APPLICATION OF FUZZY SYSTEM AND INTELLIGENT CONTROL FOR IMPROVING DMD PROCESSES

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Abstract

Manufacturing products in the United States is an extremely competitive business. Global manufacturing also has been fundamentally reshaped by the innovative improvements in computing, communications, methodology of production, and distribution. Each factor, standing alone, has greatly expanded the opportunities for trade, investment, and global production. When rapid changes in all of these factors are taken in combination, it tends to change the way manufacturing is done. What these factors have done is raise the bar for companies to compete in today's manufacturing environment. Like any other manufacturing industry, the plastic injection molding and die casting industries are also under heavy pressure to cut costs and increase productivity in order to remain competitive against global competition. Die casting is a versatile process for producing engineered metal parts by forcing molten metals under high pressure into reusable steel molds containing a cavity of the desired shape of the casting. These molds, called dies, can be designed to produce complex shapes with a high degree of accuracy and precision. Direct Metal Deposition (DMD) could be used to manufacture quality molds with comparable manufacturing costs. There are various process parameters involved with the manufacture of molds using the DMD machine. This study looked at the use of fuzzy logic and intelligent control for process optimization of DMD in the development of molds. DMD is a laser-based, additive fabrication technology that produces dense metal products from the ground up using powdered metal.

Introduction

This study focused on developing an optimal mold material composition for use in the die casting industry. The material composition was manufactured using Direct Metal Deposition (DMD). The DMD process blends five common technologies: lasers, computer-aided design (CAD), computer-aided manufacturing (CAM), sensors, and powder metallurgy, as shown in Figure 1.

A combination of tungsten and Inconel 718 as the surface layer and copper chromium as the substrate was selected for evaluation. Experiments were conducted to understand the significant variables that influence the property of the mold manufactured via DMD and also to establish a relationship between the various process parameters.

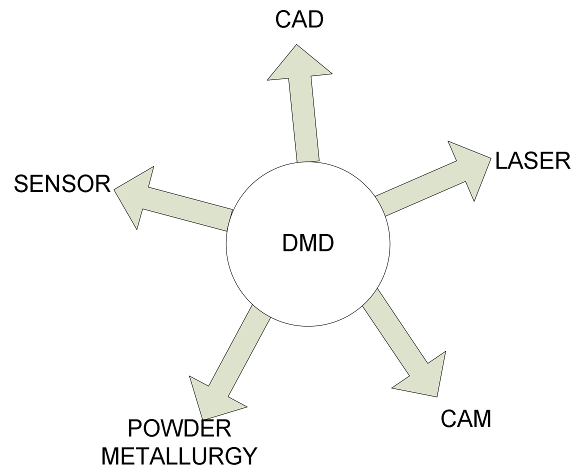

Figure 1. DMD Blend of Technology

The process parameters investigated here included laser power, transverse speed, substrate temperature, preheating, and mass flow rate, along with the composition of the metallic powders. Material properties that were evaluated included hardness, tensile strength, abrasive resistance, thermal conductivity, and porosity. Any change in any one of the process parameters made a significant change in the responses, so the optimization of the process parameters was necessary to get the desired results. This optimization of the process parameters to get the desired results could be done using fuzzy logic.

Fuzzy logic is a departure from classical two-valued sets and logic, which uses "soft" linguistic (e.g., large, hot, tall) system variables and a continuous range of truth values in the interval [0,1], rather than strict binary (true or false) decisions and assignments. It was introduced by Dr. Lotfi Zadeh of UC/Berkeley in the 1960s as a means to model the uncertainty of natural language. Fuzzy logic is useful to processes like manufacturing because of its ability to handle situations that the traditional true/false logic cannot adequately deal with. It lets a process specialist describe, in everyday language, how to control actions or make decisions without having to describe the complex behavior [1],

[2]. Formally, fuzzy logic is a structured, model-free estimator that approximates a function through linguistic input/ output associations.

The key benefits of fuzzy design are its simplified and reduced development cycle, ease of implementation, and ability to provide more user-friendly and efficient performance. Humans are generally unsuccessful at making quantitative predictions, whereas they are comparatively efficient in qualitative forecasting. Furthermore, humans are more prone to interference from biasing tendencies if they are forced to provide numerical estimates since the elicitation of numerical estimates forces an individual to operate in a mode which requires more mental effort than that required for less precise verbal statements [3], [4]. Since fuzzy linguistic models permit the translation of verbal expressions into numerical ones, thereby dealing quantitatively with imprecision in the expression of the importance of each criterion, some multi-attribute methods based on fuzzy relations are used. Applications of fuzzy sets within the field of decision-making have, for the most part, consisted of extensions or fuzzifications of the classical theories of decision making. Kahraman [5] used fuzzy logic as a multi-criteria model for his facility location problem. While decision making under conditions of risk and uncertainty have been modeled by probabilistic decision theories and by game theories, fuzzy decision theories attempt to deal with the vagueness or fuzziness inherent in subjective or imprecise determinations of preferences, constraints, and goals. Sun [6] and Buyukozkan [7] have used fuzzy logic along with neural networks in identifying a best conceptual design candidate and also for new product development. The work that had been done by these authors inspired this current study on optimizing the DMD process.

Most users of the direct metal deposition machine depend very much on the manufacturer's guidelines, experts' advice and services, and information from the suppliers who provide the metallic powders for fabrication rather than a formal evaluation practice that is used to stabilize the process. Most of the evaluation process involves subjective and qualitative criteria, which makes the decision process ineffective. The importance of these conflicting criteria often strongly depends on the type of application and different factors such as duration, quantity, and shape of the deposition [8].

Fuzzy logic is a powerful methodology that has been used in modeling to control uncertain multi-criteria decision-making processes [9], [10]. In this project, there were many parameters that could affect the final result. Many researchers have adopted fuzzy logic techniques in their decision-making problems. Graham et al. [11] applied fuzzy logic for selecting the optimum machining parameters and cutting tools for cutting selected materials.

Visual Fuzzy in Analysis

The DMD machine was used to deposit a coating material over the base material. The main process parameters involved in depositing the material were laser power, CNC speed, feed rate, composition and pre-heating. Any change in one of these parameters made a significant change in the responses. It is difficult to attain a result by visually looking at a deposit, and none of the property measurements could be done visually. The only property that could be done visually was pores and cracks, but there is not much fuzziness involved because the result will be either that there are pores and cracks in the material or not. The presence of pores and cracks is totally undesirable. The fuzziness that could be used would be something like "this deposit has fewer pores and cracks". This concept could be used in getting closer to a clear deposit. The feasibility study allowed us to conclude that deposits obtained in final runs would be free from pores and cracks. Thus, additional work should be undertaken. This current study assumed then that a good deposit would be attained with the selected five process parameters and four responses which are shown in the diagram of Figure 2.

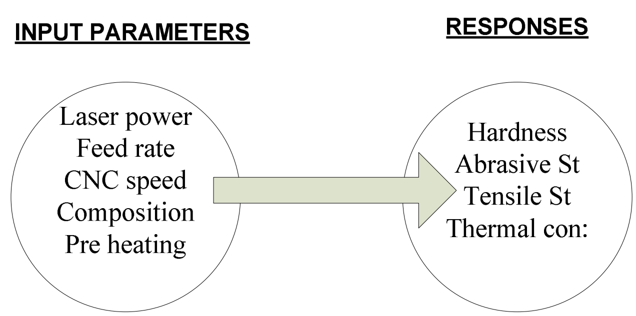

Figure 2. Relationship Between Input Parameters and Responses (Output Parameters)

For any set of input values a set of responses was obtained, and with any change in any of the input parameters there would be a change in the responses. For example, consider a fuzziness situation such as "close to a higher hardness", where the input parameters could be used to select suitably. In such a situation, one would try to fuzzify the data. Visual fuzzy, then, can generate the hardness that would be obtained by different combinations of the input parameters. So the input parameter needed to achieve the desired hardness could be found using fuzzy.

Initially, more than 32 input variables were identified which could change the output variables. Based on design of experiments and professional expertise, the list of input variables was reduced to five. And out of these five input variables, the most significant input variables were laser power and speed. Experiments were conducted on laser power and speed in order to determine the quality of the deposit as well the hardness of the deposit.

Consider Figure 3a as a Fuzzy set for F1 using hardness as an example. Similarly, different fuzzy set data can be generated for different hardnesses with the same membership functions. This means that there are different fuzzy set data for varying hardnesses.

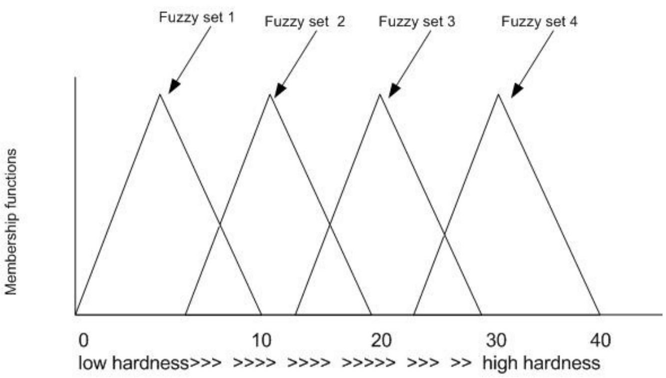

Figure 3a. Fuzzy Set Considering Hardness

Figure 3b shows the schematic design of the system. Laser power and laser speed were used to determine the output of the system, which is the hardness. If the requirement is for a desired output, then one of the inputs can be used as a variable.

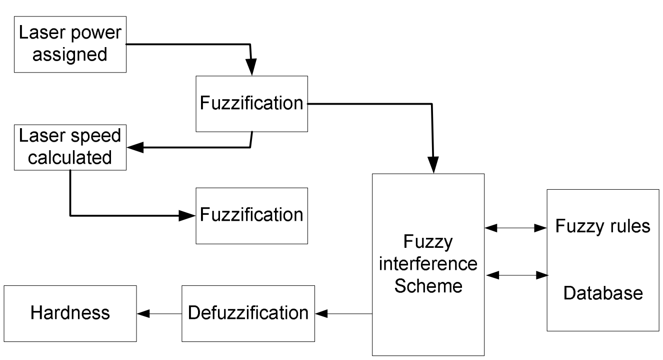

Figure 3b. System Schematic Diagram

Figure 3c is a modification for system schematic design, where a known output is desired. For example, if the hardness requirement is set to a value of 60 HRC (Rockwell hardness), the fuzzy system would automatically calculate the speed at which the laser would move for a set laser power.

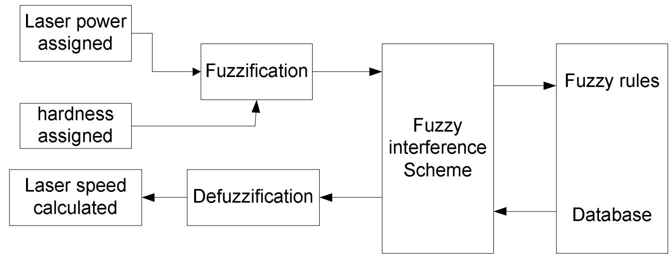

Figure 3c. Speed Calculation for a Desired Output

Fuzzy Rules

The decisions are based on rules. Although we may not be aware of it, all of the decisions that are made are based on computer if-then statements or using logical relationships. If the material hardness is low, then the decision may be made to decrease the speed, or change any other parameter that would increase the hardness. Rules associate ideas and relate one event to another. Fuzzy machines, which always tend to mimic the behavior of man, work the same way. However, the decision and the means of choosing that decision are replaced by fuzzy sets and the rules are replaced by fuzzy rules. Fuzzy rules also operate using a series of if-then statements. For instance, if X then A, if Y then B, where A and B are both sets of X and Y. Fuzzy rules define fuzzy patches, which is the key idea in fuzzy logic and is made smarter using the Fuzzy Approximation Theorem (FAT). The universe of discourse on the membership functions for each variable were defined earlier through various experiments. Laser power was controlled to between 2000 and 2900 watts; laser speed was between 5mm/second and 4.0mm/second. All of the membership functions and their corresponding labels are explained in Figures 5 and 6.

Fuzzy Control

Fuzzy control, which directly uses fuzzy rules, is the most important application in fuzzy theory. The three steps that are used to control fuzzy systems are as follows:

- Fuzzification (using membership functions to graphically describe a situation)
- Rule Evaluation (application of fuzzy rules)
- Defuzzification (obtaining the crisp or actual results)

The current experiment has five inputs and four outputs. However, to more easily explain fuzzy, consider an experiment that has only two inputs and one output. Here, the problem is to obtain a good laser deposit. Laser power and transverse speed are chosen as the inputs of the system. Hardness of the deposit, then, is chosen as the corresponding output.

STEP 1: Membership Functions

First of all, the different levels of output (high hardness and low hardness) of the platform are defined by specifying the membership functions for the fuzzy sets. The graph of the function is shown in Figure 4.

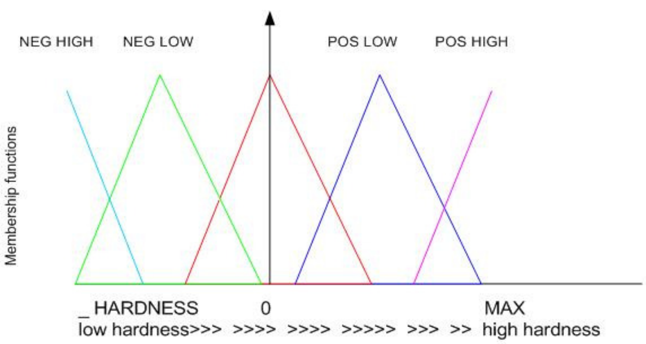

Figure 4. Membership Function for Fuzzy Set

Similarly, the different levels of the input are specified by the membership functions and similar data are collected based on the other inputs (laser power and CNC speed). Figure 5 shows the membership functions based on laser power and CNC speed.

STEP 2: Define Fuzzy Rules

The fuzzy rules are basically a series of if-then statements as mentioned earlier. These statements are usually derived by an expert to achieve optimum results. The following are the sets of fuzzy rules that are applied to the system for generating deposits that are free of pores and cracks. The output value and hardness will vary accordingly.

1) If laser power is 2700–2900 and measured speed is operating, then set laser speed to 5mm/s
2) If laser power is 2500–2700 and measured speed is 3.5mm/s – 4.0mm/s, then set laser speed to 4.9mm/s
3) If laser power is 2500–2700 and measured speed is 3.0mm/s-3.5mm/s , then set laser speed to 4.8mm/s
4) If laser power is 2300–2500 and measured speed is 3.5mm/s – 4.0mm/s, then set laser speed to 4.7mm/s
5) If laser power is 2300–2500 and measured speed is 3.0mm/s-3.5mm/s , then set laser speed to 4.6mm/s
6) If laser power is 2100–2300 and measured speed is 3.0mm/s-3.5mm/s , then set laser speed to 4.5mm/s
7) If laser power is 2300–2500 and measured speed is 3.0mm/s-3.5mm/s , then set laser speed to 4.4mm/s
8) If laser power is 2100–2300 and measured speed is 3.0mm/s-3.5mm/s , then set laser speed to 4.3mm/s
9) If laser power is 2100–2300 and measured speed is 3.0mm/s-3.5mm/s , then set laser speed to 4.2mm/s
10) If laser power is 1900–2100 and measured speed is 3.0mm/s-3.5mm/s , then set laser speed to 4.1mm/s
11) If laser power is 1900–2100 and measured speed is 3.0mm/s-3.5mm/s , then set laser speed to 4.0mm/s

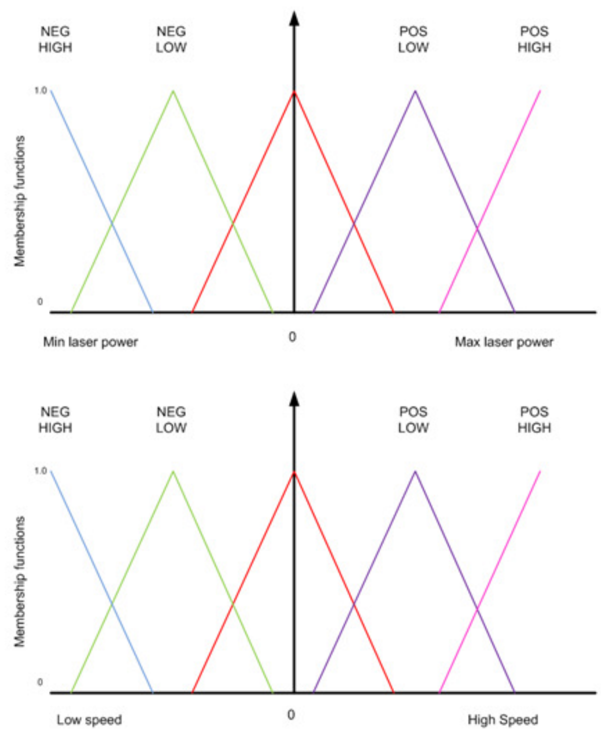

Figure 5. Membership Function Based on Varying Input, Laser Power, and for CNC Speed

Expertise in the process is needed in order to define fuzzy. Unintended results will be obtained if the rules are not followed. Based on the set rules, the input values are given. For example, 0.75 and 0.25 for zero and positive low power, and 0.4 and 0.6 for zero and negative laser speed. These points are shown on the graph of Figure 6.

Consider the rule "if speed is zero and laser power is zero, then hardness is zero". The actual value belongs to the fuzzy set zero to a degree of 0.75 for laser power and 0.4 for speed of the laser. Since this is an AND operation, the minimum criterion is used, where the fuzzy set zero of the variable "speed" is cut at 0.4 and the patches are shaded up to that area. This is illustrated in Figure 7.

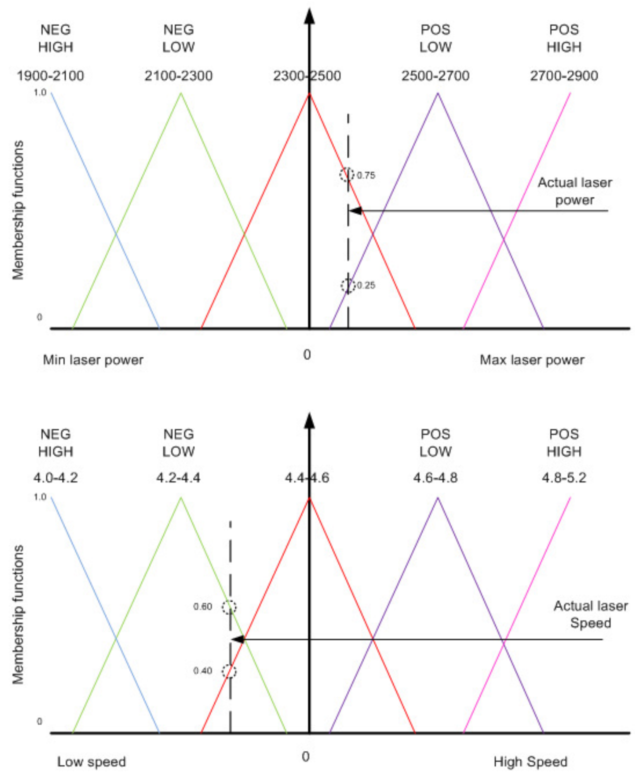

Figure 6. Defining Fuzzy Rules for Laser Power and CNC Speed Based on Defined Rules

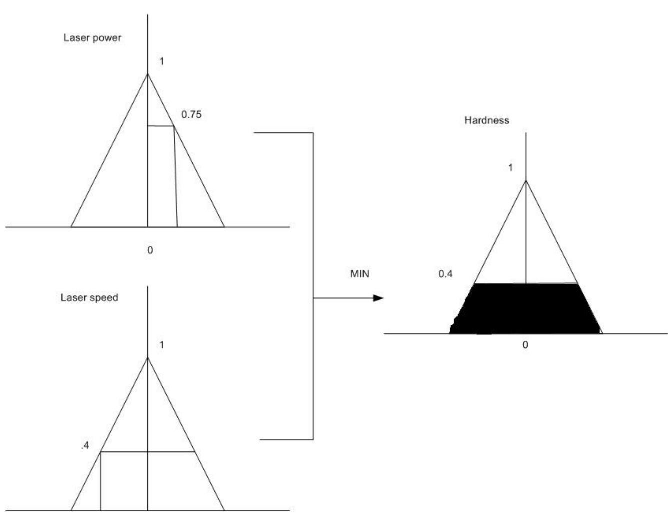

Figure 7. Applying Fuzzy Rules on Laser Power and Laser Speed to Provide the Final Value on Hardness

Similarly, using the minimum criterion rule for the other three, the following results are obtained as shown in Figure 8.

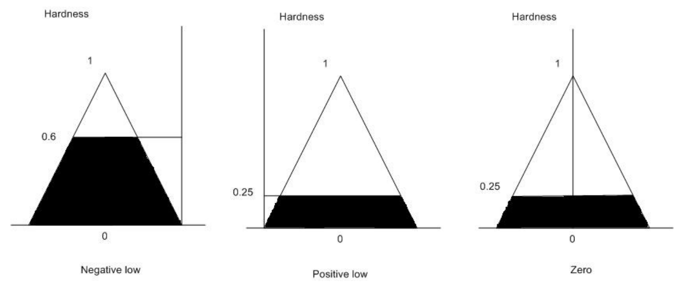

Figure 8. Minimum Criterion Rule for Hardness

Step 3: Defuzzification

The result of the fuzzy controller thus far is a fuzzy set of hardness. In order to choose an appropriate representative value as the final output (crisp values), defuzzification must be done. The five commonly used defuzzification techniques are:

- Five Methods
- Center of Gravity
- Bisector
- Middle, Smallest, and Largest of Maximum
- Picking a Method

Any of the defuzzification methods would work. For the defuzzification in this current study, the authors chose the Center of Gravity method, which is shown in Figure 9.

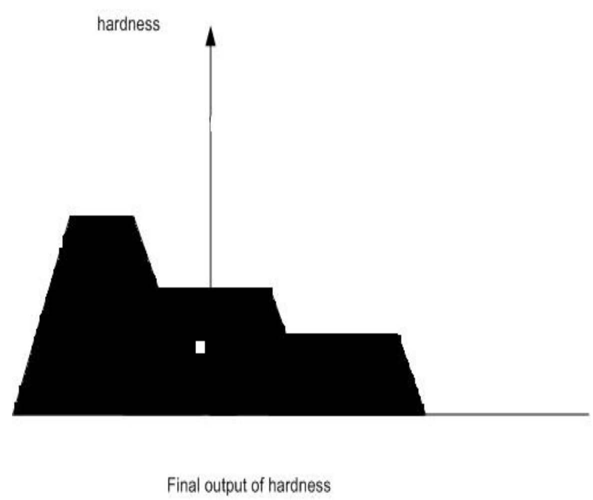

Figure 9. Defuzzification of Hardness

The white spot in the figure shows the corresponding value of the hardness. The concept of visual fuzzy could be used in the analysis of the experiments. In this example, the authors considered only one response and two inputs, and no real rules were applied. Only arbitrary values were used to try to explain the concept of how the fuzzy system and intelligent control could be applied in optimizing the response variables. In the current study, there were five inputs and factors considered with the four outputs (responses). The concept of multi-criteria decision making or multi-response fuzzy logic [10] could be used to describe the problem and to arrive at a solution.

Critical Results

It was observed that on five occasions the fuzzy logic controller brought the DMD process back into optimum conditions without any external intervention. The deposits were all free from pores and crack, but had varied hardness. On some occasions, fuzzy logic slightly over compensated for the critical laser power, which can be adjusted by tuning the membership functions. The pilot experiment involved only two inputs. But once more data are available with all the varying inputs, it could be expanded for a more in-depth study. The results of the deposits show that a fuzzy logic controller ensured that the DMD process was used to create quality deposits without any plasma formation incidents.

Conclusion

Fuzzy logic integration was successful; and, although it worked for two inputs, the authors admit that it may not be the most robust method to use with more than five varying inputs. Where there are complex factors and parameters involved, which are suitable for processes where a linear process is not achieved and also where human logic is based on experience, it would have an edge over the various manufacturing tools. What these results prove is that fuzzy logic control could be used to improve the DMD process, though further work needs to be done to establish the role of fuzzy logic with varying input parameters.

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Biographies

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