Intelligent Design Architecture for Process Control of Deep-Drawing

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ABSTRACT

A concept of design architecture with a database for an intelligent sheet metal forming system was proposed to enable designing of a process control system without experts who are skilled and experienced in the forming process. In this study, the proposed architecture was applied to the variable blank holding force (BHF) control technique for circular-cup deep-drawing. The system is available for three objective functions which are typical process requirements, cup wall uniformity, cup height improvement and energy saving. The availability of this design architecture is confirmed by experiments on aluminum alloy sheets.

INTRODUCTION

Several studies on the optimization of process control in metal forming have been performed in an approach toward intellectualization. For sheet stamping operations, intelligent deep-drawing techniques have been developed to date. One technique is an adaptive control method by means of blank holding force (BHF) with fuzzy inference for circular-cup deep-drawing[1]. Another one is a control approach based on a plastic deformation model involving the material and friction identification process with an artificial neural network (ANN)[2]. Despite their excellent advantages, each control system requires very extensive time and labor for the design and development process, and above all, the design engineer has to be a knowledge expert as well as skilled and experienced engineer on the forming process techniques, or else, the assistance of a craftsman would be essential. Therefore, it is necessary to establish a new concept for process design architecture which obviates the requirement for an expert. In general, the forming cell and system must be efficiently designed during process design and process control. In the former system, as shown in **Fig. 1** (left), the expert plays a number of roles as the core.

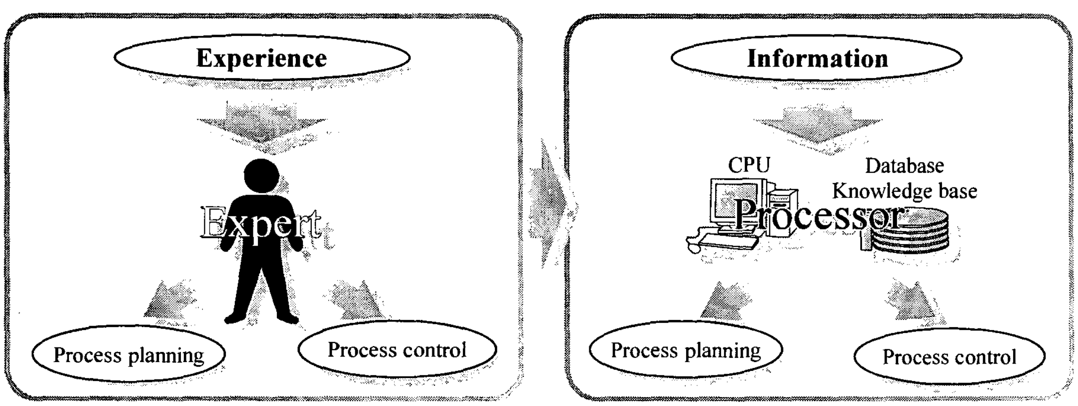

Fig. 1 A new intelligent approach for various design phases on metal forming processes

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He also acquires the required experience and transfers the knowledge to inexperienced engineers. The number of experts has been gradually decreasing over the years. Thus, in the future system, the process conditions must be automatically optimized without the aid of an expert. The purpose of this study is to enable freedom from the dependency on engineering experts in the design phases of process planning and control design and to develop an intelligent design architecture for deep-drawing process control without the aid of a knowledge expert.

OUTLINE OF A NEW INTELLIGENT PROCESS DESIGN AND ITS SYSTEM ARCHITECTURE

Our concept shown in **Fig. 1** (right) involves the replacement of the brain functions of an expert by a processor which contains an analyzer, database and knowledge base. The processor can design and control the process according to a suitable set of rules and algorithm from the database and knowledge base, and stores the sensing information from a forming cell during the process, which is similar to the experience of an expert. In other words, it can grow by acquiring experience in the same manner as an expert. Hence, the proposed system is able to automatically optimize the process and can be operated without any aid from an expert.

Figure 2 shows the outline of the system architecture based on the above concept. It can be broadly divided into two parts. One is a processor and another one is a forming cell and system. The forming cell has several sensors for supplying process information to the processor, and also has actuators to implement the commands from the processor. The processor consists of a database, knowledge base and an analyzer (commercial control design support tool; MatrixX). The database and knowledge base contain the process information under various conditions and the methodology for designing the process, respectively. The processor is capable of not only designing the process using the database and knowledge base but also identifying the material properties of the workpiece and control actuator using sensing information from the sensors. In addition, the system can handle a variety of workpieces as well as the change of workpiece material, tooling conditions and lubricating conditions, by utilizing the database and knowledge base.

APPLICATION OF THE ARCHITECTURE TO DEEP-DRAWING PROCESS

In this study, the circular-cup deep-drawing problem is adopted as a fundamental and important example of the sheet metal forming process. In the deep-drawing process, the forming limit is mainly governed by the fracture at the punch shoulder and the wrinkle at the flange part. Although it is essential to apply the BHF to avoid wrinkles, excessive BHF causes fractures. Therefore, the appropriate amount of BHF is required to carry out the process successfully. So the new design architecture is applied for the adaptive control of BHF in the deep-drawing process in order to verify the availability of the architecture. **Figure 3** shows the design system architecture for an intelligent metal forming process with a database. In the system, fuzzy inference was chosen as an AI tool for process control design.

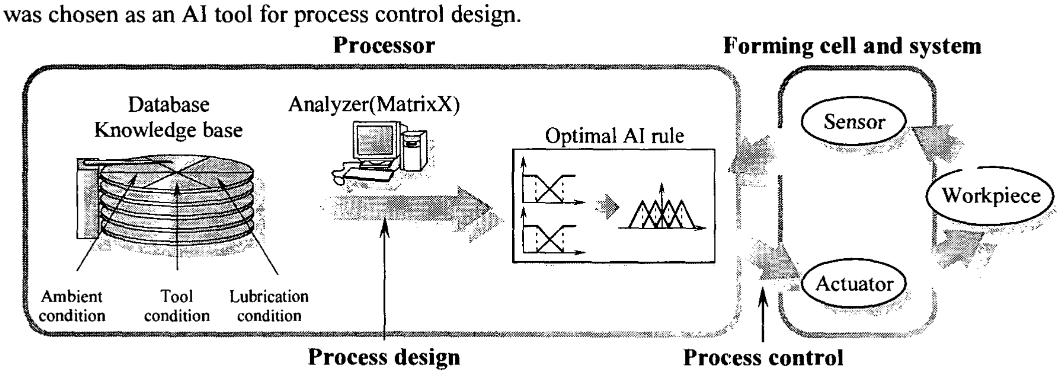

Fig. 2 A concept of intelligent metal forming cell with database

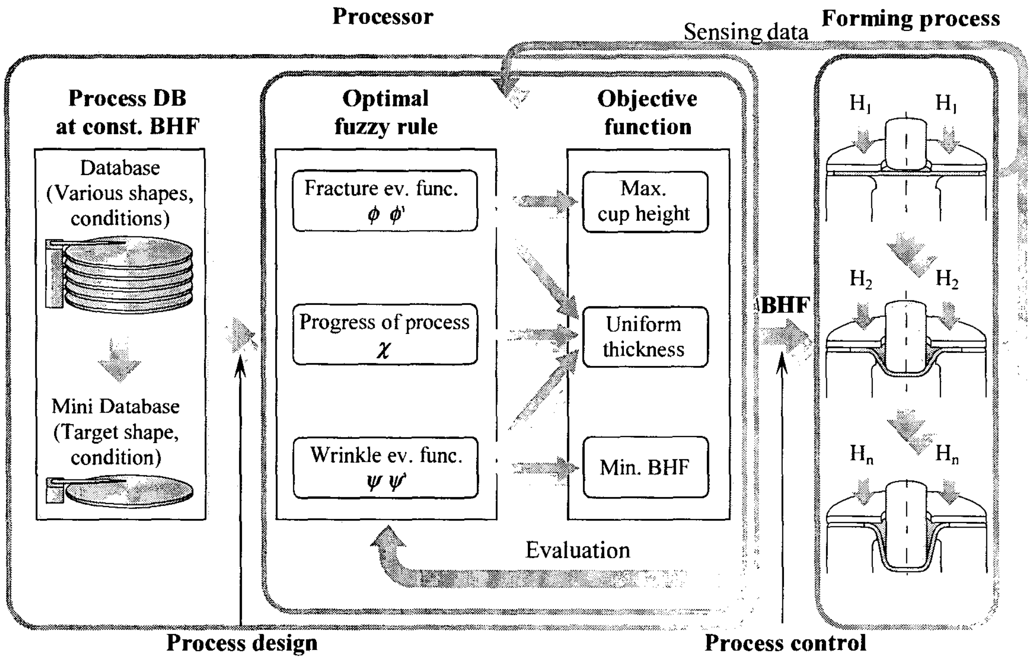

Fig. 3 System architecture of intelligent forming process for deep-drawing process

The evaluation functions should not be influenced by the blank material, tooling conditions, environmental conditions and other factors. For this reason, evaluation functions ϕ and ϕ', obtained from the punch stroke curve and ψ and ψ', from maximum apparent blank thickness curve are used. The evaluation function ϕ is the difference between the actual punch stroke curve and the ideal curve, which can be obtained geometrically by assuming uniform wall thickness. ϕ' is the differential coefficient of ϕ by blank reduction ratio ΔDR^*. A combination of ϕ and ϕ' is used for fracture estimation. The evaluation function ψ is the blank holder displacement which is equal to blank thickness at the flange edge and is used instead of the wall thickness distribution. In the same manner as ϕ, a combination of ψ and ψ' is used to evaluate wrinkle behavior. A constraint function χ is defined as the differential coefficient of the punch load curve to evaluate the progress of the process.

The database in this study is composed of four kinds of process variables, punch stroke, punch load, maximum apparent thickness, and ΔDR^*. The blank reduction ratio ΔDR^* can be obtained from the displacement of the flange edge and is given by

$$\sim DR^* = \frac{s}{R_0}$$

where R_0 is the initial blank radius and s is the displacement of the flange edge.These process data are utilized to design the sets of appropriate membership functions of the evaluation functions so that they have to be accumulated under various material and process conditions (material properties, tooling condition, lubrication condition, ambient condition among others).

In this proposed architecture, three objective functions can be designed. The first is the improvement of the cup height, which can be achieved by applying the maximum BHF below the fracture limit. The second is process energy savings by implementation of the minimum BHF beyond the wrinkle limit. The third is for the wall thickness uniformity, whose control scheme can be achieved by a combination of the above two objective functions.

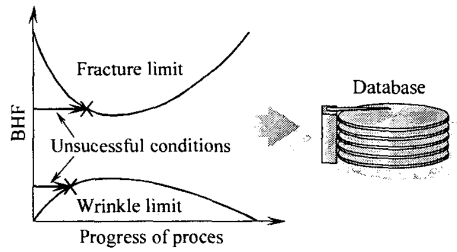

Fig. 4 Requirement of process information contained in the database

Table 1 If-then rule of ϕ, ϕ' and ΔBHF

if(ϕ, ϕ')	Then(ΔBHF)
ϕ is Small and ϕ' is Small	$\Delta BHF = \Delta BHF_{SS}$
ϕ is Small and ϕ' is Large	$\Delta BHF = \Delta BHF_{SL}$
ϕ is Large and ϕ' is Small	$\Delta BHF = \Delta BHF_{LS}$
ϕ is Large and ϕ' is Large	$\Delta BHF = \Delta BHF_{LL}$

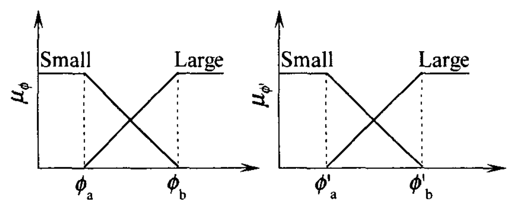

Fig. 5 Sets of input membership functions

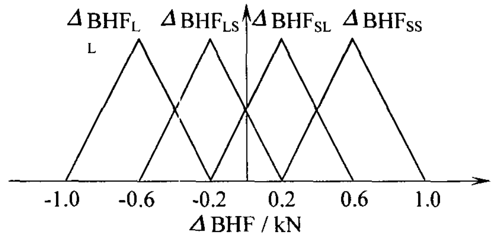

Fig. 6 A set of output membership functions

FUZZY MODEL

Application of the fuzzy model provides a suitable and easy way to optimize process control because the deep-drawing process is not only unsteady and complicated but also has nonlinear forming characteristics.

The sets of membership functions used for the antecedent of the If-then rules are designed through the database. The database must contain at least two typical conditions of the constant BHF. One is a high BHF condition which causes fracture and another one is a low BHF condition which leads to wrinkling as shown in **Fig. 4**. Two membership functions related to ϕ are built from the process data as mentioned in the previous section. The latter data create two membership functions in relation to ψ. In the present study, only two sets of membership functions concerned with ϕ and ϕ' were employed because the objective function is the improvement of cup height as described above. Two maximum values ϕ_b and ϕ'_b in **Fig. 5** should correspond to the state of fracture. Hence each value was decided on the basis of the maximum value retrieved from the database of fracture limit conditions. Meanwhile, ϕ_a and ϕ'_a were decided by substituting the minimum value stored in the database in similar to ϕ and ϕ'.

Figure 6 shows the set of membership functions used for the consequent of If-then rule. This part was decided with the assistance of an expert with experience resulting from trial and error in the previous work [4]. However, the use of this new simplified set of membership functions does not require any experience so that the designer and machine operator need not be skilled and experienced. The initial range of each membership function in Fig.6 can be automatically designed via this system. They only have to provide the multiplier to the value of the system output (ΔBHF),whose value was 0.2, due to the dependency on the forming cell used. **Table 1** shows the If-then rules for BHF control.

Figure 7 shows the fuzzy inference for ΔBHF used in this study. Although the max-min-rule is the most common inference rule, larger membership functions are omitted, when the min-operator is used. However, it is desirable that both membership functions be considered. Therefore, in this work, the areas of the membership functions are used desspite of the use of the min-operator as shown in Fig. 7. Fuzzy outputs of individual fuzzy rules are combined using the max-operator and the centroid of the area is the output.

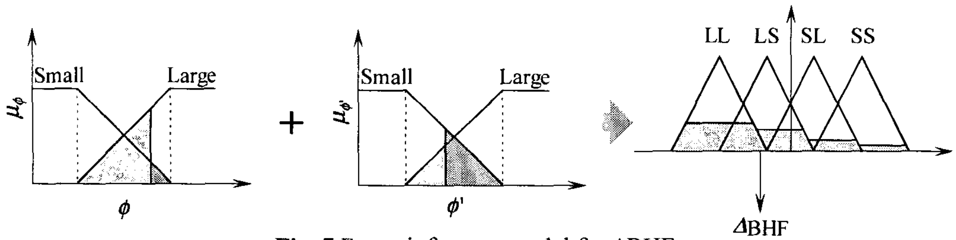

Fig. 7 Fuzzy inference model for ΔBHF

Table 2 Material properties of blank used

Yield Stress σ_S / Nmm^{-2}	Tensile Strength σ_B / Nmm^{-2}	F value / Nmm^{-2}	Elongation / %	N value	R value
117	264	398	30.1	0.28	0.6

Table 3 Experimental conditions

Punch Speed	5 mm/min constant
BHF	0.5~50 kN variable
Lubrication	Lubricating oil (218 mm^2s^{-1})
DR	1.98

Table 4 Tooling conditions

Punch shoulder radius r_p / mm	4
Punch diameter D_p / mm	33
Die shoulder radius r_d / mm	3
Die diameter D_d / mm	36.5

EXPERIMENT

Material Used and Experimental Conditions

Aluminum alloy sheet metal (A5182-O) of thickness 1.0mm was used in the deep-drawing experiment. The material properties are listed in **Table 2**. The deep-drawing system used is capable of computerized control of BHF and the punch speed during the process [3]. The system has several sensors: punch stroke, punch load, BHF, radial drawing displacement of the blank flange which was sensed by a displacement transducer and blank holder displacement by an eddy current displacement transducer. **Tables 3** and **4** show the experimental conditions and tooling conditions, respectively.

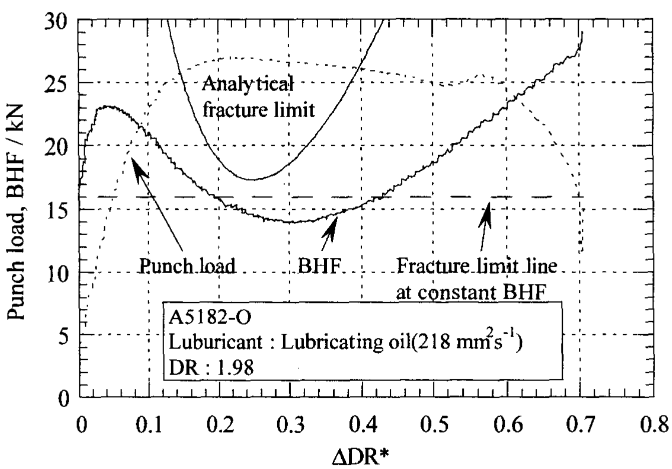

Fig. 8 Punch load and controlled BHF curves during the process.

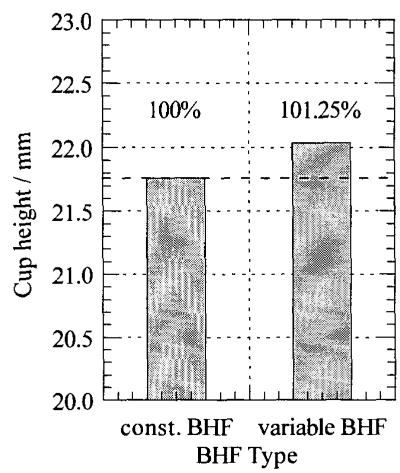

Fig. 9 Comparison of cup height between const. and variable BHF conditions.

Experimental Procedure

CONSTANT BHF DEEP-DRAWING TEST

The first step in the design process is to construct the database from the results of the constant BHF test. In the present architecture, the process information for the fracture and wrinkle limit BHF conditions are essential. However, since this study deals with the improvement of the cup height as the objective function to verify the effectiveness of the design system architecture, process information related to fracture limit BHF condition was collected and stored in the database.

FUZZY CONTROLLED VARIABLE BHF DEEP-DRAWING TEST

The variable BHF deep-drawing test with fuzzy control was conducted on the basis of the above objective function. The details of the procedure are as follows. First, membership functions are produced by using a database constructed from the constant BHF test. Second, initial BHF, blank geometry and punch speed are input into the processor and then the die descends at a constant speed. The BHF is automatically controlled in a closed loop to satisfy the objective function by the obtained fuzzy rule. In this study the initial BHF is set to 1.0kN. For the objective function of the highest cup, the processor basically controls BHF to increase it to the maximum possible value to obtain the highest drawn cup. When the evaluation function indicates a high possibility of fracture, then the BHF can be controlled to decrease it in order to avoid fracture. On the contrary, when the evaluation function shows enough allowance to fracture, then the BHF can be increased.

RESULTS AND DISCUSSION

Figure 8 shows the experimental curves for punch load and BHF which are obtained by a variable BHF control system designed by the new system design architecture with a database. The fracture limit BHF curve obtained from the plastic deformation model [2] is also indicated. Variable BHF path indicates the increase of BHF as high as possible and avoidance of the fracture limit according to the objective function. As a result, an improved drawn cup height was accomplished as shown in **Figure 9.** However the experimental results are still insufficient. At the next stage, is is necessary to feed-back the process information under variable BHF conditions shown in Fig. 8, to optimize the fuzzy rule. Such a routine will enable optimization of the process control.

CONCLUSIONS

1. A new concept of an intelligent design system with a database replacing a knowledge expert, is proposed for intelligent sheet metal forming. A system architecture based on the proposed concept is developed and applied to circular-cup deep-drawing process.

2. The validity of the proposed concept and system is confirmed through the implementation of the system architecture for the fuzzy control variable BHF deep-drawing process.

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