특 집

# Intelligent Control with Fuzzy Technologies in the Area of Metal Forming

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## Abstract

The fuzzy technologies, named with an exotic word "fuzzy", have come into fashion in recent years. However, fundamental aspects are often not emphasized or not deeply discussed. In this paper some aspects are represented, namely, the role of these technologies in this information-era and the possibilities of their application to intelligent control systems. Some Fuzzy controllers for the forming machines with a design method are also shown in view of these aspects.

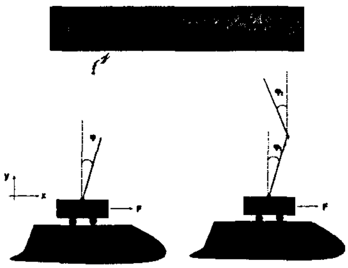
## I. Introduction

• Questions

Scientists have tried to build models of natural phenomena according to their interests in order to understand these phenomena better. The model can be gained generally by two methods. The one is mathematical method to describe an object. And the other method to set a model is experimental method. In spite of many achievements with these methods in science and engineering, the following questions can be asked.

- Can real-world-problems be described precisely enough by mathematical equations?
- If we could get the mathematical equations, could these mathematical equations be solved in acceptable time interval without simplifications?
- Are all values needed measurable?
- If it could be done, could this measurement be done in all interested interval? or only in limited interval?

- Study of Control Object
- Modelling: theo./experi. Method
- Simulation
- Implementation and On-Line-Fine-Tuning
- Documentation and Production
- Service and Feedback



$$(J+l^2 \cdot m_l)\cdot\ddot{\varphi} = l\cdot m_l\cdot g\cdot\sin\varphi - l\cdot m_l\cdot\cos\varphi\cdot\ddot{s} - c\cdot\dot{\varphi}$$

$$(m_w+m_l)\cdot\ddot{s} = F_a - F_R - m_l\cdot l\cdot[\cos\varphi\cdot\ddot{\varphi} - \sin\varphi\cdot\dot{\varphi}^2]$$

$$x_1 = s;\ x_2 = \dot{s};\ x_3 = \varphi;\ x_4 = \dot{\varphi}$$

$$\underline{\dot{x}} = A\cdot\underline{x} + B\cdot\underline{u} = \begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 & 0\\ 0 & 0 & 0 & a_{24}\\ 0 & 0 & 0 & 1\\ 0 & 0 & 0 & a_{44}\end{bmatrix}\cdot\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\end{bmatrix} + \begin{bmatrix}0\\ b_2\\ 0\\ b_4\end{bmatrix}\cdot(F_a - F_R)$$

⟨Fig. 1⟩ A classical design method and two control models as examples.

Engineers have also tried to build models in the same manner as precisely as possible. A design procedure in the area of control engineering and a mathematical model of one pole system are shown in⟨fig. 1⟩ in order to figure out this assertion : The system equation of the one pole system is nonlinear. Therefore, it can be solved only by a digital computer, if this equation is not linearized. Here is the dilemma of this method : At the first stage in the design procedure, an engineer wants to utilize his knowledge in form of a natural language. His idea can not be mathematically formulated, but verbally in this stage. Nevertheless, he normally wants to describe a controlled process precisely or mathematically, even though he should simplify his equation to realize a cheap controller (It is not worth while using a process computer to control this object). Why ? Do we have too much trust to the precision ?

It is more difficult to set a model for the second system (two poles system in fig. 1) because of its complexity). It costs time to develop the system model. This model is too complex and it must be simplified in order not to lose the track of the relation between the mathematical equations and the control behavior. This fact was formulated by Zadeh as the "*Principle of Incompatibility*" (see below). Moreover, the conventional controllers which are developed in such a way, should be tuned on line manually, that means, the knowledge of an engineer is used not in the form of formula, but in the form of sentences at this stage too. Why is this knowledge not be exploited ? Because there was no possibility of formulating this knowledge algorithmically. But fuzzy logic theory offers a method to formulate such knowledge.

- What is fuzzy set theory ?

The fundamental idea of the fuzzy set theory is that the boundary of a fuzzy set does not have to be sharply defined. An element can belong to a fuzzy set/fuzzy sets with continuum grades of membership (degree of membership), not like "belong to or not belong to" as in the conventional binary set theory. By a function (membershipfunction) a fuzzy set can be described in X (discourse of universe), whose values are mapped into the interval[0,1]. The binary logic system is based on the Boolean algebra, which is defined as B ≦ AND, OR, NOT, 0,1 > and must use words (objects) that must be defined by the sharply defined sets. The fuzzy algebra, on the other hand, is characterized as Z ≦ $AND_f$, $OR_f$, $NOT_f$, [0,1] >[1]. The "not sharply defined words" in a natural language can ,therefore, be used in a fuzzy logic system, for example, "small" or "large",

- Zadeh's original Idea : How can the complexity of a system be reduced?
- Logic system : syntacs, semantic, method : The symbols must be sharply defined : classical set-theory

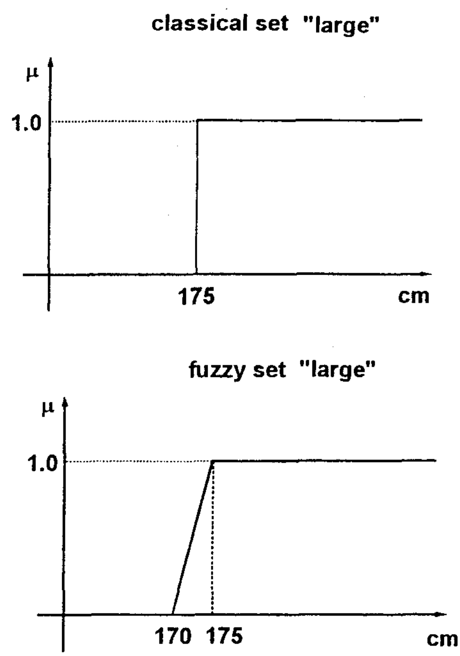
⇒But we used these words in daily life to communicate informations together!! "*large*" or "*small*" and so on.

⇒How can this method of transfer be utilzed? Or how can it be formalized?

- Fuzzy set theory : all symbols can not be sharply defined, but with grade of membership.

⇒Therefore, we can formulate controlstrategies of experts or operators using the fuzzy logic.

⇒Fuzzy Control



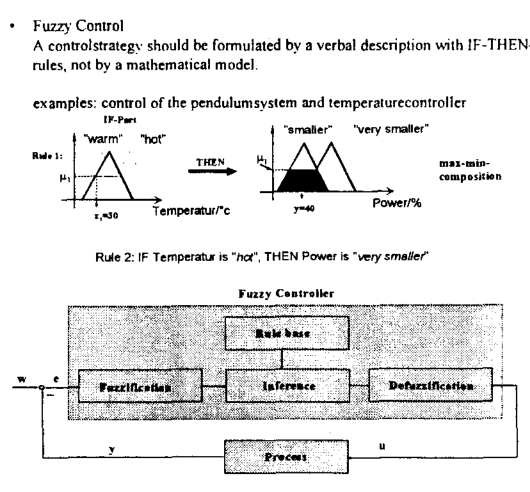

⟨Fig. 2⟩ Fuzzy logic.

etc. (linguistic variable) (see fig. 2). One of these fuzzy operator definitions is defined as minimum-, maximum-and fuzzy complement-operator.[2]

Another point of view on that theory was formulated by Prof. Zadeh : nfortunately, there is an incompatibility between precision and complexity. As the complexity of a system increases, our ability to make precise and yet nontrivial assertion about its behavior diminishes".[3] One method of minimizing the complexity is to use imprecisely defined natural words-not mathematical formula-in order to describe a complex problem.

- What is fuzzy Control ?

This Zadeh's idea was transferred to the sector of control theory. It is difficult to set a mathematical model for a complex control system. Without a mathematical model, a complex system can also be simply described by means of sentences of a natural language as a skilled human operator would do. The fuzzy control means that a control strategy is designed in the form of a natural language (see fig. 3). A suggested formulation of this control




⟨Fig. 3⟩ Fuzzy control.

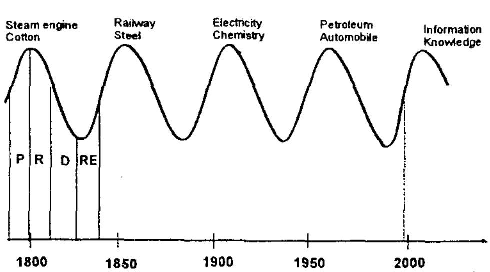
method is if the state of the input is A, then the control strategy is B", where A and B are fuzzy sets ( f-then" fuzzy rule).[4]

We take the control object as an example in ⟨fig. 1⟩ again. What we should do to design a fuzzy controller is to imagine the play pole in our childhood so that our knowledge can be exploited. Thus, our knowledge can be fully utilized in the form of "if-then-rules".

- Address of the fuzzy technologies in this information-era

Data is a sequence of numbers. Information is a compact form of data, which can be represented by formulas or by sentences and consists of the interpretation of data. But it is more effective to communicate, if the information can be formulated by a natural language as we do in everyday life. Computers, no matter what kind of computers they are-von Neumann or parallel computers-process mainly data as a data processing unit. Fuzzy logic offers a possibility of processing information or knowledge by these computers. Therefore, fuzzy technologies-fuzzy logic, fuzzy control and fuzzy expert systems and so on-can be addressed as a method of knowledge engineering.

The Russian economist Kondratieff (1892~1930) have postulated economical boom-cycles, since the invention of steam engine, there




⟨Fig. 4⟩ Kondratieff's cycles.

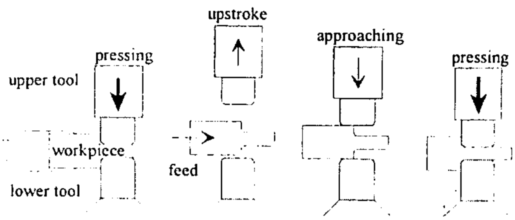
have been four cycles (see fig. 4). Each cycle has four phases; prosperity (P), recession (R), depression (D) and recovery (RE). Each economic prosperity could be achieved by corresponding basic innovation; for example, the invention of the car (diesel/otto-engine) and refinery method of petroleum played the important role in economic boom in the fourth Kondratieff'cycle. In the fifth cycle, information and knowledge is expected to work as the important resources for the basic innovation.[5] The fuzzy technologies can be regarded as a method to process information and knowledge mentioned above. Therefore, the fuzzy technologies can contribute to promote this fifth cycle.

## II. Fuzzy controllers for forging machines

Basic idea of our investigations of design fuzzy controllers is how the complexity of systems can be reduced according to the original idea of Zadeh. In this section, a fuzzy controller for a forging machine will be discussed.

1. Control object-open die forging process

The most massive forming processes are strongly nonlinear and instationary, which can be described by 10 fundamental equations; 3 differential equations of equilibrium, 1 equation of yield criterion and 6 stress-strain and stress-strain rate laws. But it is difficult to obtain exact solutions. Many solving methods to predict metal forming process is presented in.[6] An approach, which is in wide use, is FEM or FE-simulation. Interior process can be analyzed, provided that the material constants are available, for example yield stress ($k_f$). Be




⟨Fig. 5⟩ Principle of open die forging.

cause of it, a theoretical building of material model to develop a controller is almost not possible, specially on line to be calculated. Thus, simplified mathematical model should be used where control errors can be only sucessive corrected as a simplified error estimation method.

Open die forging process is the continuous sequence of upsetting in the sense that high productivity, more flexibility and precision must be reached, which can be achieved by fast forging cycle, many different modes and small forging tolerance. This process consists of 3 main phases; approaching, pressing and upstroke as is shown in ⟨fig. 5⟩. And time progress of this process is also shown in ⟨fig. 6⟩.

## 2. Control object-forging machine

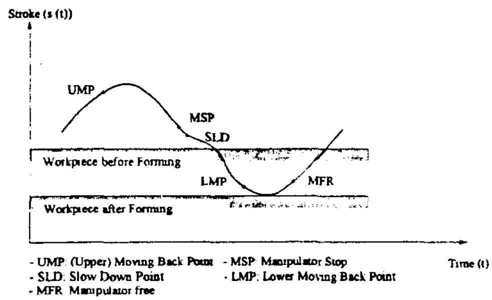
There are two types of hydraulic forging machine. One type is hydraulic forging machines, which operate with pumps, hydraulic forging valves and accumulator. The high pressure supplied by pumps is stored at first in accumulator. This accumulator saves some pump capacity for the peak requirements of the press. A disadvantage of this type of press is that the maximum energy must be stored, in spite of that the required pressure (operating pressure) is lower than maximum. But, for this reason, dimension of this type of press can be smaller as the maximum capacity.

The other type of forging press is direct pump drive system, which is driven without accumulator. The hydraulic oil, supplied by the pumps, goes directly into the main cylinder, therefore, the press velocity is directly proportional to oil delivery of the pumps or oil flow (denoted Q), provided that some disturbances can be disregarded.[7] A main advantage is that the press velocity and direction of upper tool can be varied exactly and smoothly. This character is specially profitable to forging processes with forging force strongly changed.

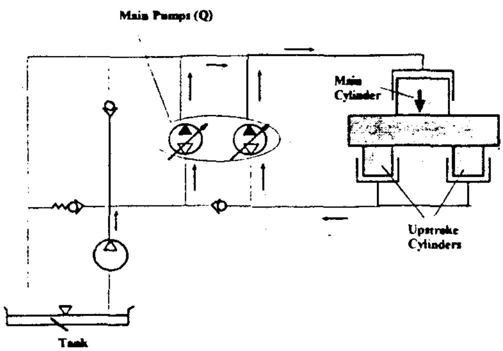
A hydraulic open die forging press of Fa. Pahnke (Germany), a type of direct pump drive (the modified sinusoidal system) integrated with two manipulators, is installed for experimental purpose. This system operates with variable oil flow reversing pumps, which allow the change of press velocity and direction almost without valves and has a maximum forging force of 160 kN. ⟨Fig. 7⟩ shows the oil hydraulic system of the forging machine. In the phase "pressing", the main cylinder pressure is increased by raising the power of pumps. The press velocity is controlled by the oil flow of pumps (Q). In the next phase "upstroke", the main pumps decompress the main cylinder by means of decreasing the oil flow of pumps and eventually reverses pump direction ("upstroke" : see fig 5 and fig. 6). After that, the pump feeds into the pullback cylinder in order to go back the upper tools upwards.

The controller for this forging machine controls only the main pumps to minimize the geometrical defects of work piece independently of the characters of workpiece and the state of the machine. The problems (disturbances) in controlling a position or speed of the upper tool are :

- the compressibility of the oil




〈Fig. 6〉 Time progress of the open die forging (one stroke).




〈Fig. 7〉 Simplified oil hydraulic system of the forging machine.[7]

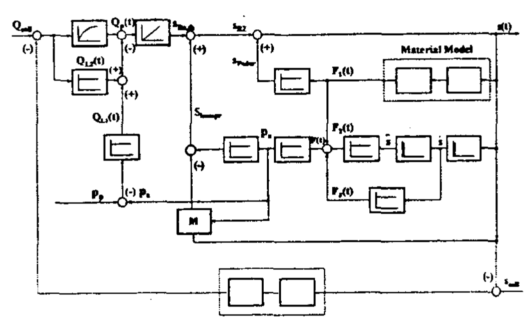
- response time of pumps and
- unpredictability of working load of the press affected by the resistance of the material to form the workpiece, which is dependent on work piece geometry and temperature.
- oil leakage
- the elastic deformation of the frame

Therefore, the signal of the upstroke must be outputted exactly in time to move the upper tool upwards before the prescribed forging height is reached (lower moving back point : see fig. 6). Unfortunately, this point can not be known in advance, because this position is strongly dependent on the kinetic energy of the upper tool and on the development of the workload after the penetration as described above.

A simplified theoretical model considering main disturbances is derived in,[8] which is not discussed in detail in this paper and is shown in 〈fig. 8〉. The nonlinearity of the system can be recognized. If one takes this theoretical model to develop an appropriate controller for real time processing, it does take large time effort to realize a conventional controller because of complexity and nonlinearity.

A mostly used conventional control method is, therefore, iterative correction of moving back point, which is gut enough for bar forging on the assumption that the geometry and temperature of work piece change the values not so fast. But it is desirable to realize "First-Stroke = First Hit"-control for complex forging process (for example incremental forging). That was the motivation to develop this fuzzy controller with the aim of higher precision, "First-Stroke = First Hit"-control, small forging time and saving of energy.

A typical design procedure of the Mamdani type of fuzzy controllers is shown in 〈fig. 9〉. At the first stage, the structure of the fuzzy controller (SISO or MIMO and so on), the hardware (cycle time, sensors and interface definitions) and other characters (disturbances,




〈Fig. 8〉 Conventional model of the forging machine.[8]

- System Analysis
- Input/Output-Definition
- Determination of Input/Output Domain
- Definition of the linguistic Variables, Definition of the Fuzzy-Sets and Definition of Rulebase (Selection of the Fuzzifications-and Defuzzificationsmethod)
- Selection of the Fuzzy-Operators
- Off-Line-Optimization/Simulation
- On-Line-Optimization

⟨Fig. 9⟩ Typical design procedure of the type of the Mamdani fuzzy controllers.

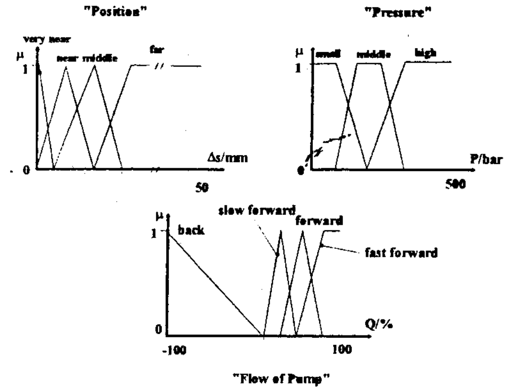
strategies) can be determined.

The input variables are the position of the upper tool (s or (s) and the hydraulic pressure (p). The output variable is the oil flow of pumps (Q). Their physical domain must be also determined at this stage, for example : 0 bar $<$ p $<$ 500 bar.

At the third stage a priori knowledge can be utilized, and the linguistic variables and corresponding fuzzy sets can be determined. On determining partition of basic domain it must be noted that the important area should not be divided so coarse : For example, the partition of the linguistic variable "position" (see fig. 10). The rules are a mapping of the progress of the process added with expert knowledge ; It is obvious that the timing of the outputting the signal for moving back or reverse must be determined and outputted dependent on the tool-velocity and demanding force, before the upper tool reaches the desired height. A rule example is as following :

IF Position is very near AND Pressure is high, THEN Oil Flow is back.

#This rule means that the desired height is very near and, therefore, the direction of the pumps must be reversed already, so that the



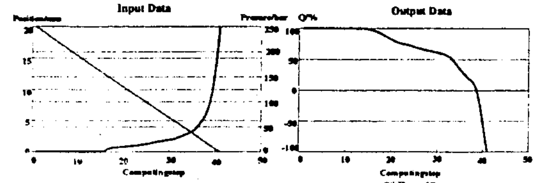

⟨Fig. 10⟩ Fuzzy sets for the fuzzy controller for a forging machine.

upper tool can be stopped at the desired height. The linguistic variable "pressure" has the function of detecting material hardness.

The sup-min-composition, the min-operator as a AND and the COM-method for difuzzification-method, because of simplicity, clearness and time saving were taken

At the stage of off-line simulation the functionality of the definitions of fuzzy controller on a computer can be tested and, if necessary, the parameters can be varied and optimized. In ⟨fig. 11⟩ a result of off-line simulation is shown. The timing of the signal for reverse should be denoted at the computing step 39.

At the last stage, the stage of implementation and on line fine tuning, the fuzzy controller must be connected with the real machine, and the fuzzy parameters must be fine tuned.



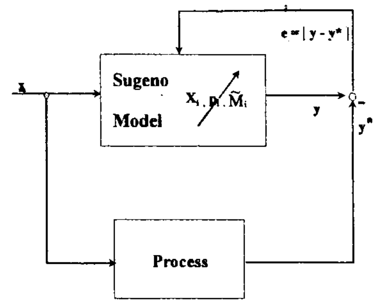

⟨Fig. 11⟩ A result of off line simulation.

This fuzzy controller was examined under the different conditions, different velocities and different forging forces. For one material, precision was reached with the deviation of ±0, 1mm, and for two different material (i.e. different forces) of 1,2mm. The advanced version of the fuzzy controller is reported in.[8] One additional input variable was the tool-velocity, so that the change of the pressure, which is dependent on material character, can be also considered. This fuzzy controller was designed by the hybrid method (see below and section 3).

## 3. A classification of fuzzy controller and examples

The function of blocks in ⟨fig. 3⟩, fuzzifi-cation, inference, and defuzzification can be found with examples in.[2] It is well known that a fuzzy controller can not be easily tuned on line to increase the performance of it. One reason is that there are too many parameters to be tuned and the other is that the exact mathematical formulation of the relation between inputs and outputs is not needed or not always be available in practice. Many design methods were introduced with the terminology "fuzzy modeling". The well known approaches are that of Mamdani[4] and that of Sugeno.[10] The Mamdani-Controller is based on a model of linguistical description of a process, whose structure is shown in ⟨fig 3⟩. The Sugeno-Controller is based on the method of parameter-identification of linear output function in ⟨fig 12⟩.

In order to reduce the effort at the stage of on line fine tuning, a systematical tuning method was introduced. The two types of fuzzy controller, intrinsic fuzzy controller (a type of the Mamdani-Controller) and hybrid




⟨Fig. 12⟩ Structure of the sugeno fuzzy controller.

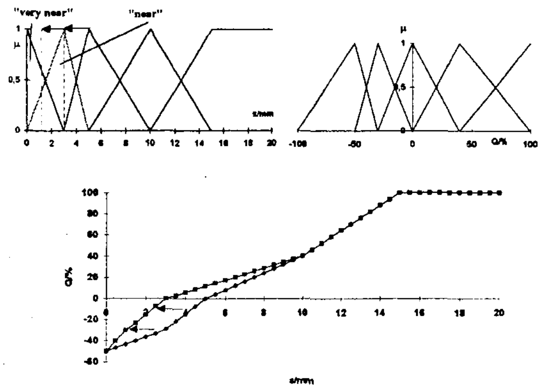
fuzzy controller, were therefore considered.[9] The principles of the two types of fuzzy controller are distinguished from one another to how membershipfunctions or rulebase can be built in order to find the fuzzy control parameters (the connervalues, the number, the form of fuzzy sets and so on) systematically that correspond to a output action. An intrinsic fuzzy controller is so designed that the development of the process can be mapped one to one into the rulebase. Thereby, knowledge of an engineer can be fully utilized. As an example for a controlling a forging machine can be taken ; "if the lower stroke end (s) is near, then the flow of the pump (Q) is reversed a little (small)". That means that the upper tool must be smoothly braked near the desired position (see fig. 6). The advantages of this type are extremely short time needed for its development and the easiness in understanding the functionality of the controller. But it should be denoted that this tuning method can still be called a "trial and error method".

Therefore, the hybrid fuzzy controller is designed besides the method of the intrinsic fuzzy controller, so that a fuzzy controller can be systematically optimized by using transfer-functions of fuzzy blocks. Briefly outlined, a fuzzy controller would be separated in SISO (single input and single output)-fuzzy blocks. This transferfunctions of each fuzzy blocks are intuitively determined, which would be pieceweise linear at first. Definitions of fuzzy sets and rulebase can be used yet to build those functions. But linguistical description of a process should be retained in definition of fuzzy sets and rulebase.

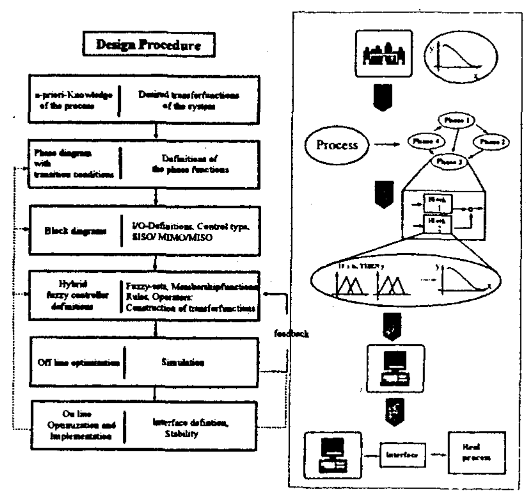
With an example, this method for optimization can be described ; there is one input, here the position ; and one the output, the flow of the pump. Assuming that we have an undesired result, for example, the desired height of a workpiece is not reached by experiment, then the result can be corrected by changing the transferfunction, that is, in turn, the changing of the fuzzy set "very near" and "near", e.g. slight moving of the transferfunction to the left (see the arrows in figure 13). If necessary, linear transferfunction can be altered to non-linear function by changing the form of membershipfunction, and in principle SISO-system can also be extended to MIMO (multiple input and multiple output)-system.

As an example for hybrid fuzzy controller, the structure of the fuzzy controller for a direct drive forging machine is shown in ⟨fig. 16⟩. As it can be seen, the structure is divided in many SISO blocks. One example of a transferfunction is also seen in this figure 15. With an additional input variable and application of this method, better results, higher precision (±0,1mm) and smaller time requirement at the fine tuning were achieved. The typical process time developments are shown in ⟨fig 17⟩.

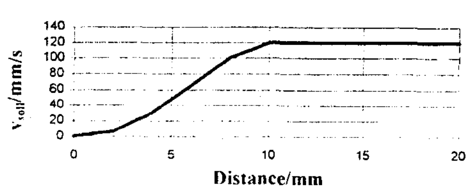
As another example of this concept, two hybrid fuzzy controllers will be discussed, which are installed at IBF for controlling hydraulic forging press (Fa. SMS in Germany) with an accumulator, which has maximum force 6,3MN. One of these fuzzy controllers was developed for Thixoforming process or SSM (Semi-Solid-metal-Forming), and the



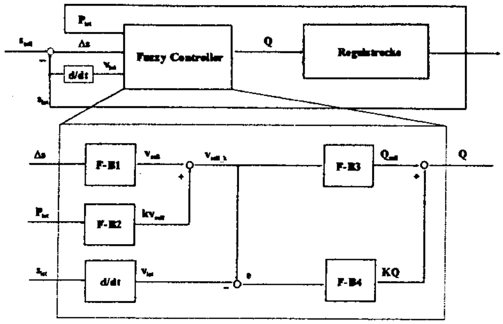

⟨Fig. 13⟩ An example of the function of hybrid fuzzy controller.



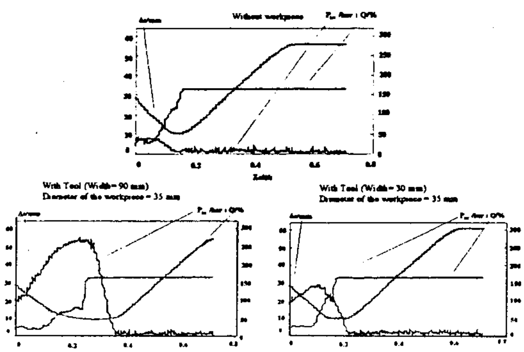

⟨Fig. 14⟩ A design procedure of the hybrid fuzzy controller.




⟨Fig. 15⟩ Transferfunction of the fuzzy block.




〈Fig. 16〉 Structure of fuzzy controller for a forging machine.



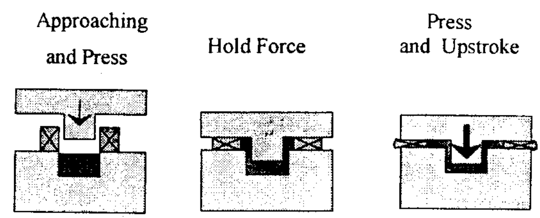
〈Fig. 17〉 Measured curves of a forging process.

other for stretch process.

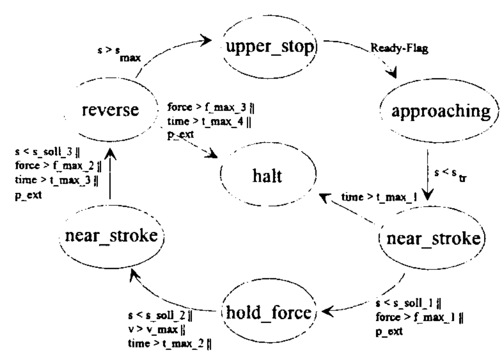
The thixoforming process is recently developed for achieving the near net shape technology. Aluminum billets, which are produced by special casting techniques, can be formed under relative lower pressure. And, furthermore, highly complex end form can be reached by this process.[11]

By a control engineer this process can be seen as a sophisticated control object, because this process is dynamic, highly nonlinear and also two types of control, namely, velocity control and force control must be realized in a control system. Normally, the combination of the two types is not trivial, because an actual position is unknown at the moment, if the demanding force should be controlled because of the lack of a workpiece model. Furthermore, the controller must switch smoothly these two control types without oscillation or force overshoot to avoid material defects (cracking). In the steady state, the controller must maintain a constant force and position to counter the workpiece force, assuming the workpiece reaction force to be constant.

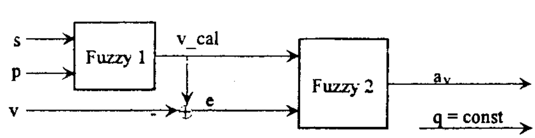
The process consists of three main sections, shown in figure 18. The "approaching and press" phase velocity control is realized. After that, the velocity control must be switched by




〈Fig. 18〉 The process of the thixoforming




〈Fig. 19〉 The phase diagram of the thixoforming.



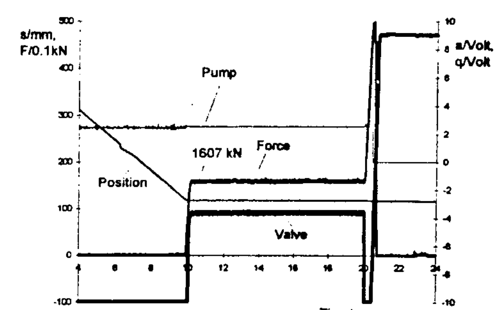

〈Fig. 20〉 Block diagram for the phase "near-stroke".

the force control. In this stage the forging force must be constant (phase "hold force"). After that, this force control should be changed in the velocity control again (phase "press and upstroke").

In order to minimize the complexity of process the phase diagram and corresponding phase functions are defined with the transition conditions (see fig. 19), as described above. Each phase function is realized by fuzzy controllers as well as by conventional controller, if necessary. For example, the phase function "near-stroke" determines the optimal moving back point, which has two fuzzy blocks (see fig. 20), and the phase function "hold-force", which has one SISO fuzzy block controls the forging force in order to hold the constant force.

The results of the fuzzy controller were superior to those of a conventional controller which was timely parallel developed by a German control system company. The fuzzy controller has no overshoot at the moment of transition from velocity control to the force control (see fig. 21), and it has force deviation under 1 % (≈50 kN at the maximum force 6,3MN) under different forging conditions.

A fuzzy controller for the ring rolling process will be published in.[12]




〈Fig. 21〉 A measured curve of the thixoform-ing process.

## III. Concepts for intelligent control

The concept "intelligent control" can be defined as following : A control system which has self diagnostic, self optimizing and learning function and whose components are connected by a network. There are many realization methods, for example GA, NN and so on. In this section, some concepts will be introduced by examples.

### 1. Fuzzy Diagnostic

Most of the machines for mass production, for example, sheet forming machine should be maintained well to avoid production stop caused by machine failures. At first, the failures must be recognized, localized, analyzed and repaired. It took place in a metal forming factory that cracks on the main frame came out and eventually the machine was broken, although the regulated maintenance has been carried out by a service plan. What was wrong ? A periodical service plan can only work, if the average machine load in each time interval is constant. That is not the case in general, because the machine loads are dependent on workpiece material, tool geometry, machine state and so on. It is better, if a machine can be constantly observed on line by a diagnostic system.

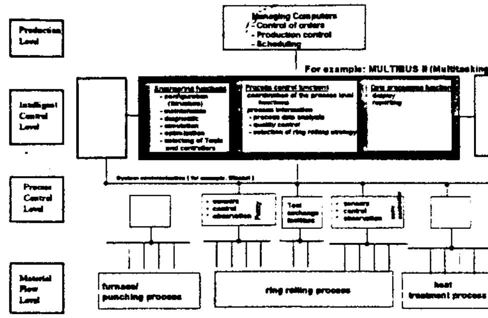
A concept of machine diagnostic system or error identification system with fuzzy logic can be introduced as following : The idea is simple. Let us imagine a railway station. An inspector knocks on the train wheel in order to check up whether there are cracks on the wheel or not. He does not use a high precision measuring device, but his experience and his ear as a sensor which is not precise. This method can be easily applied to a diagnostic system.

Machine specific signals, mechanical or acoustical signals measured can be used as a failure detector, by which the state of the machine is checked up, whether there are cracks on a frame or tools, or failures in hydraulic pump.

These characteristic signals, which are transformed by the Fourier Transformation in the frequency domain, deliver some patterns. The standard patterns previously measured or rather machine inherent patterns should be eliminated, so that the failure patterns can be easily analyzed. These patterns measured can not be clearly separated from machine inherent patterns and not be easily analyzed, because most of these patterns contain disturbance signals. Therefore, the fuzzy method as a pattern recognition method can be used to match the pattern with the predefined failure patterns.

2. Fuzzy Optimization

The target values must be first decided to optimize a process. The target values or parameters in a forging process are, for example, constant tensile strain or grain size or press cycle time: This scheme is the same as a simplified problem "traveling salesman", if one wants to find out an optimal path from a place A to a place B. The target can be minimum time duration or the shortest route. The parameters are varied by a optimization algorithm, until the target values reach the predefined conditions. By a conventional method, the bound values should be sharply defined. But, in some cases of multi-objective problems, it is not trivial to find a optimal solution, because the objectives are related together. Furthermore, a method used sharply defined bound values is not plausible: If the temperature




〈Fig. 22〉 A concept of a ring production factory networked with an intelligent control system.

200℃ is determined as a bound value, then the temperature 201℃ can not be accepted as a optimal solution, although a engineer would not do so. Is it plausible ? Thus, the fuzzy sets can be utilized. An example in the area of the metal forming is reported as a fuzzy optimization to optimize hot rolling mill schedules in.[13]

Nevertheless, the NN-Technolgy as a learning method should be integrated with a intelligent control system, which can be also combined with the fuzzy technologies. All these concepts can be integrated with a network in a factory. One example is shown in 〈fig. 22〉 for a ring production factory.

## IV. Summary

In this paper, the fuzzy controllers for the metal forming machines and some concepts for realization of a intelligent control with examples were introduced. The terminology of intelligent control must be defined more precisely in the future and corresponding realization methods must be studied in order to utilize the knowledge of experts. Linguistic models or descriptive models should be taken into account as well as mathematical models for designing intelligent control systems as a knowledge based system.

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