ROBUST DESIGN – A DECISION MAKING TOOL IN MACHINING BY LAPPING

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Abstract. The paper presents a computer-based intelligent decision support system designed to achieve the optimization of the lapping of plane surfaces, by the Taguchi's method of arrays of experiments. The steps to be followed for solving the issue of optimization are described, the most important ones concerning the defining of the targeted objective, establishing the factors influencing the process and their respective levels, selection of the optimum array of experiments, processing of the results and determining the optimum configuration of the levels of the considered factors.

Keywords: Arrays of experiments, computer-based intelligent decision support system

1. Introduction

Decision making is a cognitive process meant to guide the selection process of an optimum solution from a large number of alternatives, with the final aim of arriving at a decision.

The decision-making process does not take place instantaneously, it being a sequential action completed in a certain time interval by running through a number of steps. According to A. Brim (1962) a sequential decision making process can be divided into several stages, as follows:

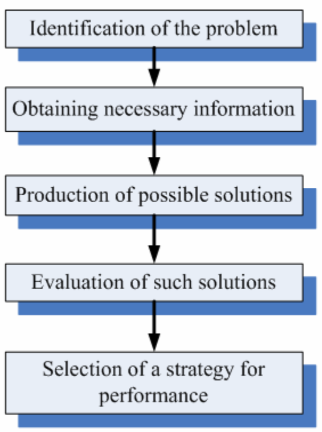

Figure 1. Stages of decision making

Structured rational decision making is an important part of all science-based professions, where specialists apply their knowledge in a given area to making informed decisions. Regardless of the field of application, decision making is based on a number of tools, the best known being: SWOT analysis, Pareto Diagram based analysis, PERT, Critical Path Method, Monte Carlo method, Robust Design, etc.

Adopting a decision depends on a multitude of elements, many of them possibly conflicting. In view of this impediment and in order to facilitate decision making, computer-based intelligent decision support systems (IDSS) were developed. These help diminishing the risk of human errors in the assessment of a situation.

The present paper presents a decision making method based on the robust design of processes, the analyzed case being that of plane surface lapping. For this reason "LappMaster", an expert decision making system was developed, based on an algorithm provided by Taguchi's methods of parametric robust design of processes.

LappMaster is a computer application that helps researchers to organize information and generates analytical results that enable them to make the best possible decisions.

The benefits of using the LappMaster application include:

- reduces the time required to make a team decision by lowering risk of making a poor decision;
- improves confidence that the best possible decision was made with existing uncertain information.
- advises about what to do next to reach a decision.
- results are reviewable, reusable and certifiable.

The developed expert system is of Wizard type, supplying an interactive use interface, meant to support decision making in relation to surface machining by lapping processes.

2. Surface lapping

Lapping is a procedure of surface smoothing by abrasive erosion, where the removal of the material tooling allowance is achieved by grains located at the interface of the transfer object and the machined part. Lapping falls into the category of machining processes by chip removal where the cutting edges of the tool are not determined geometrically. It is a machining method for finishing where the abrasive grains are freely suspended in a bearing fluid, the cutting being typically achieved by a form-generating counter-part (transfer object).

A simplified view of plane surface finishing equipment employing lapping as a machining process is shown in figure 2.

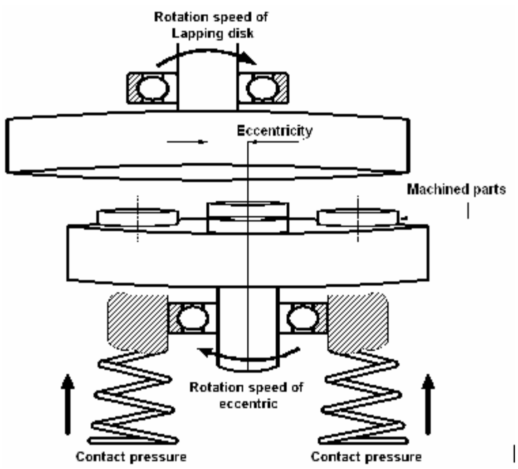

Figure 2. Lapping equipment

The above scheme highlights some of the main parameters contributing to achieving the aims of lapping, these parameters being: rotation speed of the lapping disk, rotation speed of the eccentric, contact pressure, magnitude of eccentricity. Although not shown in the scheme, but equally important are the abrasive concentration in the lapping paste, the type of the abrasive, as well as the duration of machining.

All parameters referred to above are input quantities to the system, each having a number of possible different values.

The roughness of the machined surfaces, the height of the removed material layer, the hardness of the superficial layer represent output quantities of the system, their values depending on the input parameters and on the influence of various disturbing factors.

Considering the wide range of input and output parameters which characterize surface lapping, process optimization can be achieved by robust parametric design.

3. Robust parametric design

The method of systems "robust design" (also known as Robust System Design) has been developed by Dr. Genichi Taguchi in the 1950s, its main objectives being the improvement of manufacturing process stability and increasing of their efficiency.

The basic idea of robust design is the minimization of the variability of the quality characteristics of the end-product by diminishing the sensitivity of the manufacturing process to the action of disturbing sources from the work environment. The final aim of robust design is to develop production processes which are not sensitive to the action of inevitable disturbing factors from the outer environment. Robust design is the strongest available method for reducing production costs, allowing improvement of product quality simultaneously with the shortening of the duration of its development.

Reducing the variability interval of the quality characteristics is generally acknowledged as the key to improving product reliability and increasing productivity. To date several approaches to reducing variability are known, each having its well-established place within the development cycle of a product.

Robust design is the method of diminishing the variability interval of the quality characteristics which provides the methodology of systematically obtaining production processes less sensitive to various disturbances. This type of design can be used for the optimization of product development as well as for conceiving new manufacturing processes.

Generally, when dispersion or instability of the values of product characteristics is observed, the problem is addressed by searching for the causes responsible for this situation, in order to diminish their effect or even eliminate them. These parasite causes can however be manifold: raw material characteristics non-uniformity, varying operation modes of the workers, varying environment factors, etc. The means employed for reducing the causes can prove quite costly, as they may consist, e.g. in reducing the intervals of tolerances for the analyzed quality characteristics, in over-dimensioning certain components, in employing more sophisticated working equipment, in enforcing rigid product exploitation rules, etc. These are the reasons that determined G. Taguchi to conceive a new strategy, based on a different philosophy that underlies the analytical reasoning.

The strategy developed by Taguchi and used in the robust design of systems is completely opposed to the classic approach: instead of identifying and eliminating the parasite factors (called *noises*), Taguchi focused on minimizing their impact. Concretely, the strategy consists in *identifying those combinations of values of system input parameters that reduce the effects of parasite causes, without actually addressing the causes*.

Figure 3 presents the classic perception of a production process affected by several noise factors, followed then by the representation of the same system as seen by Taguchi, that is with the level of the input parameters optimized such as to make the system insensitive to the action of disturbing factors:

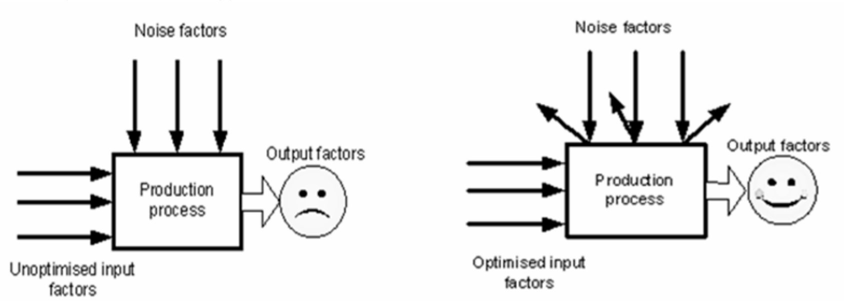

Figure 3. The difference between a classic and a robust manufacturing system

It can be noticed, that by experimentally establishing the optimum values assigned to the system input factors, the response obtained as output will ensure the desired functional performance of the system that will be robust, that is insensitive to noise factors.

According to the Taguchi strategy elimination of non-quality is feasible without actually identifying and eliminating the disturbing factors of the system, but by experimentally identifying an adequate combination of levels of the controlled input factors. Hence it can be stated that an exhaustive knowledge of the product generating process is not required, but merely adequate control of the input factors. This deliberate pragmatism can be asserted by the adage: *it is preferable for a process to function perfectly without us knowing exactly how, than to know exactly how – and the process not functioning!* [1].

Robust design uses arrays of experiments as its tools. These represent a minimum number of test runs organized such as to allow a maximum accuracy study of the possible influences of the system input parameters.

The arrays of experiments used in the robust design of processes are of fractional orthogonal factorial type. While fractioning reduces considerably the number of required runs, orthogonality assures maintaining the accuracy and relevance of the obtained results.

In order to set up fractional factorial arrays, G. Taguchi has developed a set of standard matrices that cover any practically possible situation.

An important characteristic of a fractional factorial array is its orthogonality, that is the property that allows the isolation of the individual effects of the different factors tested simultaneously under various conditions.

G. Taguchi's methods of robust design also use the concept of signal-to-noise ration (S/N). This is the performance indicator of a production process, which simultaneously takes into consideration both the target value of the analyzed quality criterion, and the variability of the quality characteristics measured around the target. The desired value, to be achieved, is defined as signal, while its variability, to be reduced is defined as noise.

The computational relations for the signal-to-noise ratio have various forms in accordance with the type of the studied quality criterion, related to the analyzed technological process. The types of quality criteria are: target criterion ("nominal is the best"), criterion to be maximized ("bigger is better"), criterion to be minimized ("smaller is better").

Robust design of the surface lapping process is achieved by applying either the classic method of arrays of experiments, or Taguchi's method of arrays of experiments (the method of fractional orthogonal factorial arrays of experiments).

Regardless of the applied method, identification of an optimum solution to ensure a robust lapping process implies a sequence of steps [1]:

- define the objective to be achieved, that is of the quality characteristic to be optimized;
- determine the factors influencing the process and their levels;
- select the experiment array to be used;
- carry out the experiments, measure and record the results;
- process results and compute the effects of the tested factors;
- select the optimum configuration of the levels of the tested factors;
- carry out a validation test.

The identification of the factors with a major influence on a surface lapping system has been achieved by mapping and analyzing an Ishikawa diagram (figure 4), and also of a Pareto diagram (figure 5), which outline a hierarchy of the factors according to their importance. This hierarchy was built based on the principle established by Taguchi, according to which the tested factors need to be directly related to the energy used in the studied system. The selection of the factors needs further to satisfy the principle according to which each factor must be able to accept all associations of the tested values with those established for the other factors.

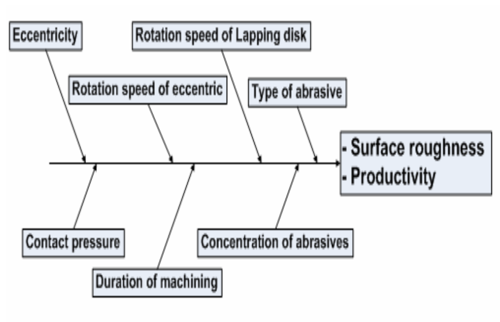

Figure 4. Ishikawa diagram

The greater the number of the tested input factors, the better the probability of correctly identifying the factors significantly influencing the production process will be. On the other hand, however, selecting a large number of factors to be taken into consideration is likely to slow down the decision making process, due to the increase number of test runs to be carried out.

4. The LappMaster Application

The **LappMaster** [3] was developed in order to enable computer aided decision making related to the optimum choice of the input factor values of the surface lapping process. Developed in Visual Basic programming environment, the application is a multi-criteria analysis tool of surface finishing by lapping processes. The program is of modular structure and allows obtaining of the following results:

- Computation of the technical time norm for surface lapping;
- Computation of the erosion parameters of the lapping disk and of the workpiece;
- Optimization of surface lapping by the classic method of arrays of experiments;
- Optimization of surface lapping by Taguchi's method of arrays of experiments (the method of fractioned factorial orthogonal arrays of experiments).

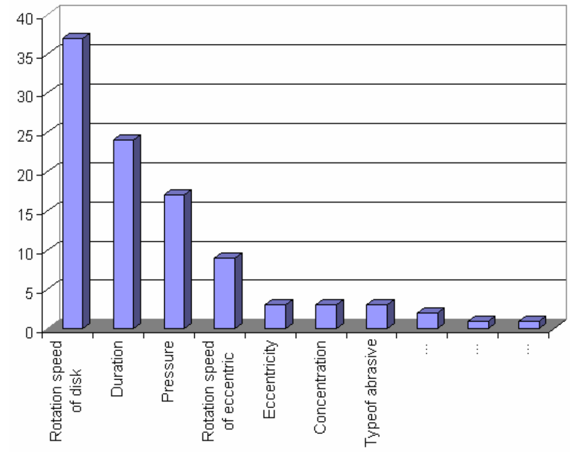

Figure 5. Pareto diagram

The application includes two main modules:

- **NormMaster**, the module for the computation of:
  - the technical time norm for surface lapping;
  - the erosion parameters of the lapping disk and of the workpiece;
- **TagMaster**, the module designed for:
  - the optimization of surface lapping by the classic method of arrays of experiments;
  - the optimization of surface lapping by Taguchi's method of arrays of experiments (the method of fractioned factorial orthogonal arrays of experiments).

The entire application is based on 26 forms and is developed in Wizard format, such as to guide the user towards the desired results, by working through a sequence of windows.

The opening window of the program is shown in figure 6, its role being of directing the user towards one of the two main modules, **NormMaster** or **TagMaster**.

The most major part of the **LappMaster** application is the optimization of lapping by the method of experiment arrays.

Figure 6. **LappMaster** window

5. TagMaster module

The access windows to the **LappMaster** application and the **TagMaster** module are shown in the figure 7.

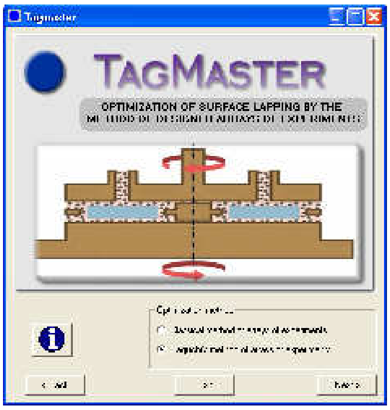

Figure 7. **TagMaster** window

The window allows the selection of the desired method of optimization and also provides the option of displaying information related to the utilization of the module. The two optimization methods provided by the applications are based on different solving algorithms; further on the variant of Taguchi's arrays of experiments is presented.

The superiority of Taguchi's method in relation to the classic one consists in using the performance indicator known as the ***signal/noise ratio*** (S/N – signal/noise). This ratio considers simultaneously the targeted value (the signal) and its undesired variability (the noise). The use of the signal/noise ratio as a performance indicator of a production process allows identifying a combination of levels of the factor to be controlled, such as to yield a process insensitive to noise factors.

In a Taguchi array of experiments the signal/noise ratio is computed for each test required in the array, and it establishes the dispersion of the measured values on each side of the mean obtained for the respective combination of levels of the tested factors. As each such combination is subjected to a wide range of noise factors, the signal/noise ratio represents an indicator of "noise strength", that is an indicator of robustness. The signal/noise ratio is derived from the "quality loss" function, and can be regarded as a bridge allowing the correlation between the technical and the economic approach to quality.

Regardless of the type of criterion used to define quality in a given case (target criterion, criterion to be minimized or maximized), the utilization rule of the signal/noise criterion is the same: *performance will be the higher, the greater the algebraic value of the S/N ratio is*. In other words, a high algebraic value of the S/N criterion indicates a small dispersion of the measurements [5].

The first step of the Taguchi optimization method requires the user to select the analyzed factors and the number of levels considered for each. Upon selection of a minimum of three factors and of the number of their levels, the application computes the number of degrees of freedom and displays the code and formula of the array (matrix) of experiments which is to be used for optimization.

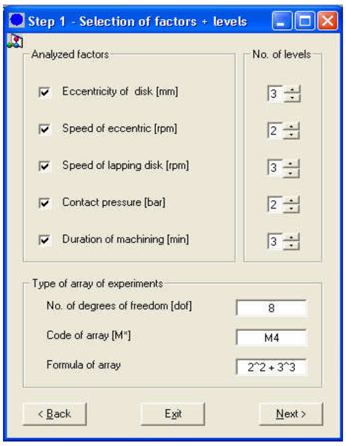

Figure 8. Step 1 – Selection of factors

The larger the number of tested input parameters, the greater the chance of correctly identifying the essential factors for the analyzed machining process. On the other hand, a large number of considered factors delays the decision process of optimum factor values, due to the increased number of tests to be carried out.

Steps two and three of the application display the window corresponding to the structure of the array and the one for entering the values selected for the levels of the considered factors, respectively (figures 9 and 10).

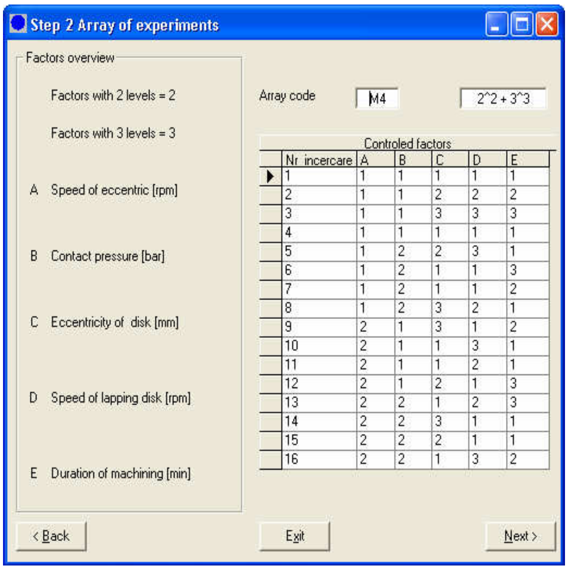

Figure 9. Step 2 – Array of experiments

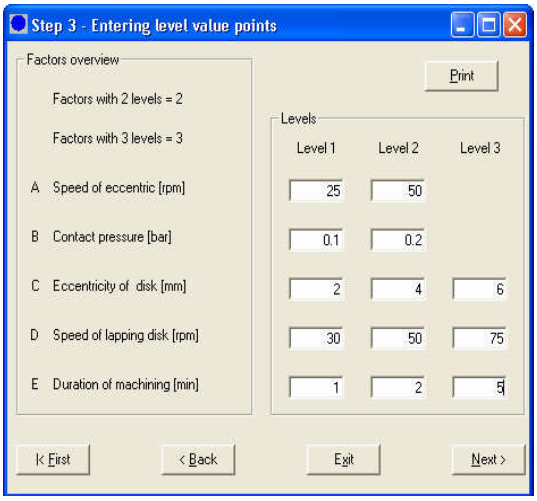

Figure 10. Step 3 – Level values

The fourth step of the module allows the user to select the optimization criteria adequate for the analysis, from the three available types:

- criterion to be minimized (Smaller is Better);
- criterion to be maximized (Bigger is Better);
- target criterion (Nominal is the Best). Upon selection of this criterion the target value needs to be entered as a condition for continuing the application to the next step.

In the case of the user choosing the target criterion, first one of the two process parameters made available by the application needs to be selected as such. Then its nominal value and the admitted deviations have to be entered.

Step 5 of the application (figure 12) requires entering the test results, followed by their processing. The difference to the classic method of arrays of experiments consists in the fact, that the "Response statistics" table includes an additional column for the signal/noise (S/N) ratio. The ratios are computed by different formulae, according to the type of used optimization criterion.

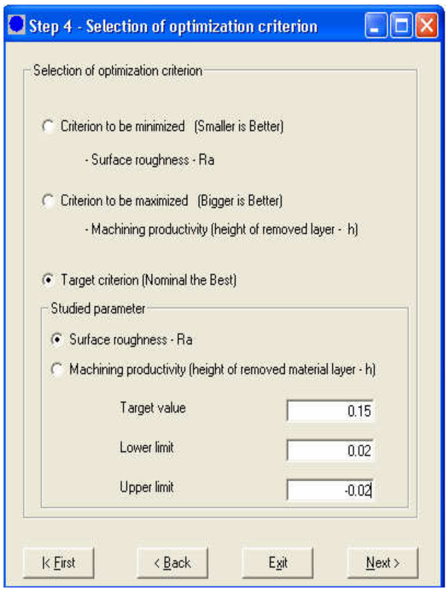

Figure 11. Step 4 – Optimization criterion

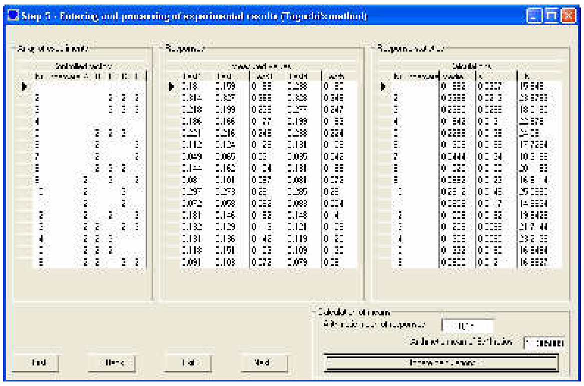

Figure 12. Step 5 – Experimental results and Response statistics

The following steps of the application involve computing of the mean S/N responses for all levels of the analyzed factors, as well as of the mean S/N effects for each factor.

Comparing the mean effects of the factors on the analyzed quality characteristic is achieved by graphic representation of the obtained results (figure 13). The optimum levels for each analyzed factor can be established easily, knowing that the recorded quality loss will be the smaller, the greater the algebraic value of the signal/noise ratio is, that is the process performance grows with the algebraic value of the S/N ratio. Hence those levels of the considered factors will be selected, which have the highest algebraic value of the signal/noise ratio. The last step (Step no. 9, figure 14) of the Taguchi analysis displays the optimum levels of factors.

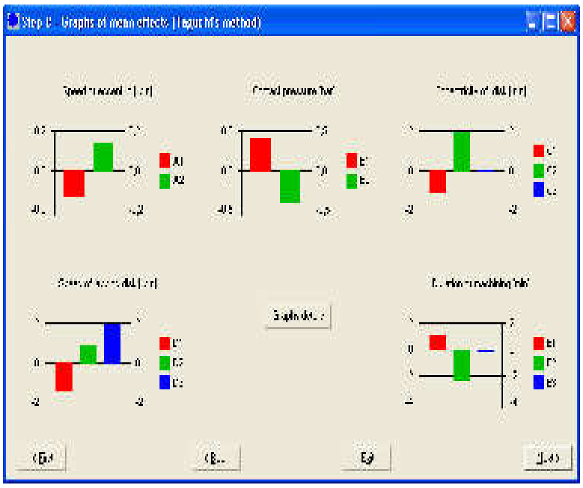

Figure 13. Step 8 – Graphs of mean effects

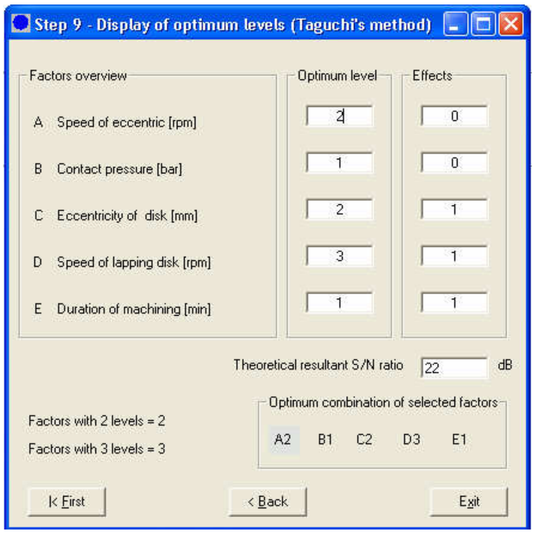

Figure 14. Establishing the optimum levels

The optimization of the production process was thus achieved by maximization of the resulting signal/noise ratio, which is given by the influence of the selected optimum levels of all considered factors. The resulting S/N ratio is computed starting from the mean value of the signal/noise ratio, to which the values of maximum computed mean effects are added.

Taguchi's method of arrays of experiments has as its final point the last test, which is the validation test. This is meant to ensure the achievement of the desired result, that is it physically verifies the hypothesis of additivity of the effects of all factors.

6. Conclusion

The paper analyses, in view of optimization of machining, the influence of various parameters on lapping as a plane surfaces finishing process. The final aim of research, as highlighted in the paper, was to minimize the variability of the studied quality characteristic of the end product, by reducing the sensitivity of the machining process to disturbances (noises) from the working environment. This was achieved by the development of a computer-based intelligent decision support system, called LappMaster.

Optimization of surface machining by lapping was achieved by robust parametric process design, the strategy being to identify those combinations of system input parameter values that reduces the effects of parasite causes (noises), without however addressing them directly.

It could be noticed that by the experimental determination of the optimum values to be assigned to the system input factors, the responses obtained as output yielded the desired functional performance, the entire production system being rendered robust, that is insensitive to noise factors.

7. Acknowledgment

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