-loop control without use of a force sensor. This idea was obtained from the author's experience of the open-loop force control of a direct drive robot (a robot where a reduction gear is not used in the joint axis) carried out over 20 years ago.^[20]

Through the collaboration with Daitoh Spinning, we were able to increase our repertoire of elemental technologies rooted in on-site use. In the development of the prototype of the working machine, the practicality was enhanced by adding various peripheral functions that conventional spinning machines have, such as a tailstock rod to fix the metal material to the spindle, a blank holder, and a back-up roller that prevents wrinkles in the metal blank.

5.2 Accumulation of spinning know-how by trial runs – desire to approach the actual site, the actual thing, and the actual situation

In this research, trial runs as below to fabricate actual parts through joint research with companies played an important role. AIST does not have a site of production and we definitely lacked feedback to the elemental technologies based on the accumulation of experience. For example, even if we successfully formed a noncircular shape, it was merely a simple shape under specific conditions and for a specific material. It had to be extended to various metal materials as well as hot forming under heat, multipass spinning, and complex shapes with steps and constrictions. On the other hand, unnecessary effort would be made if we did not narrow down the priorities of which element should be developed.

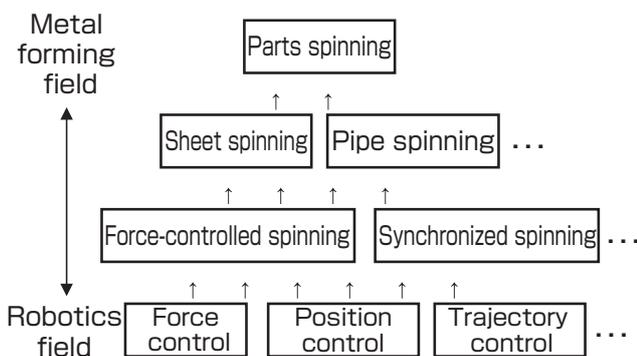


Fig. 10 Hierarchical structure of elemental technologies

To select the know-how worth developing and to do so efficiently, the shortest route is to collaborate with companies and to fabricate actual parts. The developed spinning technology will at least be useful for similar parts. It is possible to handle diverse spinning processes by increasing the available know-how and then combining it.

Upon receiving a request for trial runs from several manufacturing companies including those involved in sheet metal working, automotive parts, measurement equipment, and metal materials, we fabricated the parts as designated by the companies using our experimental spinning machines, and the know-how necessary for processing was developed (Fig. 11). There were about 10 tests actually carried out, and we received over 30 inquiries. Even if an inquiry did not involve testing, we were able to gain an understanding of which shapes were in demand through the process of meeting with the companies. In testing, since the development lead time was important, we were provided with materials and tools from the companies. We also obtained the necessary design data for improving the machine. The accumulation of sample products through these experiences also provided materials for advertising the spinning method. Although an actual shipment of the machine has not yet been realized, several user companies have requested estimates for the machines from Daitoh Spinning.

Through the trial runs, we recognized the importance of the knowledge of plastic working such as material properties. We realized it was necessary to provide the forming know-how as well as the machines to the users. As the number of types of tools and jigs at hand increased through repeated tests, it became easier to handle shapes and materials which used to be difficult. The laboriousness of the formable shapes increased to include square tubes, irregular-shaped pipes, and shapes with curved axis. The range of materials also increased and we were able to expand the know-how of forming noncircular parts. As we repeated spinning tests at factories, the opportunities to incorporate and utilize the on-site knowledge for development increased. The author found that the communication with on-site workers became smooth

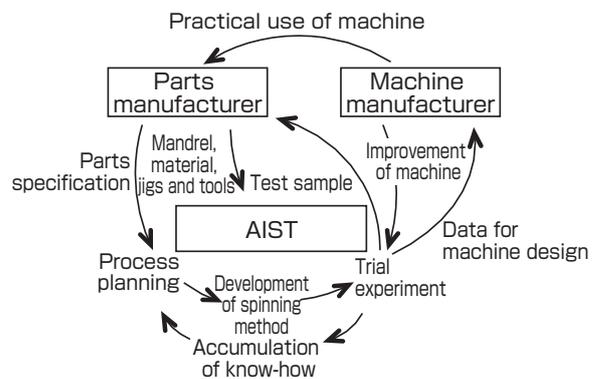


Fig. 11 Accumulation of spinning know-how by trial runs

as we became more like craftsmen.

5.3 Fusion of sales and research activities

5.3.1 Spinning demonstrations at exhibitions

In this research, the emphasis was placed on spinning demonstrations of the machine at external exhibitions, and we have participated in 11 exhibitions so far. Exhibitions are effective as a medium for advertising the results of our research, and they are also used as places to gain feedback from potential users. At large exhibitions where many specialist manufacturers participate, such as the Japan International Machine Tool Fair, we were able to obtain opinions and questions by presenting the metal spinning process to a wide range of professionals from craftsmen at small to medium-size companies to managers at large corporations. Including some extremely critical opinions, we obtained findings that were far more useful than comments at academic societies on issues that we had to tackle toward achieving practical use. The majority of the companies that requested trial runs were those that had witnessed the metal spinning demonstrations at exhibitions. On the other hand, few specialists visited and not much could be gained from the nonspecialized exhibitions that were held for the promotion of industry-academia cooperation.

5.3.2 Sales activities on the web

While trial runs and exhibitions were part of the sales activities, we also conducted sales and public relations activities on the web. When we started the research, we used a search engine to search for companies in metal-spinning-related fields to learn about the metal spinning business, regional distribution, examples of spun products, and so forth. We found 115 companies in Japan and 189 companies overseas, and we were convinced that this industry was sufficiently large to be the recipient of the developed technology. An online link called “Metal Spinning Links” was created.^[21] When we notified the companies of the link, we also sent an outline of our research at AIST. In addition, a list of contacts for the companies was created and invitations were sent to nearby companies when an exhibition was held. When companies showed interest at the exhibitions, we followed it up by sending printed materials, a CD containing a movie of our metal spinning technology, and sometimes sample products. When a Google search is carried out for the term “metal spinning” (in Japanese), our research site appears at the top, and the second item is the above link (about 29,000 hits as of January 2012). We received many contacts from companies that requested links and technological consultations, and made inquiries for trials through this page. Such sales activities may be considered as a type of bricolage in the sense that the results were obtained by combining the limited resources at hand. In fact, since cooperating with Daitoh Spinning, which has a wide sales channel in the metal spinning industry, such amateur sales activities have been decreasing.

6 Discussion and future development

The value of this research, which is composed of basic existing technologies, is that we were able to find a niche among the specialties that was overlooked. I consider that a breakthrough in noncircular forming occurred when we jumped into the area that no one had entered because of the difference in the way of thinking between robotics and metal forming. Robot researchers did not have high interest in manufacturing and failed to seek applications there, while metal forming researchers shied away from the application of novel control technology since their lack of knowledge of mechatronics was a barrier. Therefore, we fitted well in an area that had been overlooked by both sides.

Originally, bricolage appeared in the literature as a way of thinking that was in opposition to modern science and technology.^[8] However, bricolage played an important role in our research activity. Bricolage starts from existing and limited resources, but by recomposing the meaning of each resource, infinite combinations are generated and new values are created.^[14] In the development of a new product, the novel elemental technology is normally only part of the product and most of the product is synthesized from existing technologies, meaning that, bricolage is required. Also, in bricolage, elemental technologies that are readily available and familiar are used; thus, highly reliable and readily applicable technology can be obtained.^[11]

In this research, good results were obtained by altering the research flexibly in response to the feedback of results and external factors, without fixating on an initial scenario or core technology, and particularly by retreating quickly from paths that may have led to a dead end. The three actuals of site, object, and situation helped early decision-making.

At the present point in time, owing to the economic situation, the developed technology is not fully utilized at the sites of production, and I am disappointed by the fact that it is not yet a selling technology. We are looking toward follow-up research rather than the easy wrapping-up of this research, and we hope to be responsible for the research up to the final stage. Although the developed technology is advantageous for high-mix low-volume production, we found that the speed of metal spinning is important from exchanges with companies. Therefore, as a future development, we wish to work on increasing the speed and power of the machines and the issues that arise from this. Also, we are working on applications to materials that are difficult to process such as magnesium, for which we feel that fusion with the findings of material science is further needed.

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Discussions with Reviewers

1 Composition of chapter 4

Question (Yasuo Hasegawa, AIST Tsukuba)

In chapter 4 that summarizes the results of the research, please clarify the flow of the original research development from the setback of robot arm application, the attempts to create an advanced tool rather than creating a robot that may replace a skilled worker, the success of the approach to improve the machine, and the development of force-controlled spinning that enables the production of high added-value products.

Answer (Hirohiko Arai)

Chapter 4 was broken down into subchapters, and the titles that represent their contents were added. The point I wanted to emphasize in chapter 4 is: "Looking back at the progress of research, it can be seen that there was no consistent scenario and the research goal changed greatly due to external and coincidental factors." This is closely related to the bottom-up, exploratory approach taken in this research. Several factors flowed in multiple streams in the process of R&D, various events occurred randomly, and flexible responses were taken for each event. I adopted such a style of description to reflect the reality of the rather chaotic research process.

2 Composition of chapter 5

Question (Yasuo Hasegawa)

Chapter 5 is the specific description of the action principles explained in chapter 3. Please create subchapters and titles for the three principles: bricolage, three actuals, and the sales mentality. I think it will help the reader's understanding if you insert a diagram for bricolage in R&D.

Answer (Hirohiko Arai)

I set the titles for the subchapters of chapter 5 as follows: 5.1 Synthesis by bricolage – bottom-up integration of elemental technologies; 5.2 Accumulation of spinning know-how by trial runs – desire to approach the actual site, the actual thing, and the actual situation; and 5.3 Fusion of the sales and research activities. I also made clear where in the activities of chapter 5 the action principles explained in chapter 3 are reflected. I also added the figure showing the “hierarchical structure of elemental technologies” to explain the synthesis by bricolage.

3 Achievement level and breakthrough of the developed technology

Question (Norio Matsuki, AIST Shikoku)

In the outline of the developed technology in chapter 1, please self-evaluate the level of achievement. For example, please discuss the developed technology compared to the metal spinning by conventional skilled workers with respect to the precision, work speed, and limitations. Also, please describe any breakthroughs possible only by the technology developed.

Answer (Hirohiko Arai)

In chapter 1, I added the description, “These enable the forming of noncircular shapes that cannot be made by a conventional spinning machine for circular products nor by manual metal spinning by a skilled worker,” and showed that this developed technology has advantage compared to the conventional spinning technology. For the noncircular formation

that can be considered the greatest breakthrough of this developed technology, there is no direct comparison in the field of metal spinning. Therefore, as a comparison to pressing, I added the expression, “Currently, the processing time necessary per product is several tens of seconds to several minutes, and it is not so suitable for mass production.”

4 Flow of R&D that generated the breakthrough

Question (Norio Matsuki)

It will become easier to understand if you contrast chapters 3 with 5 from the viewpoint of what kind of research style and action principle led to the breakthrough and characteristics of the technology. Similarly, in chapter 4, I think that it would be better to emphasize the viewpoint of how the newly achieved technology emerged.

Answer (Hirohiko Arai)

The activities of chapters 3 and 5 place more weight on the efforts of molding the breakthroughs into realistic solutions that can be actually used, rather than the activities to obtain the breakthroughs mentioned in chapter 1. To clarify where in the activities of chapter 5 the action principles explained in chapter 3 are reflected, I modified the titles of the subchapters of chapter 5.

In chapter 4, I primarily wanted to express the point: “Looking back at the progress of research, it can be seen that there was no consistent scenario and the research goal changed greatly due to external and coincidental factors.” I intentionally selected the description that reflected the reality of the chaotic research progress where several factors flow in multiple streams, various events occur randomly, and flexible responses are taken for each event. I think the factor that allowed new accomplishment of technology was “that we were able to find a niche that was overlooked among the specialties,” and I emphasized the descriptions of this point.