Research Journal of Applied Sciences, Engineering and Technology 7(10): 1961-1977, 2014
DOI:10.19026/ajfst.7.488
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: May 07, 2013 Accepted: June 04, 2013 Published: March 15, 2014

Research Article

An Expert System for Powder Selection Using EXSYS-CORVID

[1]M.H. Es-Saheb and [2]I.M. Al-Harkan
[1]Mechanical Engineering Department,
[2]Industrial Engineering Department, King Saud University,
P.O. Box 800, Riyadh 11421, Saudi Arabia

Abstract: In this study, a part of a complete Expert System (ES) for powder technology is presented. It deals with the powder selection according to predetermined recommended or required material properties and specific powder characteristics. This leads to the determination of 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, EXSYS-CORVID, is used as the development tool. The forward and backward chain technique is 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. 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.

Keywords: Expert system, EXSYS-CORVID, powder selection, powder technology

INTRODUCTION

One important industry witnessing an increasing importance and vast development in the production as well as the processing of tremendous products of ever increasing new material is powder technology. In this industry, the main objective is to produce sound compacted components of homogeneous uniform density 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.

Actually, in the powder technology there are three main areas of work, which can be clearly identified. These are:

- The loose powder area (i.e., the production, characterization and classification of powders)
- The compaction and consolidation area (i.e., the compaction equipments and the compactability of powders)
- 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 numbers of variables involved in these areas are huge. Therefore, the powder technology field is one of the most suitable fields for expert systems implementation. Unfortunately, mostly of the huge amount of variables, information and data available in this industry are empirical. Analytical analysis is rare and extremely difficult to obtain due to the complex nature of this field as reported by Hausner and Kumar (1982) and Es-Saheb (1992). 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, very demanding and extremely difficult. Therefore, 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.

Corresponding Author: M.H. Es-Saheb, Mechanical Engineering Department, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia

Radwan and Es-Saheb (1995, 1998) envisaged that the powder technology expert system consists of various parts. It utilizes the computers to automate the activities of powder selection and controlling the powder manufacturing process parameters according to specific required powder characteristics.

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 as stated by Sirilertworakul *et al*. (1993). 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.

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 recently made in this regard by Smith *et al*. (2002) and Pereza *et al*. (2006) as well as Fan *et al*. (2010). These attempts tend to concentrate on selecting a powder material to satisfy specific process requirements. To the authors' knowledge, a design of a complete Powder Technology Expert System (PTES) is not available yet. 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 and witnessed intensive research activities by numerous workers such like Codd (1990), Date and Darwen (1993), Date (1995) and Radwan and Es-Saheb (1995, 1998).

The work presented in this study 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 main focus was 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 developed and ready to be used by the industry. Also, an attempt is made to include the economic consideration, which is one of the essential aspects of CIM. Therefore, 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. The application of such system in powder technology is attempted. It constitutes, actually, 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.

POWDER SELECTION

For the 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. The powder production methods, characteristics and applications are well documented and available in literature, Goetzel (1949) and Farag (1989). However, in the following sections the typical powder characteristics and the main powder production methods are briefly discussed. 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 study have been collected from many references, Goetzel (1949), Farag (1989) and Dowson (1990), as will be seen clearly in the following sections, (Table 1 and 2).

Powders characteristics: Generally, powders characteristics can be grouped into two main categories. These are:

- Primary characteristics, which include the powder particles size (i.e., meshes) and shape
- Secondary characteristics, which covers powders material properties, performance and process-ability

These characteristics include the powder density, friction, flow, compact-ability, purity, softness, etc. Beside the reflected final product characteristics and process properties, such like the green strength, growth, hardness, mechanical properties, etc.

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 by Hausner and Kumar (1982), Goetzel (1949), Fayed and Otten (1984), Farag (1989) and Dowson (1990). However, Table 1, displays the most common metallic powders commercial production methods (e.g., atomization, grinding,

Table 1: Some distinguishing characteristics of metal powders made by various commercial methods, from Goetzel (1949), Farag (1989) and Dowson (1990)

		Particle characteristics					
Method of production	Typical purity(1)	Shape	Meshes available	Compressibility (softness)	Apparent density	Green strength	Growth-with-copper-of iron(2)
Atomization	High 99.5 +	Irregular to smooth, rounded dense particles	Coarse shot to 325 mesh	Low to high	Generally high	Generally low	High
Gaseous reduction of oxides	Medium 98.5 to 99.0 +	Irregular, spongy	Usually 100 mesh and finer	Medium	Low to medium	High to medium	Low
Gaseous reduction of solutions	High 99.2 to 99.8	Irregular, spongy	Usually 100 mesh and finer	Medium	Low to medium	High	Iron not produced by this method
Reduction with carbon	Medium 98.5 to 99.0 +	Irregular, spongy	Most meshes from 8 down	Medium	Medium	Medium to high	Medium
Electrolytic	High + 99.5 +	Irregular, flaky to dense	All mesh sizes	High	Medium to high	Medium	High
Carbonyl decomposition	High 99.5 +	Spherical	Usually in low micron ranges	Medium	Medium to high	Low	?
Grinding	Medium 99.0 +	Flaky and dense	All mesh sizes	Medium	Medium to low	Low	High

(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

Table 2: Metal powder production method and typical applications of the powders, from Goetzel (1949), Farag (1989) and Dowson (1990)

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

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.).

Typical powders and applications: Again the most widely used commercial metallic powders in industry are: iron, copper, aluminum, nickel, brass, stainless steel and magnesium, Goetzel (1949), Fayed and Otten (1984), Farag (1989) and Dowson (1990). 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 2, gives a summary of the most common metal powders produced by the various commercial production methods and typical applications of the powders (Goetzel, 1949; Farag, 1989; Dowson, 1990).

EXPERT SYSTEM STRUCTURE FOR POWDER SELECTION

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 as reported early by Singha and Sekhon (1999), Guessasma *et al*. (2003) and Es-Saheb and Radwan (2003) and later in a decade review by Liao (2005), Rao *et al*. (2005), Park *et al*. (2007), Qian *et al*. (2008), Chu and Hwang (2008) and Aguilar-Díaz *et al*. (2009) on the use of diluents-disintegrants for direct compression, as well as Papic *et al*. (2009) and Lyu Jr and Chen (2009) and recently by Ahmadi and Ebadi (2010), Dymova *et al*. (2010) and Ruiz-Mezcua *et al*. (2011) on aluminium applications.

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 as described by Liao (2005), Chu and Hwang (2008) and Aguilar-Díaz *et al*. (2009) on the use of diluents-disintegrants for direct compression and recently by Ruiz-Mezcua *et al*. (2011) on aluminium applications.

In general, ES methodologies can be classified into the following eleven categories: rule-based systems, knowledge-based systems, neural networks, fuzzy ESs, object-oriented methodology, case-based reasoning, system architecture, intelligent agent systems, database methodology, modeling and ontology together with their applications for different research and problem domains, Liao (2005).

Expert Systems (ES) are a branch of applied Artificial Intelligence (AI) and were developed by the AI community in the mid-1960s. The basic idea behind ES is simply that expertise, which is the vast body of task-specific knowledge, is transferred from a human to a computer. This knowledge is then stored in the computer and users call upon the computer for specific advice as needed. The computer can make inferences and arrive at a specific conclusion. Then like a human consultant, it gives advices and explains, if necessary, the logic behind the advice. ES provide powerful and flexible means for obtaining solutions to a variety of problems that often cannot be dealt with by other, more traditional and orthodox methods. Thus, their use is proliferating to many sectors of our social and technological life, where their applications. 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 as reported early by Jackson (1999), Singha and Sekhon (1999), Guessasma *et al*. (2003) and Es-Saheb and Radwan (2003) and later in a decade review by Liao (2005) Rao *et al*. (2005), Park *et al*. (2007), Qian *et al*. (2008), Chu and Hwang (2008) and Aguilar-Díaz *et al*. (2009) on the use of diluents-disintegrants for direct compression, as well as Papic *et al*. (2009) and Lyu Jr and Chen (2009) and recently by Ahmadi and Ebadi (2010), Dymova *et al*. (2010) and Ruiz-Mezcua *et al*. (2011) on aluminium applications. 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, Jackson (1999), Liao (2005) and Ruiz-Mezcua *et al*. (2011).

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 (1995, 1998). Though the system display good performance, it proved to be difficult, times consuming and requires tremendous efforts to be achieved. Thus, in this study, it is suggested to use a commercial expert system such like EXSYS CORVID system for the obvious practical advantages. However, both approaches serve the same goals and each of them has its advantages and short comes. For more detailed discussion of these issues are available in literature, see Jackson (1999), Liao (2005) and Ruiz-Mezcua *et al*. (2011).

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, Exsys CORVID (1989), is used as the development tool.

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

- Obtain all information from the user
- Attempt to satisfy the user's goals
- Try to select the best production method according to powder applications or powder characteristics

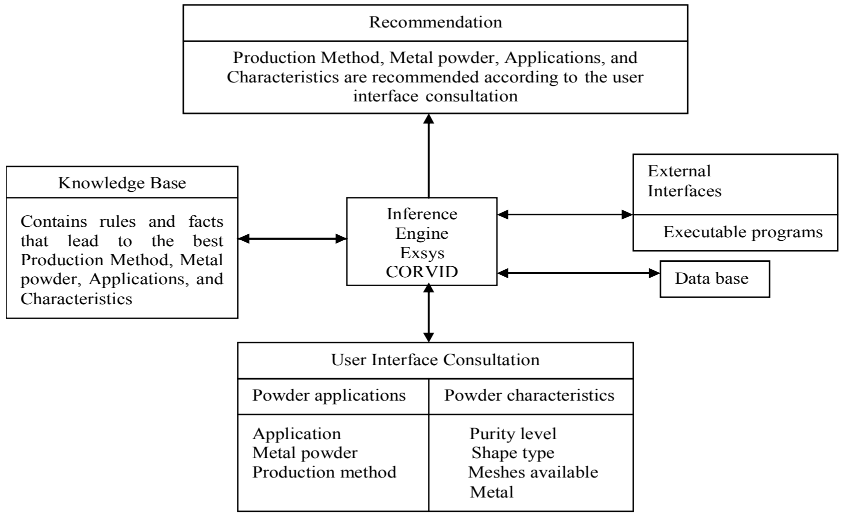

Fig. 1: The expert system structure

- Recommend the best production method, applications, metal powder and characteristics

The structure of the expert system, as used in this study, 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.

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.

Inference engine: The inference engine EXSYS-CORVID, is used in this study. 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.

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 (Table 1 and 2). The decision tree used to build the knowledge-base structure is given in Fig. 2b and 3b. Production rules form the knowledge representation model used in this study. In this knowledge base, there are many if-then structure rules excluding the rules for inference engine operations. Therefore, for purpose of illustration, two examples are shown below with brief description, First example will consider powder characteristics and at the end describe powder applications where as second example describes powder characteristics while considering powder application, Both examples are elaborated using decision tree, rule view and screen shots:

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 and what kind of powder characteristics need to use for different applications. In Example 1 from Fig. 2c to n different screens are shown in order to find different powder applications using different powder characteristics, finally Fig. 2n shows the consultation summary which includes the application of powder as well the options selected to reach at this powder application which could be useful for further powder characteristics selection. There are eleven screen displays for the consultation of Example 1. The very first screen shows the options, it is clear that the user selected the first option. On the second screen, the user chose the third option for purity. On the third screen, the third option has been selected for shape, On the next screen first option selected for meshes available and then second, fourth, third, first, third options are selected consicutively, finally at consultation summary screen powder application and powder characteristics are shown. After this point, the user have two options in consultation summary screen: either to rerun the consultation by pressing restart key or to exit the system.

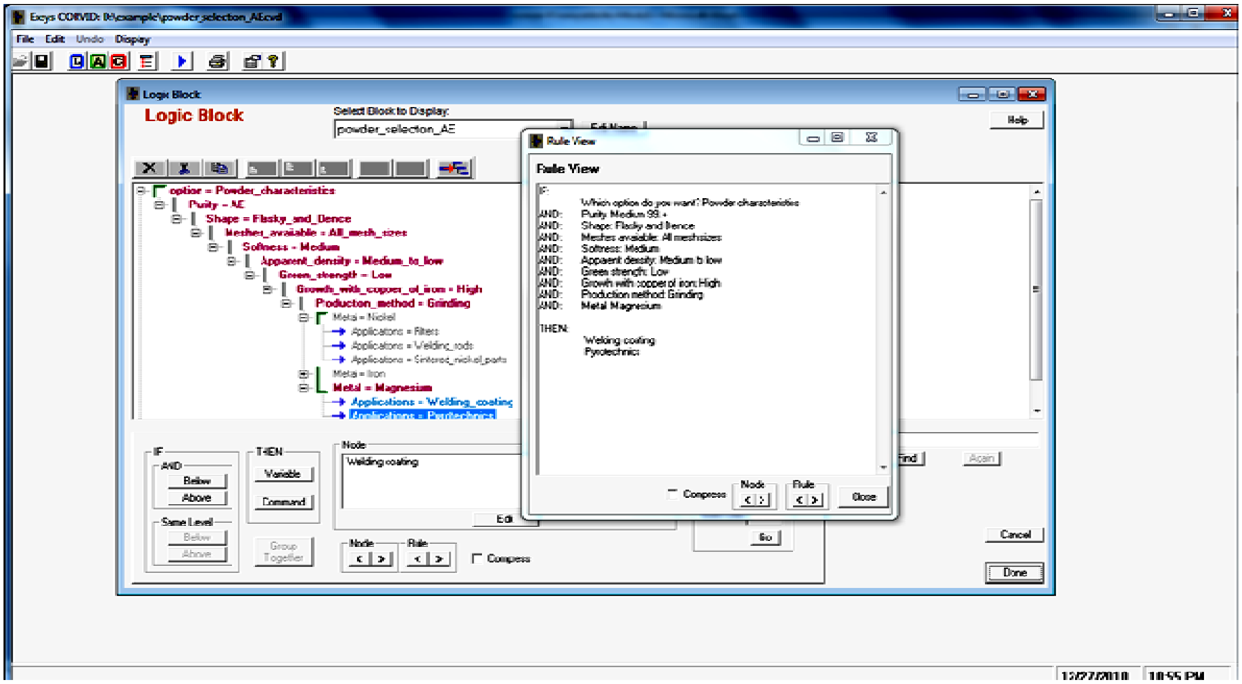

Fig. 2a: Consultation example number one, screen 1

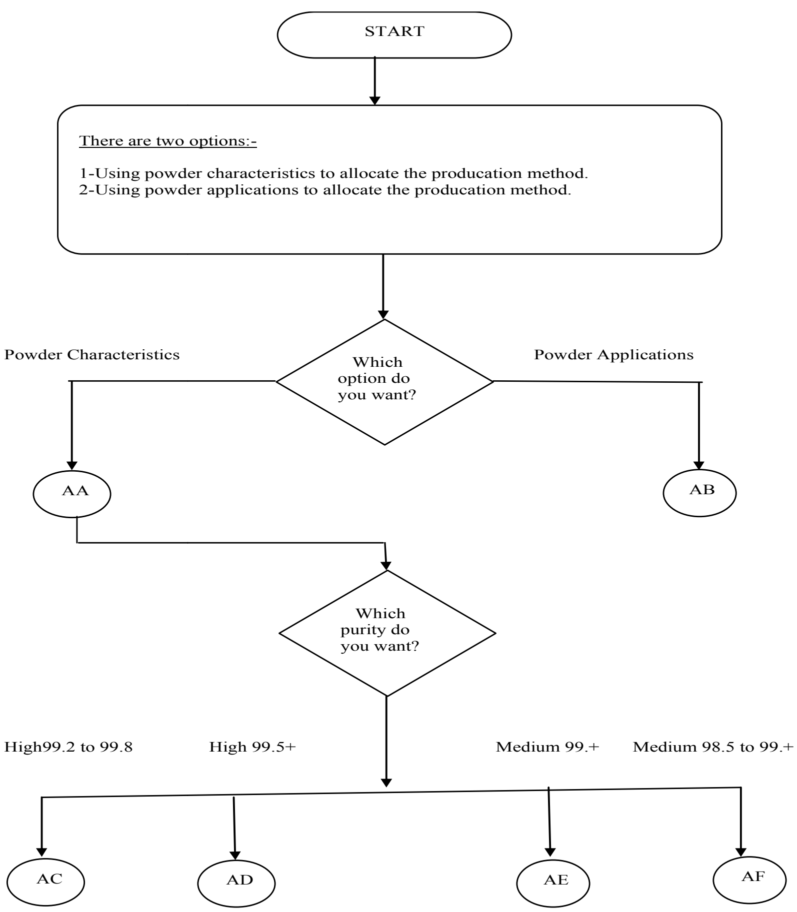

Fig. 2b: Decision tree for powder characteristics

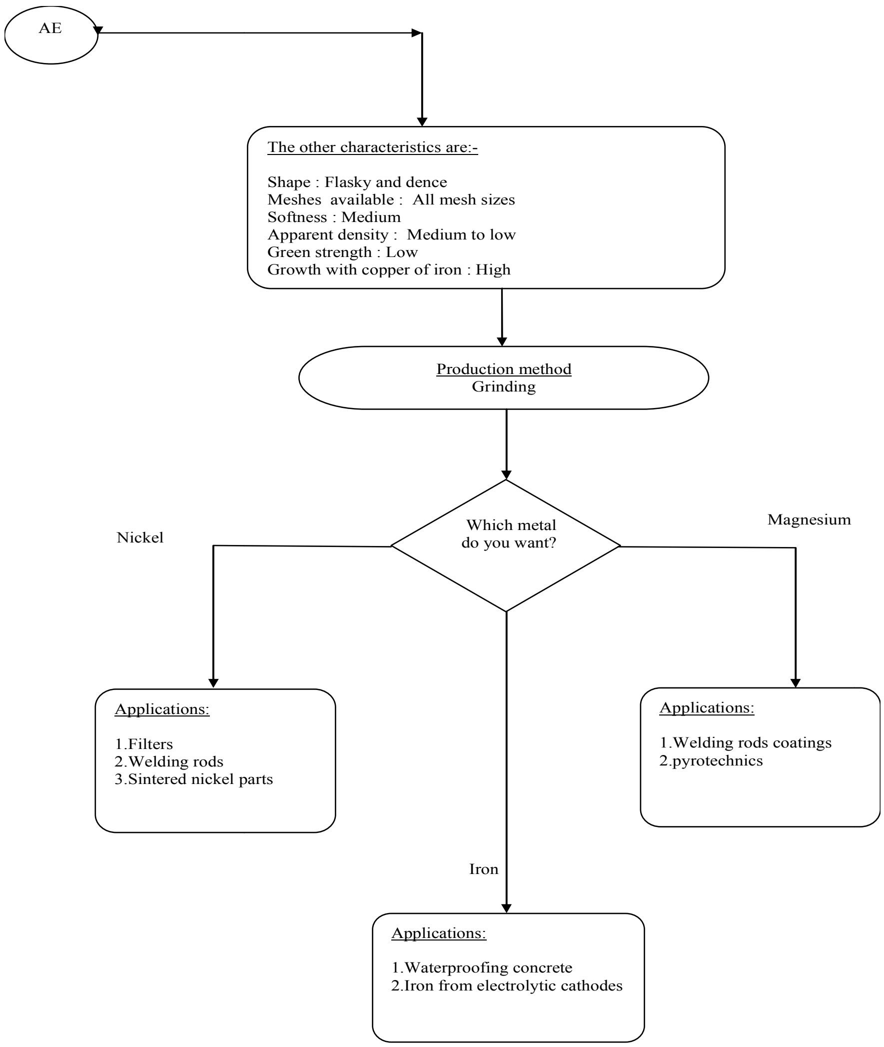

Fig. 2c: Decision tree for powder characteristics

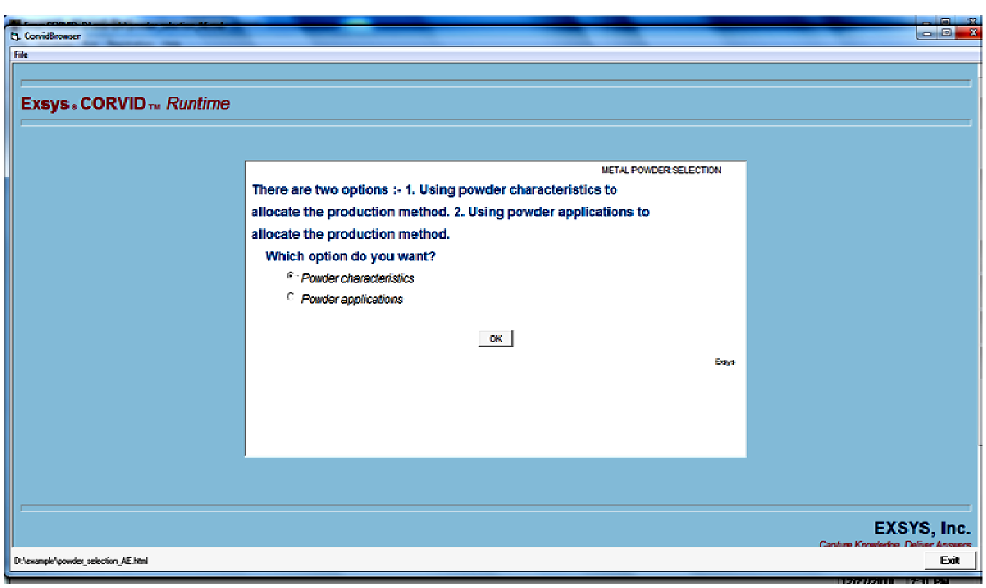

Fig. 2d: Consultation example number one, screen 2

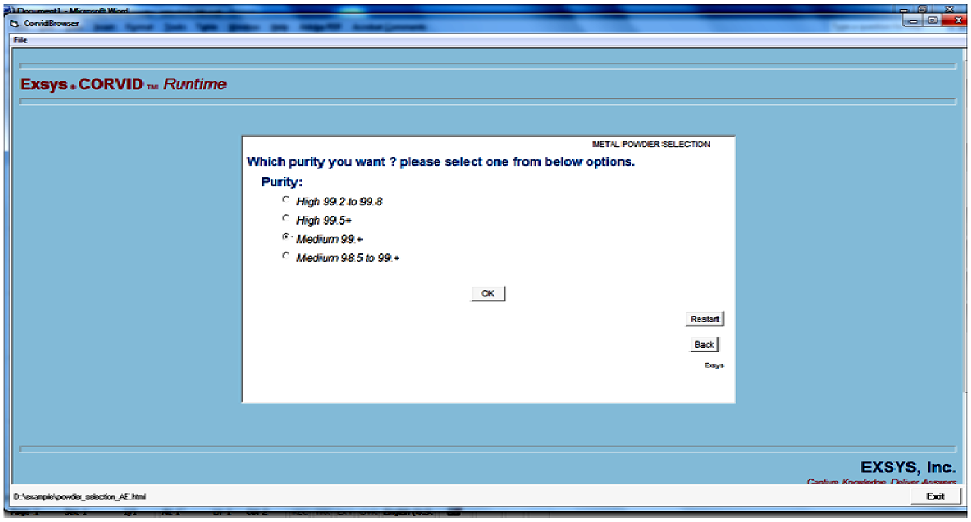

Fig. 2e: Consultation example number one, screen 3

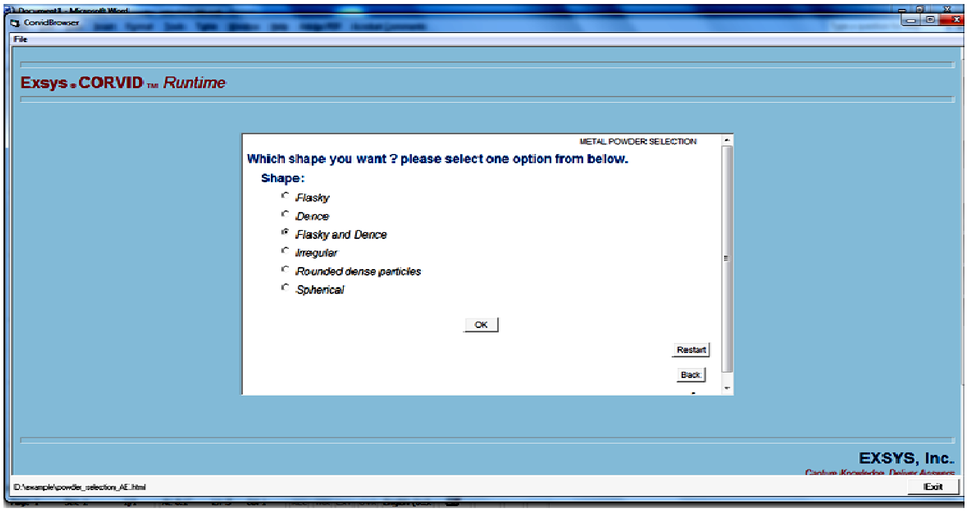

Fig. 2f: Consultation example number one, screen 4

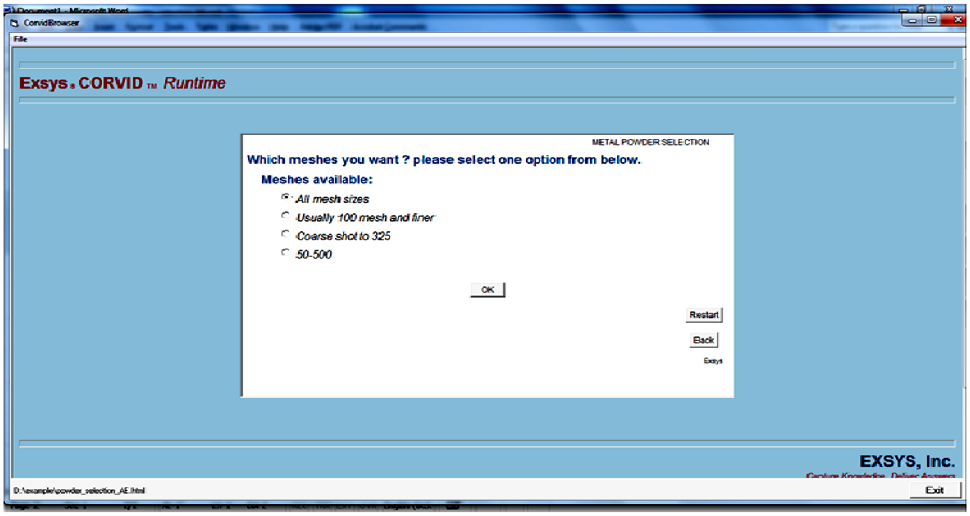

Fig. 2g: Consultation example number one, screen 5

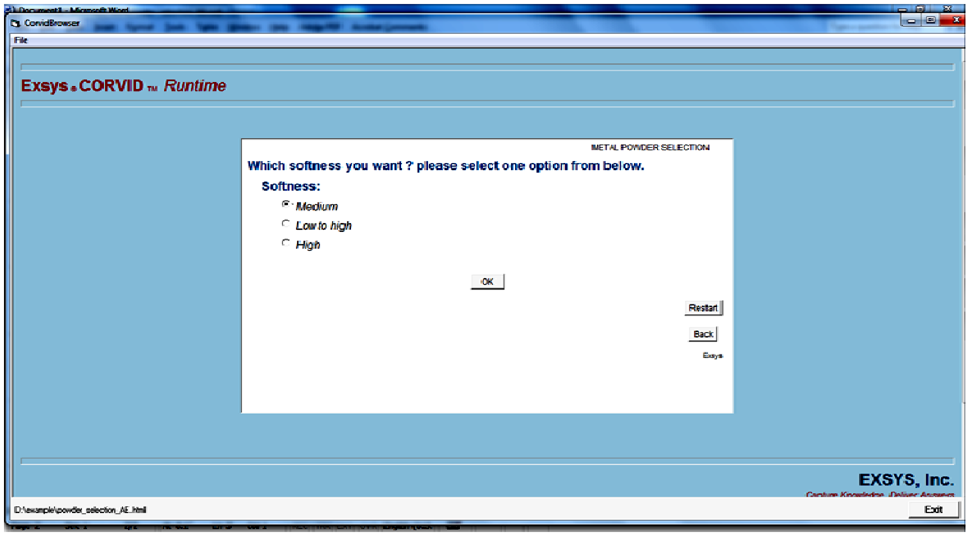

Fig. 2h: Consultation example number one, screen 6

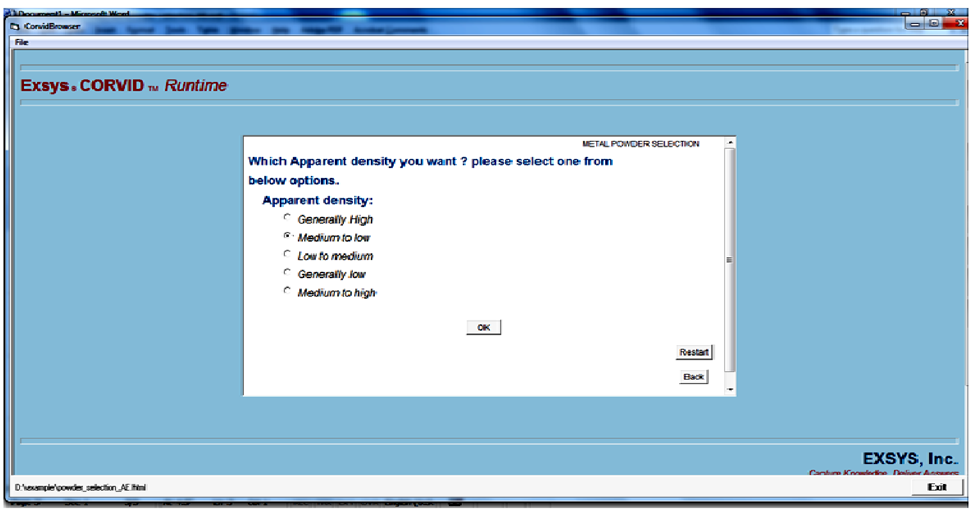

Fig. 2i: Consultation example number one, screen 7

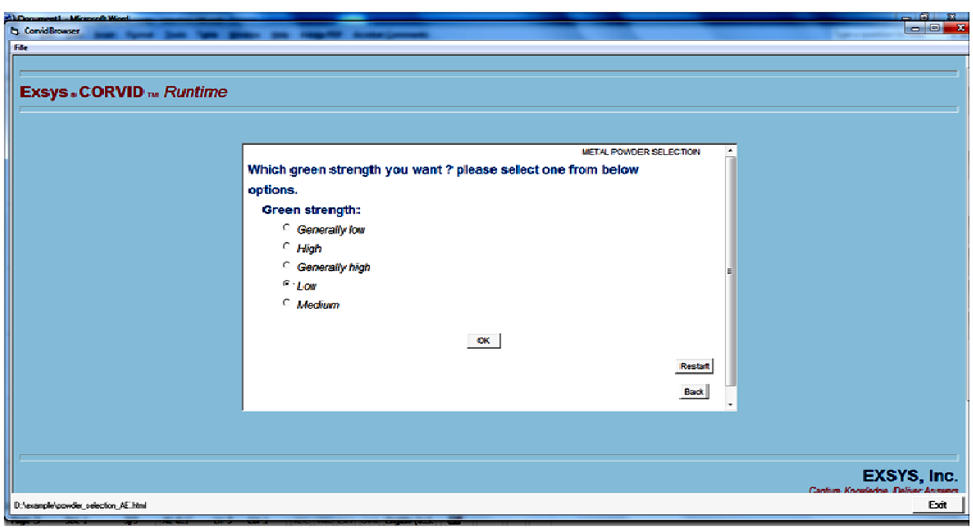

Fig. 2j: Consultation example number one, screen 8

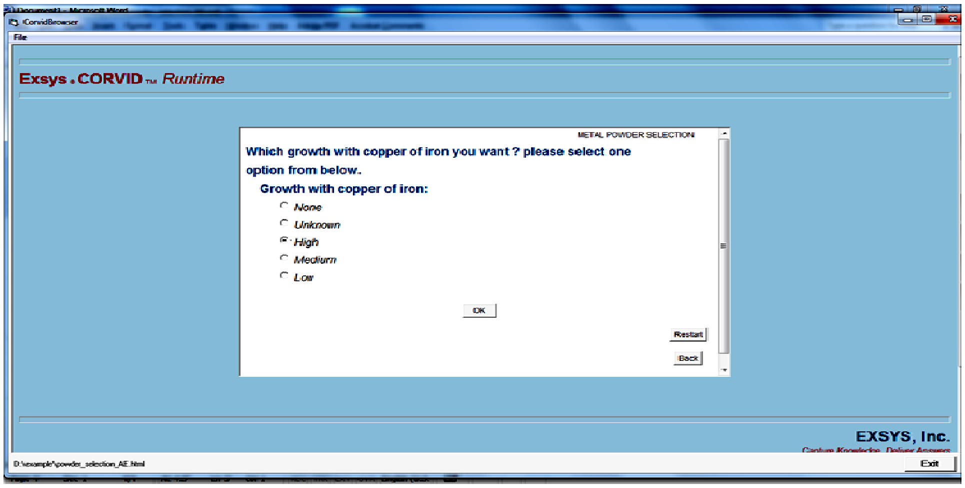

Fig. 2k: Consultation example number one, screen 9

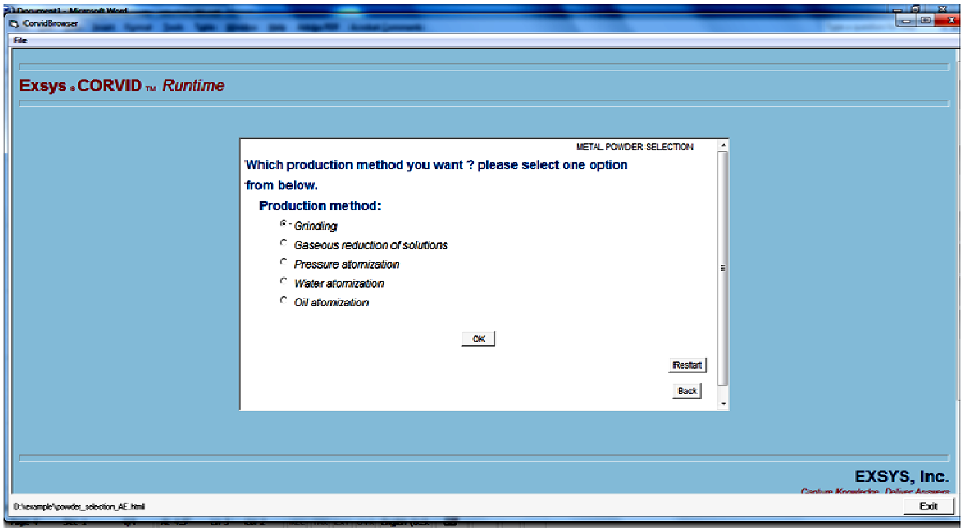

Fig. 2l: Consultation example number one, screen 10

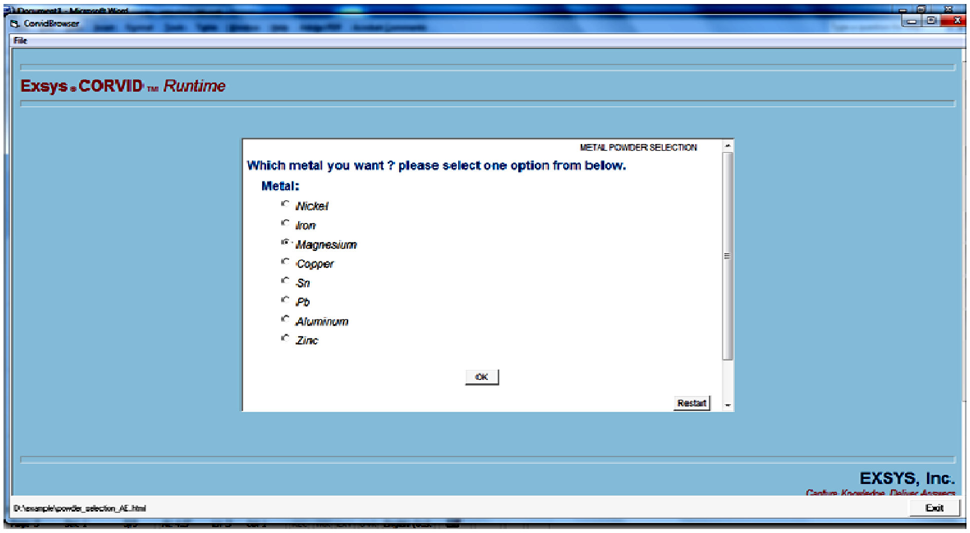

Fig. 2m: Consultation example number one, screen 11

Fig. 2n: Consultation example number one, screen 12

Where as in Example 2 we are starting from powder applications and try to reach at powder characteristics. The sample consultation are shown from Fig. 3c to h. There are five screen displays for the consultation. The first screen shows the options, it is clear that the user selected the second option. On the second screen, the user chose the thirteenth application. On the third screen, the suitable metal powder for this application and the production method needed to produce the powder are shown. On the last screen, the powder characteristics are shown along with the powder application as sonsultation summary. After this point, the user has two options in last screen: either to rerun the consultation by pressing restart button or to exit the system.

Example 1:
Rule view
IF:
Which option do you want? Powder characteristics
AND : Purity: Medium 99.+
AND : Shape: Flaky and Dense
AND : Meshes available: All mesh sizes
AND : Softness: Medium
AND : Apparent density: Medium to low
AND : Green strength: Low
AND : Growth with copper of iron: High
AND : Production method: Grinding
AND : Metal: Magnesium
THEN:
Welding coating
Pyrotechnics

As explained in above rule view and shown in below screen shot of rule view Fig. 2a. If the option to allocate the production method is powder characteristics and purity is Medium is 99.+, shape is flaky and dense, meshe size are all mesh sizes, softness is medium, apparent density is medium to low, green strength is low, growth with copper of iron is high, production method is grindng and metal is magnesium then the applications for these powder applications will be welding coating and pyrotechnincs as describe in Table 2.

Example 2:
IF:
which option do you want ? Powder applications
AND : Application: Motor brushes
AND : Metal powder: Copper
AND : Production method: Gaseous reduction of oxides
THEN:
Purity: Medium 98.5 to 99.+
Shape: Irregular, spongy
Meshes available: Usually 100 mesh size and finer
Softness: Medium
Apparent density: Low to medium
Green strength: High to medium
Growth with copper of iron: Low

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, Table 1 (Fig. 3a).

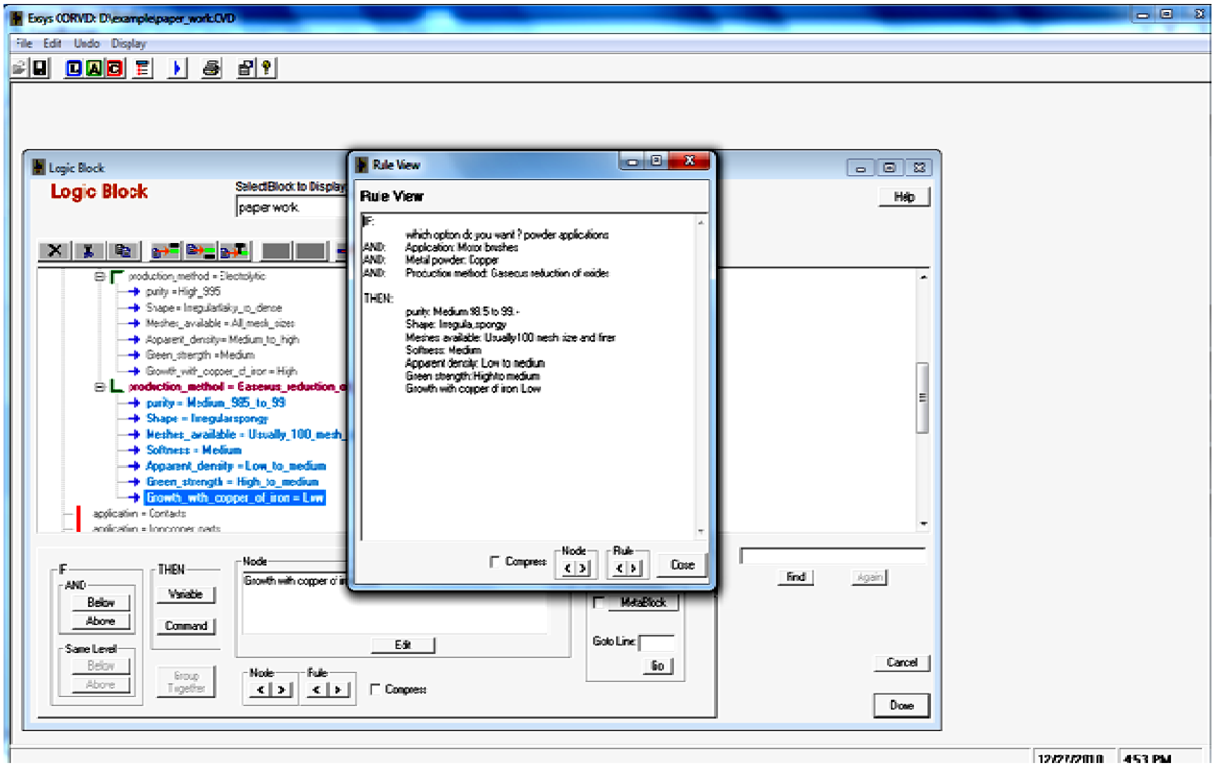

Fig. 3a: Consultation example number two, screen 1

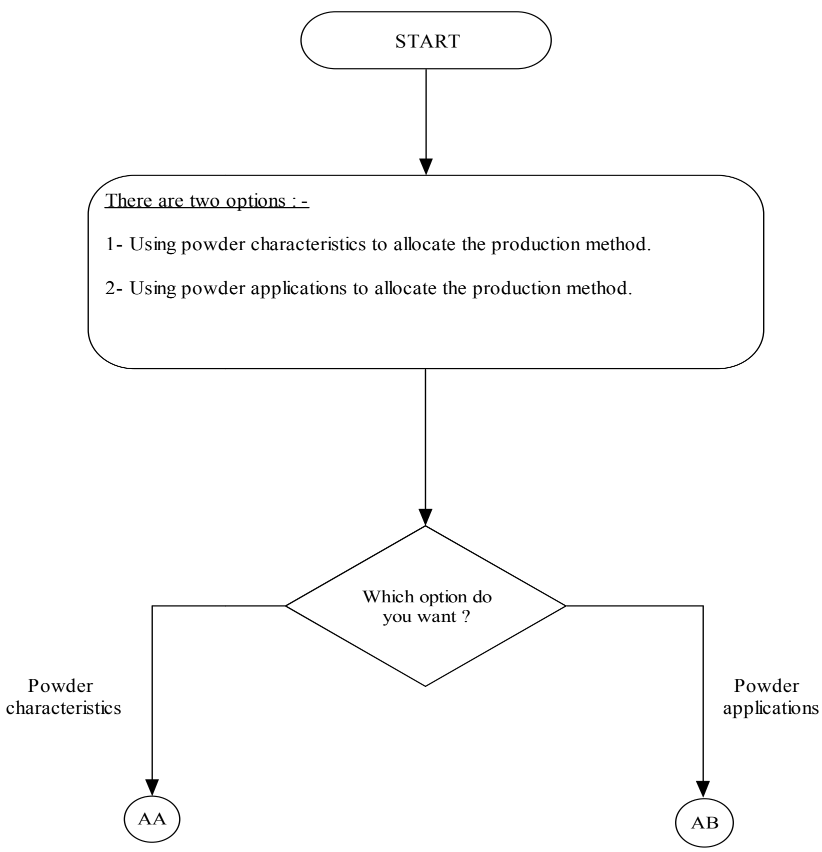

Fig. 3b: Decision tree for powder application

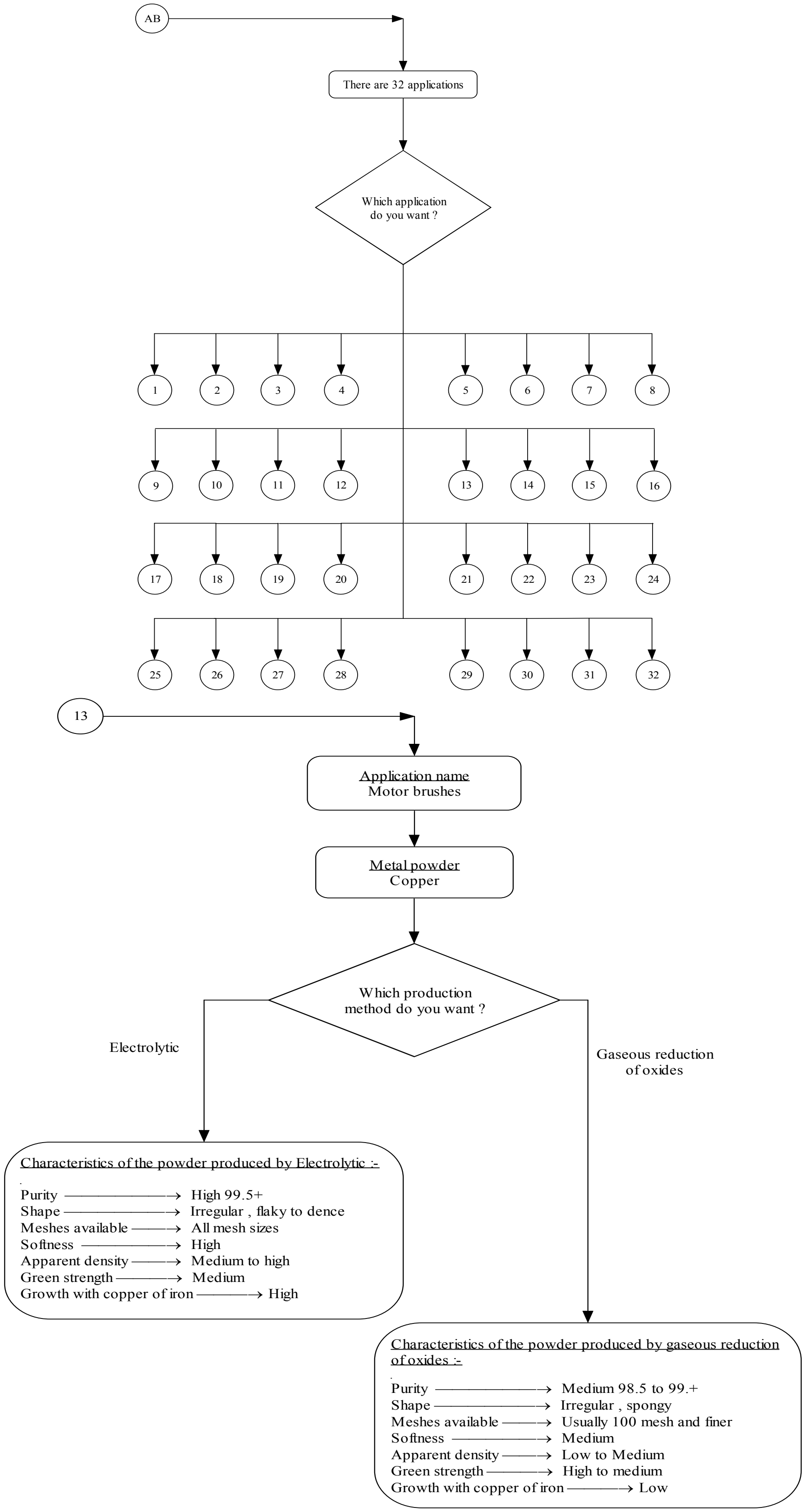

Fig. 3c: Decision tree for powder application (continued)

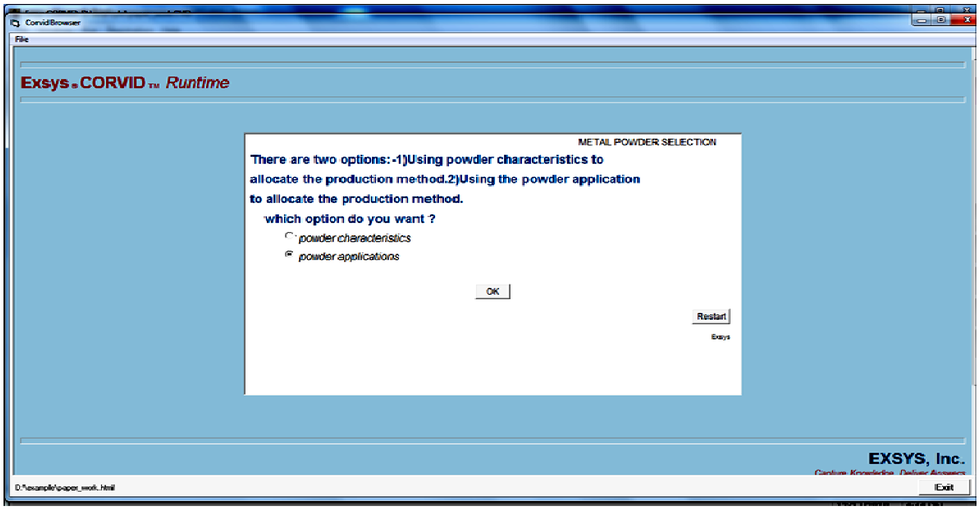

Fig. 3d: Consultation example number two, screen 2

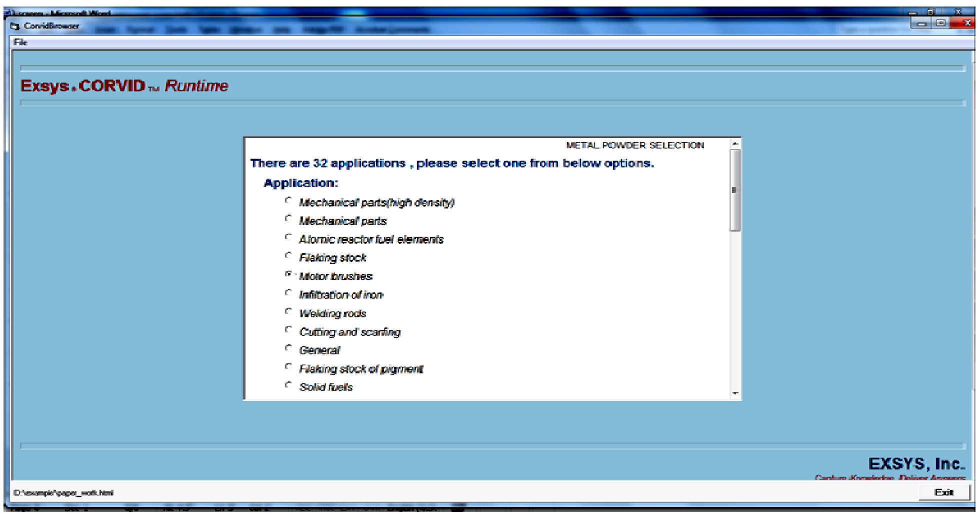

Fig. 3e: Consultation example number two, screen 3

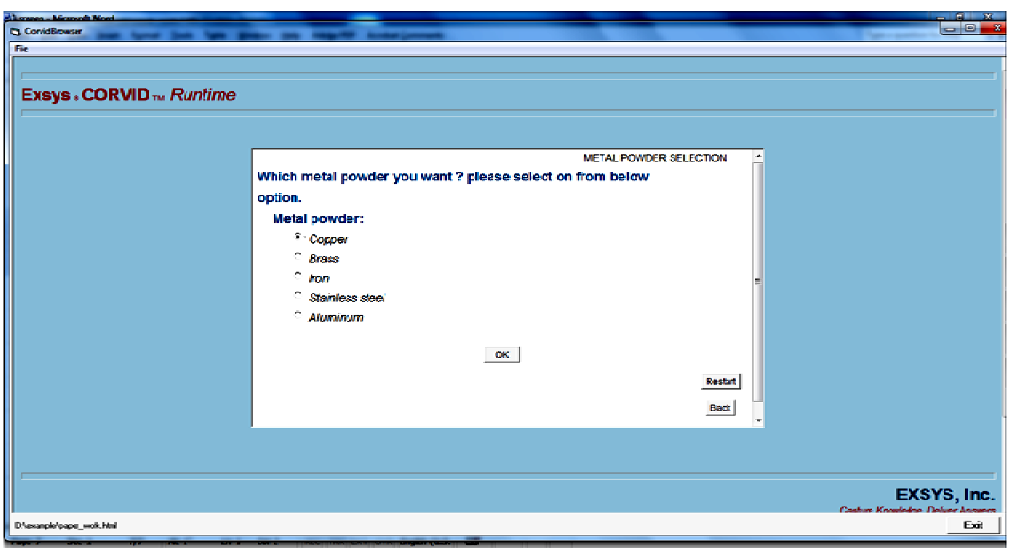

Fig. 3f: Consultation example number two, screen 4

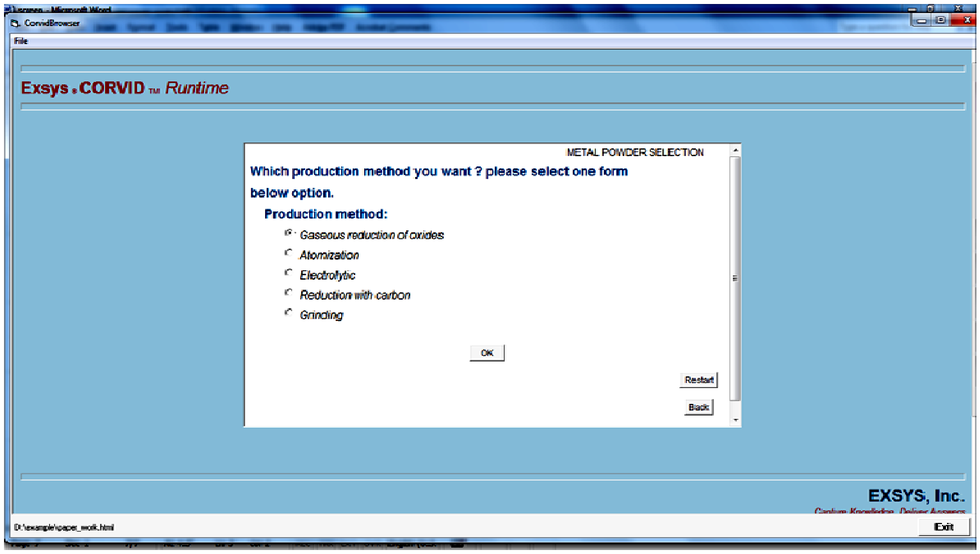

Fig. 3g: Consultation example number two, screen 5

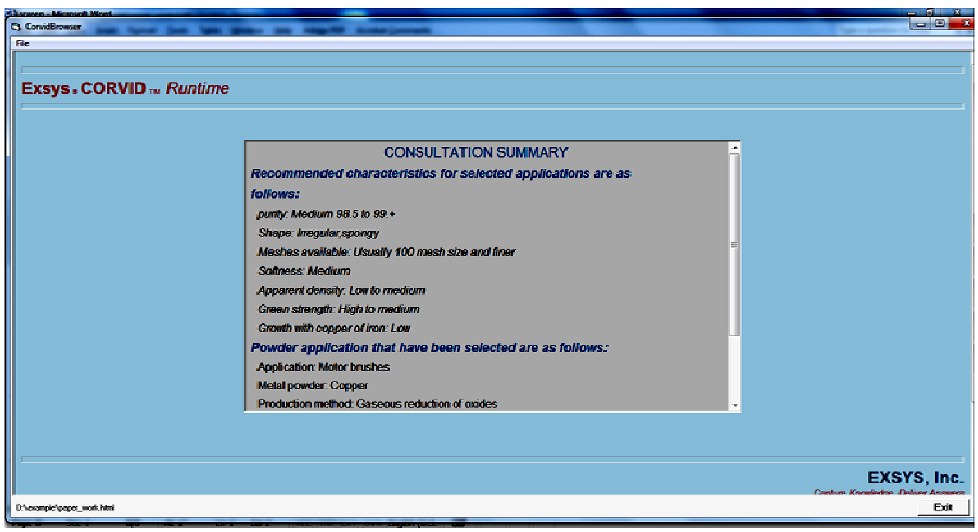

Fig. 3h: Consultation example number two, screen 6

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 an expert; 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 numerous manufacturing routes, which convert these materials into engineering components and products.

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, EXSYS-CORVID 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.

ACKNOWLEDGMENT

This project was supported by King Saud University, Deanship of Scientific Research, College of Engineering Research Center.

REFERENCES

Aguilar-Díaz, J.E., E. García-Montoy, P. Pérez-Lozano, J. M. Suñe-Negre, M. Miñarro and J.R. Ticó, 2009. The use of the SeDeM diagram expert system to determine the suitability of diluents-disintegrants for direct compression and their use in formulation of ODT. Eur. J. Pharm. Biopharm., 73: 414-423.

Ahmadi, F.F. and H. Ebadi, 2010. Design and implementation of an expert interface system for integration of photogrammetric and geographic information systems for intelligent preparation and structuring of spatial data. Exp. Syst. Appl., 37: 8006-8013.

Chu, H.C. and G.J. Hwang, 2008. A Delphi-based approach to developing expert systems with the cooperation of multiple experts. Exp. Syst. Appl., 34: 2826-2840.

Codd, E.F., 1990. The Relational Model for Database Management Version 2. Addison-Wesley, Reading, Mass.

Date, C.J., 1995. An Introduction to Database Systems. Addison Wesley, Boston, Mass.

Date, C.J. and H. Darwen, 1993. A Guide to the SQL Standard. 3rd Edn., Addison-Wesley, Reading. Mass.

Dowson, G., 1990. Powder Metallurgy the Process and its Products. Adam Hilger, Bristol, New York.

Dymova, L., P. Sevastianov and P. Bartosiewicz, 2010. A new approach to the rule-base evidential reasoning: Stock trading expert system application. Exp. Syst. Appl., 37: 5564-5576.

Es-Saheb, M.H., 1992. Uniaxial strain rate in pharmaceutical powders during cold compaction. J. Mat. Sci., 27: 4151-4159.

Es-Saheb, M.H. and A. Radwan, 2003. Towards an expert system for powder production processes. JKAU Eng. Sci., 14: 115-123.

Exsys CORVID, 1989. Rule-Based Expert System Development Tool. Paperback Software International.

Fan, K.C., S.H. Chen, J.Y. Chen and W.B. Liao, 2010. Development of auto defect classification system on porosity powder metallurgy products. NDT&E Int., 43: 451-460.

Farag, M.M., 1989. Selection of Materials and Manufacturing Processes for Engineering Design. Prentice Hall, New York, pp: 533.

Fayed, M.A.E. and I. Otten, 1984. Handbook of Powders Science and Technology. Von Nostrand Reinhold Co., New York.

Goetzel, C.G., 1949. Treatise on Powder Metallurgy. Interscience Pubs., INC., New York.

Guessasma, S., G. Montavon, P. Gougeon and C. Coddet, 2003. Designing expert system using neural computation in view of the control of plasma spray processes. Mater. Design, 24: 497-502.

Hausner, H.H. and M.M. Kumar, 1982. Handbook of Powder Metallurgy. 2nd Edn., Chemical Publishing Co., Inc., Neq York.

Jackson, P., 1999. Introduction to Expert Systems. 3rd Edn., Addison Wesley Longman Ltd., Harlow, England.

Liao, S.H., 2005. Expert system methodologies and applications-a decade review from 1995 to 2004. Exp. Syst. Appl., 28: 93-103.

Lyu Jr, J. and M.N. Chen, 2009. Automated visual inspection expert system for multivariate statistical process control chart. Exp. Syst. Appl., 36: 5113-5118.

Papic, V., N. Rogulj and V. Pleština, 2009. Identification of sport talents using a web-oriented expert system with a fuzzy module. Exp. Syst. Appl., 36: 8830-8838.

Park, Y.C., J.K. Lee and G.C. Lee, 2007. Development of an expert system for evaluation of the strength of matrix shape memory composites. Compos. Struct., 77: 241-248.

Pereza, P., J.M. Negrea, S. Minarro, M. Roiga, M. Garcıa-Montoya, R.F.E. Hernandez, C. Ruh and R.J.R. Tico, 2006. A new expert systems (SeDeM Diagram) for control batch powder formulation and preformulation drug products. Eur. J. Pharma. Biopharm., 64: 351-359.

Qian, Y., L. Xua, X. Li, L. Lin and A. Kraslawski, 2008. LUBRES: An expert system development and implementation for real-time fault diagnosis of a lubricating oil refining process. Exp. Syst. Appl., 35: 1252-1266.

Radwan, A. and M. Es-Saheb, 1995. Knowledge based powder selection system. Proceeding of International Conference Advances in Materials and Processing Technologies (AMPt'95). Dublin, Ireland, August 8-12, pp: 839-847.

Radwan, A. and M.H. Es-Saheb, 1998. Computerized relational models for powder technology: Powder and process selection. J. Int. Manuf., 9: 467-473.

Rao, M.P., D.M. Miller and B. Lin, 2005. PET: An expert system for productivity analysis. Exp. Syst. Appl., 29: 300-309.
Ruiz-Mezcua, B., A. Garcia-Crespo, J.L. Lopez-Cuadrado and I. Gonzalez-Carrasco, 2011. An expert system development tool for non AI experts. Exp. Syst. Appl., 38: 597-609.
Singha, R. and G.S. Sekhon, 1999. An expert system for optimal selection of a press for a sheet metal operation. J. Mater. Process. Technol., 86: 131-138.
Sirilertworakul, N., P.D. Webster and T.A. Dean, 1993. A knowledge base for alloy and process selection for casting. Int. J. Mach. Tools Manufact., 33(3): 401-416.
Smith, L.N., R.M. German and M.L. Smith, 2002. A neural network approach for solution of the inverse problem for selection of powder metallurgy materials. J. Mater. Process. Technol., 120: 419-425.