AN EXPERT SYSTEM FOR METAL POWDER SELECTION USING VP-EXPERT

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ABSTRACT

A part of a complete expert system for powder technology is presented. This part of the system deals with the powder selection according to predetermined recommended or required material properties, and specific powder characteristics. Then, determining the most common powder production (i.e. processing) method, which satisfies the specified powder requirements for a specific application. For this purpose a detailed functional prototype expert system is developed using a rule-based knowledge representation model. The expert system is designed to acquire knowledge from the user then give recommendations. The inference engine, VP – Expert, is used as the development tool. The forward and backward chain techniques are utilized, thus the reverse process is also be possible. Therefore, the system will determine or assign some primary powder characteristics and production method to satisfy or achieve the required product and vice versa. The developed expert system is flexible, easy to be implemented, modified, and extended. The system displayed excellent performance and typical illustrative examples are shown.

KEYWORD: EXPERT SYSTEM, METAL POWDER SELECTION, VP-EXPERT SYSTEM

1. INTRODUCTION

In the powder technology field, the industries’ main objective is to produce final products with specific characteristics in accordance with predetermined properties. This, however, depends on controlling a huge number of interdependent parameters at the various stages of the process. Therefore, a complete expert system for powder technology is essential.

In the powder technology there are three main areas of work, which can be clearly identified. These are: (i) The loose powder area (i.e. the production, characterization and classification of powders); (ii) The compaction and consolidation area (i.e. the compaction equipment and the compactability of powders) and; (iii) The final product area (i.e. the final product characteristics, quality, testing, and post compaction processes). These three areas are interacting and heavily interdependent on each other. Thus the number of variables involved and the amount of information as well as the databases of the material properties and powder production processes are huge [1-5]. Therefore, the powder technology field is one of the most suitable fields for expert...
systems implementation. Particularly, that the area contains a huge amount of variables, information and data, which are mostly empirical. Analytical analysis is rare and extremely difficult to obtain due to the complex nature of this field [6-8].

In fact, the production of a successful product in powder technology is an ‘art’ seldom based on scientific relations and requires intensive experimental work, knowledge and expertise. In practice, each company relies on their own secret information and experience in developing any new product. Hence, the use of computers and portable microcomputers is an advantage, particularly with the increasing capacity and speed of data processing. But due to the complex nature of this problem, a complete integrated approach is huge, and extremely difficult. Therefore, as suggested by the authors in recent works [9,10], the building of the expert system will be divided into stages, which will be tackled separately. Later attempts could be made to integrate these stages and form a complete CIM for powder technology (CIMPT), where most of the powder technology activities are to be integrated. Thus, the envisaged powder technology expert system consists of various parts [9,10]. It utilizes the computers to automate the activities of powder selection, and controlling the powder manufacturing process parameters according to specific required powder characteristics. Finally designing the manufacturing processes or the final powder products according to their specifications.

With the increasing pressure to produce cheaper and more reliable components and with the greater number of new engineering materials and manufacturing processes that are now available, there is growing need for an integrated approach to economic analysis, design and materials and process selection [10-12]. The industry today is strongly oriented towards computer integrated manufacturing (CIM) techniques. Now, computer aided design, computer aided manufacture, computer aided economic analysis and computerized materials properties data banks are proven to be very essential tools for profitability and competitiveness of the modern industry [13-19].

Though the increasing use of computers in the various stages of product development has made the integrated approach easier to attain; yet in the field of powder technology this approach is still lacking and not easy to be implemented due to the large number of factors that have to be taken into consideration. However, very few scattered attempts are made in this regard by various investigators [13-16,20]. Some of these attempts tend to concentrate on selecting a powder material to satisfy specific process requirements. Amongst these, the work published by Kipphut and German [13] on powder selection for shape relation in powder injection molding and later by Griffio et al. [14] on powder selection and sintering pathways for zero dimensional changes, and most recently by Radwan and Es-Saheb [9,10,18] on some aspects of powder databases and expert systems implementations. To the authors knowledge, a design of a complete Powder Technology Expert System (PTES) is not yet available. Also, to date, the implementation of an effective Computer Aided Engineering (CAE) system to control and manage all activities of Powder Technology (PT) is still not available.
In the last few decades, the field of relational database technology has received wide attention by numerous workers and witnessed intensive research activities. Amongst the prominent researches in this area, since the 60's, that due to Codd [21] on relational models and Date [22], Darwen [23] and later Date and Darwen [24], Hall et al [25] and Mcleod [26] on the database systems. Mittra [27] and most recently Radwan and Es-Saheb [9,10,18], defined an intelligent database to be an application that combines a relational database consisting of relations, a knowledge base consisting of rules, and an inference mechanism that is activated by queries from end users and draws conclusions by using data from the relations to execute rules in the knowledge base. In addition, Smith and Midha [34 &35 ] have described the elements of a prototype knowledge based system (KBS), which was developed to provide advice relating to the manufacture of components through the use of powder metallurgy technology. In other word, they have developed a new modelling technique which employed Monte Carlo type simulations for prediction of powder packing behaviour. They claim that their system will enable production of comprehensive KBS modules, able to advice on optimum and concurrent design and manufacture of powder metallurgy components. Finally, Cherian et al. [36] have developed an artificial neural network (NN) methodology for selection of powder and process parameters for Powder Metallurgy (PM) part manufacture. Employment of a NN approach allows specification of multiple input criterion, and generation of multiple output recommendations. The inputs comprise the required mechanical properties for the PM material. The system employed these data within the NN in order to recommend suitable metal powder compositions and process settings. Their results showed that this approach, for predicting the materials and process settings needed for attainment of required process outcomes.

The work presented in this research, however, is concentrated on the first area mentioned above, with particular emphasis on the loose powder materials and the powder production process selections for certain application. The focus will be, mainly, on the metallic materials available in the powder form, with particular emphasis on those properties related to powder metallurgy (P/M) techniques. A knowledge based metallic powder selection system is to be developed and ready to be used by the industry.

Therefore, first the practical definition for the expert system, as a system simulating the expert methods and knowledge in dealing with or manipulating special tasks is presented. Then, the application of such system in powder technology is attempted. Thus, the work constitutes another part of an effort towards building a complete expert system for powder technology. A functional prototype expert system was developed using a rule-based knowledge representation model. This system which is structured on intelligent technology and engineering knowledge, is believed to be the backbone of the suggested Computer Integrated Manufacture for Powder Technology (CIMPT). Particularly, with the development of greater number of new engineering materials and manufacturing processes that are now available, and growing lag of expertise in this field.

The details of the suggested system and a complete description of the modules, structure, and techniques utilized are given in the next sections. Also, typical illustrative examples of the system are presented.
2. POWDER SELECTION

For correct selection of a powder production method, one has to keep in mind the final properties of the part (i.e., product) and the desired characteristics of the powder. This requires wide and deep knowledge in the powder production methods, characteristics, and applications. These are well documented and available in literature [1,2,7,11,28]. However, in the following sections the typical powder characteristics and the main powder production methods are briefly discussed and presented. Also, some of the most common powder materials used are given, particularly the metallic powder materials. Finally, the typical applications of these powders are also given. Therefore, the data used in this work and displayed in Tables: I and II below have been collected from many references [1,2,7,11,28]. This data can be expanded by adding more information as discussed in the following sections, (see Tables: I and II below).

2.1. Powders Characteristics

Generally, powders characteristics can be grouped into two main categories [1,2,4,7,20]. These are:

(I) Primary characteristics, which include the powder particles size (i.e., meshes) and shape, and

(II) Secondary characteristics, which covers powders material properties, performance and processability. These characteristics include the powder density, friction, flow, compactability, purity, softness, etc. Besides the reflected final product characteristics and process properties, such like the green strength, growth, hardness, mechanical properties, etc.

2.2. Powders Production Methods

Powders are known to be produced by various techniques and methods. These processes and procedures are well described and documented in the literature [1,2,7,28]. However, Table: I, displays the most common metallic powders commercial production methods (e.g., atomization, grinding, gaseous reduction of oxides, electrolytic, gaseous reduction of solutions, carbonyl decomposition, reduction with carbon), as well as the distinguishing main primary and secondary characteristics of the powders (e.g., size, shape, purity, density, compressibility, green strength, etc).
Table I: Some distinguishing characteristics of metal powders made by various commercial methods [1,2,7,28].

<table>
<thead>
<tr>
<th>Method of production</th>
<th>Typical purity (1)</th>
<th>Particle characteristics</th>
<th>Compressibility (softness)</th>
<th>Apparent density</th>
<th>Green strength</th>
<th>Growth-with-copper - of iron (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomization</td>
<td>High 99.5+</td>
<td>Irregular to smooth, rounded dense particles</td>
<td>Coarse shot to 325 mesh</td>
<td>Low to high</td>
<td>Generally high</td>
<td>Generally low</td>
</tr>
<tr>
<td>Gaseous reduction of oxides</td>
<td>Medium 98.5 to 99. +</td>
<td>Irregular, spongy</td>
<td>Usually 100 mesh and finer</td>
<td>Medium</td>
<td>Low to medium</td>
<td>High to medium</td>
</tr>
<tr>
<td>Gaseous reduction of solutions</td>
<td>High 99.2 to 99.8</td>
<td>Irregular, spongy</td>
<td>Usually 100 mesh and finer</td>
<td>Medium</td>
<td>Low to medium</td>
<td>High</td>
</tr>
<tr>
<td>Reduction with carbon</td>
<td>Medium 98.5 to 99. +</td>
<td>Irregular, spongy</td>
<td>Most meshes from 8 down</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium to high</td>
</tr>
<tr>
<td>Electrolytic</td>
<td>High + 99.5 +</td>
<td>Irregular, flaky to dense</td>
<td>All mesh sizes</td>
<td>High</td>
<td>Medium to high</td>
<td>Medium</td>
</tr>
<tr>
<td>Carbonyl decomposition</td>
<td>High 99.5 +</td>
<td>Spherical</td>
<td>Usually in low micron ranges</td>
<td>Medium</td>
<td>Medium to high</td>
<td>Low</td>
</tr>
<tr>
<td>Grinding</td>
<td>Medium 99. +</td>
<td>Flaky and dense</td>
<td>All mesh sizes</td>
<td>Medium</td>
<td>Medium to low</td>
<td>Low</td>
</tr>
</tbody>
</table>

(1) Purity varies with metal powder involved.
(2) Growth-with-copper of iron during sintering is increase in radial dimension of compacted iron-plus-copper powders.

2.3. Typical Powders and Applications
Again the most widely used commercial metallic powders in industry are: iron, copper, aluminum, nickel, brass, stainless steel, and magnesium [1,2,7,28]. These powders are used in many fields in industry to produce vast numbers of powder compacted parts and components. Examples include gears, rotors for pumps, bearings, cams, levers, contact parts, magnets, metallic filters, sintered carbides, etc. Table II, gives a summary of the most common metal powders produced by the various commercial production methods, and typical applications of the powders [1,2,7,28].
Table II: Metal powder production method and typical applications of the powders [1,2,7,28].

<table>
<thead>
<tr>
<th>Production Method</th>
<th>Typical powders</th>
<th>Typical applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomization</td>
<td>Stainless steel</td>
<td>Filters, mechanical parts, atomic reactor fuel elements</td>
</tr>
<tr>
<td>Brass</td>
<td>Mechanical parts, flaking stock, infiltration of iron</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>Mechanical parts (medium to high density), welding rods, cutting and scarfing, general</td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>Flaking stock for pigment, solid fuels, mechanical parts</td>
<td></td>
</tr>
<tr>
<td>Gaseous reduction of oxides</td>
<td>Fe</td>
<td>Mechanical parts, welding rods, friction materials, general</td>
</tr>
<tr>
<td>Cu</td>
<td>Bearings, motor brushes, contacts, iron-copper parts, friction materials, brazing, catalysts</td>
<td></td>
</tr>
<tr>
<td>Gaseous reduction of solutions (hydrometallurgy)</td>
<td>Ni</td>
<td>Iron-nickel sinterings, fuel cells, catalysts, Ni strip for coinage</td>
</tr>
<tr>
<td>Cu</td>
<td>Friction materials bearings, iron-copper parts, catalysts</td>
<td></td>
</tr>
<tr>
<td>Reduction with carbon</td>
<td>Fe</td>
<td>Mechanical parts, welding rods, cutting and scarfing, chemical, general</td>
</tr>
<tr>
<td>Electrolytic</td>
<td>Fe</td>
<td>Mechanical parts (high density), food enrichment, electronic core powders</td>
</tr>
<tr>
<td>Cu</td>
<td>Bearings, motor brushes, iron-copper parts, friction materials, contacts, flaking stock</td>
<td></td>
</tr>
<tr>
<td>Carbonyl decomposition</td>
<td>Fe</td>
<td>Electronic core powders, additives to other metal powders for sintering</td>
</tr>
<tr>
<td>Ni</td>
<td>Storage batteries, additive to other metal powders for sintering</td>
<td></td>
</tr>
<tr>
<td>Grinding</td>
<td>Mg</td>
<td>Welding rod coatings, pyrotechnics</td>
</tr>
<tr>
<td>Ni</td>
<td>Filters, welding rods, sintered nickel parts</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>Waterproofing concrete, iron from electrolytic cathodes (see Electrolytic above)</td>
<td></td>
</tr>
</tbody>
</table>

3. EXPERT SYSTEM STRUCTURE FOR POWDER SELECTION

3.1 General Background
Expert systems are rapidly becoming one of the major approaches to solving engineering and manufacturing problems. Expert systems have been implemented for several practical applications in many decision problems [29]. The growing interest in the technology of expert systems has surpassed anything previously witnessed in the scientific community.

Expert systems are helping major companies to diagnose processes in real time, schedule operations, troubleshoot equipment, maintain machinery, and design service and production facilities. With the implementation of expert systems in industrial environments, companies are finding that real-world problems are best solved by an integrated strategy involving the management of personnel, software, and hardware systems [29-31].

By definition, an expert system is a computer program that simulates the thought process of a human expert to solve complex decision problems in a specific domain.
A general definition which is representative of the intended functions of expert systems is presented below. An expert system is an interactive computer-based decision tool that uses both facts and heuristics to solve difficult decision problems based on knowledge acquired from an expert [29]. The growth of expert systems is expected to continue for several years. With the continuing growth, many new and exciting applications will emerge. An expert system operates as an interactive system that responds to questions, asks for clarification, makes recommendation and generally aids the decision making process. Expert systems provide “expert” advice and guidance in a wide variety of activities, from computer diagnosis to delicate medical surgery [29-31].

Thus, as stated above, one of the applications that is suitable to develop an expert system for is the selection of powders. The selection process should take into consideration the production method and the desired properties and characteristics of the powder and the final product.

Therefore, human experts are not available in all the process of powder selection stages, and even if they are, human forgets crucial details of a problem, are inconsistent in their day-to-day decisions, have a limited memory, and die. Therefore, an expert system (ES) can be utilized to help the non-expert powder selector in determining the best production method, the best powder to use, and the best associated application given the wanted properties and characteristics of the powder.

At this stage, it is important to state that, the use of available expert systems or the development of our own special expert system could be adopted. The later approach has been adopted successfully by Radwan and Es-saheb [9,10,18]in recent works. Though the system display good performance, it proved to be difficult, times consuming and requires tremendous efforts to be achieved. Thus, in this work, it is suggested to use a commercial expert system such like VP-Expert system for the obvious practical addvantages. However, both approaches serve the same goals and each of them has its advantages and short comes. For more detailed disscusion of these issues are available in literature [32].

Thus, a functional prototype expert system is developed using a rule-based knowledge representation model. The expert system developed is designed to acquire knowledge from the user then give recommendations. The inference engine, VP-Expert, is used as the development tool [33].

3.2 System Structure
The structure of the expert system is presented below. The steps of the general procedure for the expert system are as follows:

1- Obtain all information from the user.
2- Attempt to satisfy the user’s goals.
3- Try to select the best production method according to powder applications or powder characteristics.
4- Recommend the best production method, applications, metal powder and characteristics.

The structure of the expert system, as used in this work, is given in Fig. 1. The knowledge base, the inference engine, the user interface (consultation and data entry),
the external interfaces, and recommendation are the five components of the expert system. A brief description of these components is given in the next sections.

![Diagram of Expert System Structure]

**Fig. 1. The expert system structure.**

3.3. User Interface
The user interface is the link between the user and the inference engine. There are two distinct user interface modes. The first is the user interface consultation and the second is the user interface data entry.

3.4. Inference Engine
The inference engine VP-Expert, is used in this work. Using the knowledge-based rules and facts, the inference engine directs and controls the system to reach the required conclusion. After the user answers the questions in the user interface consultation, the inference engine will activate external interface and/or database if needed. The activation will come from the knowledge base, which will be explained next. Finally, the inference engine gives the recommended production method, material, and applications.
3.5. Knowledge Base

The knowledge base is the third main level of the expert system. The knowledge base contains rules and facts that guide the inference engine to achieve the goal wanted. Hence, this knowledge base will contain knowledge about the production methods, metal powders, and powder applications and characteristics (see Tables I and II). The decision tree used to build the knowledge-base structure is given in Fig. 2. Production rules form the knowledge representation model used in this work. In this knowledge base, there are 124 if-then structure rules excluding the rules for inference engine operations. Therefore, for purpose of illustration, a rule developed is shown below with brief description:

RULE 8

IF Option=PC AND
Purity=High_99.5 AND
Shape=Flaky_to_dense
THEN Meshes=All_mesh_sizes
Softness=High
Density=Medium_to_high
Green=Medium
Growth=High
PM=Electrolytic;

In this rule, the meshes available in powder will be all mesh sizes, the powder softness will be high, the powder density will be medium to high, the powder green strength will be medium, growth with copper of iron will be high, and electrolytic will be selected as a powder production method when the powder characteristics (PC) have been chosen, powder purity is high 99.5, and powder shape is flaky to dense, see Table: I.
There are two options:

1- Using powder characteristics to allocate the production method.
2- Using powder applications to allocate the production method.

Which option do you want?

Powder characteristics

AA

Powder applications

AB

Fig. 2. Decision tree for powder selection.
There are 32 applications

Which application do you want?

Fig. 2. Decision tree for powder selection (continued).
Fig. 2. Decision tree for powder selection (continued).

Application name
Motor brushes

Metal powder
Copper

Which production method do you want?
Electrolytic

Characteristics of the powder produced by Electrolytic:
- Purity → High 99.5+
- Shape → Irregular, flaky to dense
- Meshes available → All mesh sizes
- Softness → High
- Apparent density → Medium to high
- Green strength → Medium
- Growth with copper of iron → High

Characteristics of the powder produced by gaseous reduction of oxides:
- Purity → Medium 98.5 to 99.+
- Shape → Irregular, spongy
- Meshes available → Usually 100 mesh and finer
- Softness → Medium
- Apparent density → Low to Medium
- Green strength → High to medium
- Growth with copper of iron → Low
4. SAMPLE CONSULTATION
In this section, a sample consultation will be demonstrated to allocate production method using either powder characteristics or powder applications.

The expert system developed advises us on which production methods to use to produce different types of powder. Presented below the first screen display for the consultation of powder selection. The other screen displays are shown on the following pages, Figs.3-9. There are seven screen displays for the consultation. The second screen shows the options, it is clear that the user selected the second option. On the third screen, the user chose the thirteenth application. On the fourth screen, the application name, the suitable metal powder for this application, and the production method needed to produce the powder are shown. On the fifth screen, the powder characteristics are shown. The summary is shown on the sixth screen. After this point, the user is given two options in screen 7: either to rerun the consultation or to exit the system.

Fig. 3. Sample consultation screen 1.
Which option do you want to use to allocate the production method?

1- Powder characteristics.
2- Powder applications.

Enter your choice (1, or 2):

2

There are 32 applications:-

1- Mechanical parts (high density)  
2- Mechanical parts
3- Atomic reactor fuel elements  
4- Flaking stock
5- Infiltration of iron  
6- Welding rods
7- Cutting and scarfing  
8- General
9- Flaking stock for pigment  
10- Solid fuels
11- Friction materials  
12- Bearings
13- Motor brushes  
14- Contacts
15- Iron-copper parts  
16- Brazing
17- Catalysts  
18- Iron-nickel sinterings
19- Nickel strip for coinage  
20- Fuel cells
21- Welding rod coatings  
22- Chemical
23- Food enrichment  
24- Electronic core powders
25- Additive to other metal powders for sintering  
26- Storage batteries
27- Pyrotechnics  
28- Sintered nickel parts
29- Iron from electrolytic cathodes  
30- Waterproofing concrete
31- Mechanical parts (medium to high density)  
32- Filters

Which application do you want? (Type a number from 1 to 32)

13

Fig. 4. Sample consultation screen 2.

Fig. 5. Sample consultation screen 3.
APPLICATION
Motor brushes

METAL POWDER
Only one metal powder is suitable for this application. This metal powder is Copper.

PRODUCTION METHOD
The Copper powder needed to make this application can be produced by two production methods. These two production methods are:
1- Electrolytic.
2- Gaseous reduction of oxides.
Which production method do you want? (Type 1 or 2)
1

CHARACTERISTICS
Presented below the metal powder characteristics produced by Electrolytic:

1- Purity : High 99.5
2- Shape : Irregular or Flaky to dense
3- Meshes available : All mesh sizes
4- Softness : High
5- Apparent density : Medium to high
6- Green strength : Medium
7- Growth with copper of iron: High

Fig. 6. Sample consultation screen 4.

Fig. 7. Sample consultation screen 5.
SUMMARY

1-Application : Motor brushes
2-Metal powder : Copper
3-Production method : Electrolytic
4-Characteristics:-
   Purity : High 99.5
   Shape : Irregular or Flaky to dense
   Meshes available : All mesh sizes
   Softness : High
   Apparent density : Medium to high
   Green strength : Medium
   Growth with copper of iron : High

This is the end of the consultation

Press F2: Run Consultation Again
Press F8: To Exit System
Finally, it is important to state that, the system is very flexible, extendable and friendly to use. For example, the knowledge base developed can be used as a tool to train and enhance the powder designer trainee’s knowledge in the powder science school. In fact, this knowledge base is still in the process of learning and acquiring knowledge from experts; therefore, practical experience from the industry can be acquired and translated into rules and constraints to improve the present knowledge base. This practical experience will be translated into what-if-analysis to enhance the intelligence of the expert system. However, some economic consideration can be included in the system to achieve the 'optimal' most economic production method for a specific metal (powder) and application. This is one of the essential aspects of CIM. Therefore, an appropriate utility function for such a purpose can be developed to assess the various characteristics and economics of the numerus manufacturing routes which convert these materials into engineering components and products.

5. CONCLUSION

The practical definition for the expert system, as a system simulating the expert methods and knowledge in dealing with or manipulating special tasks is presented. An expert system for the best selection of powder and production method according to desired properties and characteristics for a certain application is successfully developed. The inference engine, VP-Expert is used as development tool for this system. Actually, the system constitutes another part of an effort towards building a complete expert system for powder technology. It helps the powder designers and producers to allocate the best production method of powder that meets the requirements of the users. The system is interactive in nature, flexible and friendly to use. The system and the knowledge base developed displayed excellent performance and could be modified, and extended. Some economic consideration can be incorporated in the system, through the use of a proper utility function, which is one of the essential aspects of CIM. The proposed system is believed to assess in increasing productivity in the field of powder technology and increases the profitability and competitiveness of the process in a modern ever increasing industries.

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