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Sensors and Their Real In-process Control Application to Advanced Deformation Processing

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To promote the "Connected Industries" project by utilizing the Internet of Things (IoT) and artificial intelligence (AI) systems, sensing of various deformation process information during processing is required to develop advanced metal forming technology in the deformation processing field. In recent years, sensors and sensing systems based on new sensing principles have been studied and developed. In this paper, a state-of-the-art typical sensor and its system applicable to metal forming processes are described, in which it is difficult to visualize the processing conditions and material deformation state inside dies. Also, the issues and initiatives for intelligent metal forming processes are introduced. In addition, we discuss the advantages and necessity of advanced in-process intelligent control metal processing technology with sensors embedded into a practical forming machine.

1. Introduction

In recent years, intelligence and artificial intelligence (AI) technologies have been rapidly evolving in the logistics and service industries, healthcare, energy, mobility, and management (infrastructure) fields toward the realization of the Internet of Things (IoT), Industry 4.0, and "Connected Industries". On the other hand, in the manufacturing field, the cycle of digital information collection, information storage, data analysis, and processing (control) is also advancing in the metal forming field, which is behind the machining system industry. As for the collection of digital information in the processes, the sensor is an extremely important element. Nowadays, the evolution of sensor performance is also remarkable.

However, in metal forming processing, it is necessary to sense the material deformation and flow in the die cavity, the die-contact state (pressure and friction), and the temperature state. In addition to the fact that the material deformation in a die cavity cannot be directly visualized, the applied stress is also high, and the sensor is put in a very severe environment. The critical problem that makes the material deformation invisible is the barrier that prevents

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the visualization of material deformation and environmental conditions. Although a similar injection molding process for plastic materials is also not visible in the mold, the visualization of the injection molding with low material flow stress is relatively possible, and in fact, its visualization has also been realized.

If material process information during processing in metal forming can be actually collected by sensors, AI would realize an optimum forming process adapted to actual momentary processing conditions during processing, which has not been possible so far. The realization of a more advanced processing and a dramatic improvement of product accuracy/quality and productivity would be expected.

Many intelligent metal forming research studies have been carried out using AI techniques such as fuzzy control and artificial neural networks (ANN). However, most of the research has been offline intelligent control and optimization using intelligent technology in finite element (FE) simulation (virtual intelligent forming process), or it is an online control of database utilization, and any attempts of metal forming processing, which carries out intelligent control by sensing in actual in-process, were hardly made.

In this paper, we present in-process sensors that can measure the material deformation/flow in the die cavity and show the experimental results of deep drawing and tube hydroforming processes with an in-process intelligent control scheme applied to an actual machine. Through the results, we discuss the high potential and effectiveness of the real in-process adaptive metal forming control method with mounted sensors.

2. Typical Sensors Developed for Metal Forming Processes

From the 1990s, the paradigm shift of the production system was seen, and a flexible manufacturing system (FMS) gave rise to new words such as computer-integrated manufacturing (CIM) and intelligent manufacturing systems (IMS). As part of that, research on intelligence for metal forming processes and their processing machines and systems became active, as well as research on only manufacturing systems. At the same time, research and development related to sophisticated sensors has made a great deal of progress. Academically, various concepts of sensors and sensing systems have evolved;(1) however, such sensors and sensing systems have remained in the research phase and have not reached the stage of practical use or the spread of their technology.

Until now, various sensors have been developed for sheet stamping and tube forming processes. Considering the application of process sensing to the intellectualization of metal forming processes, in which it is difficult to visualize the deformation processing described above, the major objects detected in metal forming processes are “displacement” including deformation, strain, angle, “forces, pressure, torque”, and “temperature”. Their distributions are also important for high-accuracy and high-quality production.

Typical sensors developed in the past for bending, sheet forming, and tube forming are listed in Table 1. In recent years, the number of applications of nondestructive sensors such as acoustic emission (AE) sensors, ultrasonic sensors, and image sensors has been increasing for metal forming processes.

Table 1
Typical sensors developed in the past for metal processing.

Sensing object/item	Measurement principle	Applied processing method	Reference
Bending angle	Optical type, mechanical type	Sheet bending(V-bending)	[2][3]
Embedding sensor	Strain gage	V-bending of sheet	[4]
Flange edge draw-in	Strain gage	Sheet stamping (deep drawing)	[5][6]
Blank flow/displacement	Optical type, "Mouse"	Sheet stamping (deep drawing)	[7][8]
Friction sources	AE	Sheet stamping (deep drawing)	[15]
Die flange surface sensor for detecting wrinkle defects	Ultrasonic	Sheet stamping (deep drawing)	[16]
Temperature and deformation profile	Image sensor ("Machine vision")	Dieless bellows forming with local assisted heating (Bellow forming, tube drawing)	[12][13][14]
Die contact evaluation, material deformation behavior	Strain gage embedded inside die	Tube hydroforming	[9]
Die contact status	Microswitch type	Tube hydroforming	[11]
Die separation/contact behavior	Eddy current type	Tube hydroforming	[10]

2.1 Bending

In the V-bending process, a camera image processing method using a laser beam and a mechanical method are put into practical use as a bending angle sensor capable of in-process measurement.(2,3) In recent years, development aimed at measuring the deformation resistance and bending angle of materials during bending using a microsensor that can be built into a bending die has advanced.(4)

2.2 Sheet stamping

To realize sophisticated deep drawing, sensing of draw-in displacement at the flange end is essential in addition to conventional processing information with punching force and punch stroke (displacement). Figure 1 shows sensors for measuring the draw-in displacements at the flange corner portion and at the flange straight side portion, which can measure two typical draw-in displacements at different flange ends in the process of the square cup deep drawing.(5,6) In addition to the vertical load of the punch load and punch displacement and the vertical displacement of each segment part of the divided blank holder (BH), the fuzzy control of the BH under the momentary sensing data of these two flange draw-in displacements mentioned above is performed to confirm the enhancement effect on the deep drawability.

Also, in the cylindrical cup deep drawing, the sensing of the flange draw-in displacement is important for process control, and a special displacement sensor has been used since 1995. On the other hand, in the case of rectangular cup deep drawing, an advanced system in which eight noncontact optical sensors are incorporated in a die flange surface to perform in-process measurement has been developed, and the material flow control of each part of the flange was attempted.(7,8)

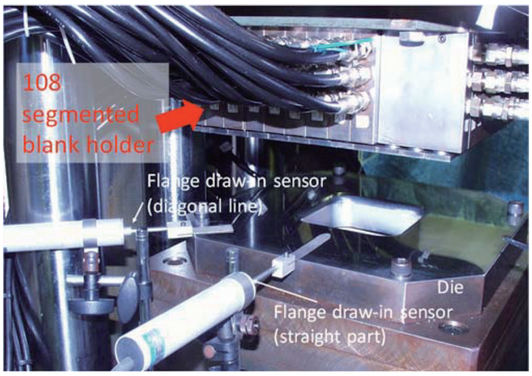


Fig. 1. (Color online) Flange draw-in sensors in typical two directions used for square cup deep drawing with 108-segmented BH.

2.3 Tube hydroforming and tube dieless forming

For a tube hydroforming process of expanding from a circular to a rectangular cross section, a sensing system with strain gages in the split die was developed and used to evaluate the die-contact state with a deformed tube and the tube deformation state.(9) In the system, two sensors for detecting the stress generated in the die are embedded in the vicinity of the corner of the two-split structure rectangular cross-sectional die. These sensors are also available in the die closing stage.

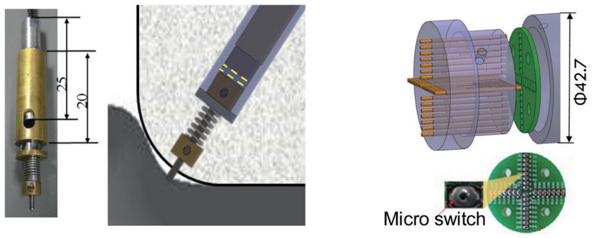
For T- and Y-forming processes, special sensors have been developed to detect the contact state between the tube and the counter punch head. Figure 2 shows the appearance of the two sensors embedded in the die and punch for the T- and Y-shaped hydroforming processes. Figure 2(a) shows an eddy-current-type miniature displacement sensor for detecting a gap between the tube and the die corner,(10) and Fig. 2(b) shows that for detecting and evaluating the fitting length on a counter-punch head with microswitches.(11)

In the local heat-assisted dieless forming of a tube, noncontact sensors are available for applications in collecting forming conditions and deformation information so that deformation is visible outside without a die. Recently, noncontact-type "Machine Vision" has come to be applied to various measurements in metal forming processes. The technology was adopted in local heat-assisted dieless tube drawing(12) and dieless bellow forming(13) processes to measure the deformation profile and forming temperature under a locally heated area of the tube during processing. Furthermore, advanced vision-based fuzzy control was achieved for these processes utilizing process sensing data.(13,14)

3. Intelligent Metal Forming Processes

3.1 Virtual intelligent forming system

The intelligent forming system fully operated on a computer is named the virtual intelligent forming system. All processing information including the die and tooling modeled can easily



(a) (b)

Fig. 2. (Color online) Special sensors developed for detecting (a) fitting between tube and die corner and (b) contact state between tube bulged part and counter-punch head.

be obtained through numerical simulation [Computer-aided engineering (CAE)]. Even with the blank material inside the die, all deformation and environmental information can be acquired for advanced intelligent control and process evaluation.

3.1.1 Virtual intelligent controlled sheet stamping system

Manabe and coworkers have carried out virtual intelligent control forming for circular and square cup deep drawing processes with a monoblock BH, divided BH, and segmented BH, as well as real sheet stamping processes since 1995.

3.1.2 Virtual intelligent controlled tube hydroforming system

On the basis of the above virtual intelligent control sheet stamping, Manabe and coworkers have carried out virtual intelligent T- and Y-forming since 2003. However, the technological issues for virtual intelligent forming processes have remained as follows.

- Necessity of material properties as input data for FE simulation
- Importance of material testing and establishment of material modeling
- Stress–strain relationship in the large-strain range to improve prediction accuracy
- Appropriate modeling and characterization of blank mechanical characteristics
- Identification of friction coefficient between die/tool and blank
- Difficulty in coping with variation in tube blank and lubrication/friction during processing

Therefore, a real in-process intelligent forming process is expected to be realized because the real process does not have the above technological issues based on the numerical simulation technique and its modeling.

3.2 Real in-process intelligent control forming system with die-embedded sensors

The solution is to develop and establish a "real" in-process intelligent control metal forming system that can sense processing information during processing in an actual machine and execute intelligent control based on the online processing information, and develop the forming process sensors that can obtain the processing information online. Specifically, (1) the development of sensors is required to detect and measure the deformation and flow of a blank material in the die cavity. Therefore, to realize this, the development of die-embedded sensors is essential. (2) The development of sensors that can predict the forming defect and failure is required. (3) To utilize fuzzy control algorithm, the development of evaluation functions to be used for simple intelligent control suitable for prediction/evaluation of failure is required.

On the other hand, the merits of the real in-process intelligent forming process with die-embedded sensors are as follows. (1) The material test of material workpiece is not needed. (2) There is no need to determine the friction coefficient. (3) It is possible to cope with fluctuations such as lubrication variation during forming. (4) There is no need for process FE modeling. Thus, the design development time using CAE can be greatly reduced.

Y-forming is a typical example of real in-process intelligent control tube hydroforming. Figure 3 shows an overview of special sensors embedded in the tooling shown in Fig. 2 for a real in-process control Y-shape hydroforming system. The tubular materials used are aluminum alloy A6063-T5 with an outer diameter of 42.7 mm and wall thicknesses of 1.1 and 2.1 mm. The final protruding bulge height is set to 20 mm and the lubricant used was spray-type fluorocarbon resin.

In the real in-process intelligent control, fuzzy control was adopted by using two evaluation functions for the buckling risk at the left and right corners [Fig. 4(a)] and for the counter-punch head contact/fitting ratio [Fig. 4(b)].

Figure 5 shows the samples formed by the previous method and the new control system with die-embedded sensors shown in Fig. 2. In the previous method, buckling occurred despite the low fitting ratio, and further fitting in the later forming stage was difficult. In the new real in-process intelligent control, the buckling was avoided and the hydroformed flatness on the counter-punch head was significantly enhanced. It is seen that product accuracy for real in-process intelligent control can be greatly improved. The new method shows good results with respect to the formed shape and wall thickness distribution.

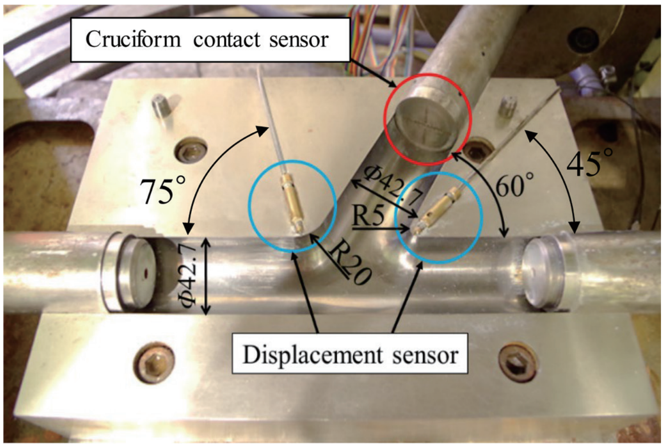
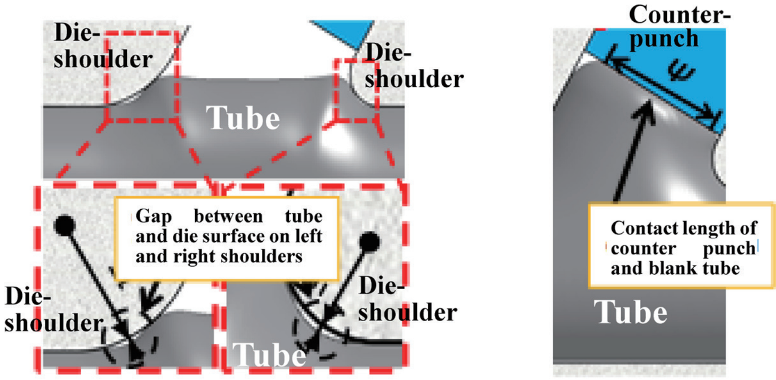


Fig. 3. (Color online) Overview of special sensors embedded in the tooling for real in-process control Y-shape hydroforming system.



(a) (b)

Fig. 4. (Color online) Evaluation functions used real in-process fuzzy control Y-shaped hydroforming process for (a) buckling risk of left and right corners and (b) contact/fitting ratio of counter-punch head.

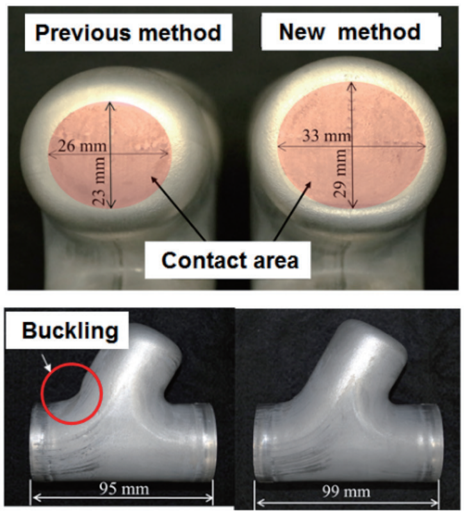


Fig. 5. (Color online) Appearance of hydroformed samples formed by previous control method and new control system with die-embedded sensors.

4. Conclusions and Future Prospects

In this paper, many sensors capable of digitally measuring various processing data that can be effectively utilized for metal working are introduced. To realize IoT utilization, Industry 4.0, and Connected Industries, the environment for developing advanced intelligent control metal forming processes is growing through connection to the Internet. In particular, an advanced real in-process intelligent control process that incorporates microsensors in the dies and uses real in-process information during processing can achieve advanced optimum/adaptive in-process control reflecting the forming stage. We can say that this is the ultimate ideal metal forming process as mentioned above.

The keys are miniature/microsensors, sensing of the real in-process forming conditions, and combination of intellectualization (AI) technology. This advanced metal forming process can cope with changes in any forming conditions, such as friction/lubrication conditions during the process and variation in material size and material properties, without any simulation and material testing works.

In the near future, pattern recognition technology combined with digital simulation techniques will advance and develop rapidly. Thereby, it will be expected that highly intelligent metal forming processes with high productivity is realized, which can achieve high precision, high forming degree, and high quality, which are unprecedented in accordance with the real forming state by combining in-process sensing and die-embedded sensors.

In recent years, machine learning and deep learning have been developing rapidly. Even in metal forming processes, if various sensors fabricated by high-precision and high-dimensional sensing techniques were developed, and big data obtained from them for metal forming processes were constructed, a sophisticated intelligent metal forming process control will no longer be a dream only. In the past, the authors and coworkers used ANN to identify the properties of blank materials and have developed a variable BH control deep drawing process.[17] Nowadays, it is expected that the development of highly intelligent control metal forming processing with high accuracy, less product quality dispersion, and high flexibility will be realized much more easily.

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