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AI Applications to Metal Stamping Die Design – A Review

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***Abstract*—**Metal stamping die design is a complex, experience-based and time-consuming task. Various artificial intelligence (AI) techniques are being used by worldwide researchers for stamping die design to reduce complexity, dependence on human expertise and time taken in design process as well as to improve design efficiency. In this paper a comprehensive review of applications of AI techniques in manufacturability evaluation of sheet metal parts, die design and process planning of metal stamping die is presented. Further the salient features of major research work published in the area of metal stamping are presented in tabular form and scope of future research work is identified.

***Keywords*—**Artificial Intelligence, Die design, Manufacturability Evaluation, Metal Stamping Die.

I. Introduction

METAL stampings are important structural components of automobiles, computers, refrigerators, type writers, kitchen utensils, electrical, electronics and tele-communication equipments. Sheet metal operations are economical and quick means of producing intricate, accurate, strong and durable metal stampings in huge quantities. Applications of these operations are increasing day by day due to their high productivity, low cost per part, improvement in material quality, minimum scrap material and energy consumption. One of the important tasks in the production of metal stampings is the design of metal stamping dies to suit the product features.

The design of metal stamping dies is a complex and highly specialized procedure [1]-[3] and typically it takes 20% of the lead-time from the concept design to the final stamping manufacture. The diverse nature of products produced by stamping die demands a high level of knowledge on the part of the die designer that can only be achieved through years of practical experience [4]. To check the manufacturability of sheet metal part, development of strip-layout, selection/design of die components and die modeling are some of the major activities to be carried out by die designers in stamping industries. The traditional methods of carrying out these tasks require expertise and are largely manual and therefore tedious, time consuming and error-prone [5], [6]. Also the knowledge gained by die design experts after long years of experience is often not available to others even within the same company. It creates a vacuum whenever the expert retires or leaves the company. The quality of die design depends to a large extent on the designer's skill, experience and knowledge. Commercially available CAD/CAM systems are providing assistance in drafting and analysis in die design process, but human expertise is still needed to arrive at the final design. Also, the high cost associated with setting up such systems is quite often beyond the reach of small and medium sized sheet metal industries, especially in developing countries. With the advancement in the area of computer graphics, CAD/CAM and Artificial Intelligence (AI), some researchers [7]-[13] started to exploit these techniques for the design of metal stamping dies. AI is the study of how to make computers perform intelligent things for the processing of unstructured scattered knowledge for the solution of complex problems [14]. One of these problems that have attracted a considerable amount of researchers attention is the use of AI techniques in manufacturability evaluation of sheet metal work; and development of intelligent systems for metal stamping die design and process planning.

In this paper, major published literatures on the use of AI techniques in manufacturability evaluation of sheet metal work and design of stamping dies are reviewed. Salient features of some important systems developed by worldwide researchers are presented in tabular form and then finally, the scope of future work in the area of design of metal stamping dies using AI techniques is identified.

II. Review on AI Applications to Manufacturability Evaluation of Sheet Metal Work

In order to develop better concurrency between design and manufacturing of metal stamping die a stampability assessment or evaluation is necessary. It is estimated that decisions made at the part design stage determine 70%–80% of the manufacturing productivity [15]. Therefore, as a first step in the planning for manufacture of a sheet metal part, it is useful to check its internal as well as external features for assessing its manufacturability on stamping die. Such checks are useful to avoid manufacturing defects, section weakness, and need of new dies, tools or machines. It requires that die

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designer should have extensive knowledge of the capabilities of available sheet metal operations and materials, and have an understanding of the design requirements for those processes. Over the years, the industrial practices of checking of the internal and external features of sheet metal parts have not changed significantly. Traditional methods involve calculations and decisions, which have to be made on the basis of experience and practice for highly experience based die design task without the computer aids. Later on, some AI techniques developed by researchers. But the die designers have realized the applications of AI tools around 1980s. The assessment of manufacturability aspects is done by using various approaches such as neural network (NN), fuzzy logic (FL), agent-based system (ABS), rule-based system (RBS), analytical hierarchy process (AHP), object oriented techniques (OOT), and case-based reasoning (CBR).

Nakahara et al. [16] introduced a progressive die design system that examines the part design data to decide whether blanking can stamp it or not. De Sam Lazaro et al. [17] developed a knowledge-based system for identifying design rule violations to improve part manufacturability. Shpitalni and Saddan [18] addressed the problem of automatic tool selection and bending sequence determination using graph search heuristics. Meerkamm [19] developed a system to detect design violations concerning manufacturability of sheet metal parts. Tisza [20] developed a Knowledge-based expert system using principles of group technology for multi-stage forming process for feature recognition, material selection, blank determination, optimum sequencing of operations, tool and machine selection. Lee et al. [21] developed an assessment system consisting of a knowledge-based geometric analysis module, a finite element module and a formability analysis module. The geometric analysis module uses geometric reasoning and feature recognition with a syntactic approach to extract high-level geometric entity information from vertices in two-dimensional forming. The empirical rules for stamping die design are represented as frames in the knowledge base. Mantripragada et al. [22] developed a feature based design system, which acts like an interactive design tool and can be used to alert designers for potential production

TABLE I
RESEARCH WORK REPORTED IN THE LITERATURE IN THE AREA OF MANUFACTURABILITY EVALUATION OF SHEET METAL COMPONENTS

Ref. No.	Researchers	Input Mechanism	AI Techniques	Output
[10]	Prasad and Somasudaram (1992)	User-system interactions	Rule-based system	For blanking & piercing parts.
[20]	Tisza (1995)	From CAD model	Rule based expert system	Optimum sequencing of operations, tool and machine selection for deep drawn part.
[21]	Lee et al. (1995)	From CAD model	Geometric reasoning and feature recognition	Developed an assessment system consisting of a geometric analysis module, a finite element method module and a formability analysis module.
[17]	Lazaro et al (1993)	User-system interactions	Used Rule based & object oriented tech.	Identified design rule violations and suggests alternatives redesign solutions to improve manufacturability.
[22]	Mantripragada et al. (1996)	From CAD model	Knowledge based system	Perform formability analysis of sheet metal part and gives redesign solutions.
[23]	Yeh et al. (1996)	Collection of manuf. information and User-system interactions	Rule based expert system	Design advisor system for sheet metal components that suggests alternatives redesign solutions and estimates cost.
[24]	Radhakrishnan et al. (1996)	From CAD model	Geometric Reasoning	Design Rule Checker and design advisor for holes, slots, or other features of sheet metal part.
[40]	Ong et al. (1997)	Collection of manufacturing information	Fuzzy set and Rule based system	Optimal set-up and bending sequences for the brake forming of sheet metal components.
[12]	Choi and Kim (2001)	From CAD model, User-system interactions	Rule based Expert system	Strip and die-layout for manufacturing for blanking or piercing operations of stator & rotor part.
[26]	Xie et al. (2001)	From CAD model	Knowledge based system	Automatic tool selection, mfg. sequencing and cost estimation module for small- and medium-sized job shops.
[27]	Tang et al. (2001)	From CAD model	Feature based & Rule based expert system	Developed stampability evaluation system for sheet metal part at design stage itself.
[28]	Ramana and Rao (2005)	From CAD model	Rule based expert system	Design evaluation and process plan generation for sheet metal parts in mass production.
[29]	Kumar and singh (2006)	From CAD model, User-system interactions	Rule based expert system	Part design check and die selection module for sheet metal parts.
[30]	Giannakakis and Vosniakos (2008)	Using user-system interactions	Knowledge based system	Process planning, finishing operation, die and press selection, and tools selection.

problems, defects and failures. Yeh et al. [23] developed a rule-based design advisor for sheet metal parts. This system also suggests alternatives redesign solution and estimates cost. Radhakrishnan et al. [24] presented the advisory design rule checker system, integrated into ProMod-S using medial axis transformation algorithm to check the number of features for complicated sheet metal parts. Gupta et al. [25] described a process planning system for robotic sheet metal bending press. The system automatically determines bending sequences, selection of punches and dies and manufacturing costs etc. and gives feedback to improve the plan on operation-by-operation basis. Xie et al. [26] developed a compound cutting and punching production method for small and medium size sheet metal industries. The system uses concurrent and global design and manufacturing environments by integrated data integration platform based on Pro/INTRALINK and STEP, and a knowledge-based real time CAPP (RTCAPP) system into existing CAD system. Tang et al. [27] proposed an intelligent feature based design for stampability evaluation of a sheet metal part for quick check of potential problems in stamping process and stamping die at the design stage itself. They integrate design evaluation and cost estimation in a single system. Ramana and Rao [28] presented a system for automated manufacturability evaluation. The system described design evaluation, process planning, data and knowledge modeling for shearing and bending operations. Kumar and Singh [29] developed a rule-based expert system for assessing manufacturability of sheet metal parts to assist product designers, process planners and die designers working in small and medium sheet metal industries. It is coded in AutoLISP and interfaced with AutoCAD. Giannakakis et al. [30] presented an expert system for process planning and die design. This system includes initial calculations, process planning, die and press selection, and tools selection modules for cutting and piercing operations of progressive die. It is coded into CLIPS expert system development environment. Shukor and Axinte [31] discussed key issues and technologies related to the construction of manufacturability analysis systems (MAS). Research work reported in literature in the area of manufacturability of sheet metal part is summarized in Table I.

III. REVIEW OF AI APPLICATIONS TO DIE DESIGN AND PROCESS PLANNING

Research and development of die design automation systems was given a new dimension in the late 1980s and early 1990s, when the applications of AI techniques in engineering design started to take off. One area of the research that has attracted a considerable amount of researchers is development of knowledge-based die design and process planning systems.

Lin et al. [32] developed PC based expert system using FORTRAN, Micro Expert and AutoCAD for design of die set of blanking and simple drawing die. Sitaram et al. [33] proposed a knowledge-based system for process sequence design in axisymmentric sheet metal forming. Duffey and Sun [9] from University of Massachusetts described a proof-of-concept system for progressive die design for simple hinge part. The system was implemented using knowledge collected from manufacturability data, industry experts and standard die components; the system generates flat pattern geometry and develops a strip layout automatically. Li et al. [34] developed a knowledge based CAD/CAM package for progressive dies for small sheet metal parts. Nee and Foong [35] reviewed the techniques employed in punch design automation for progressive dies and made an attempt to link the programs together to form a useful package for the design of progressive dies. The program incorporates knowledge-based tools, heuristic rules, and number of expert design rules.

Prasad and Somasundaram [10] developed a computer aided die design system (CADDS). The system is capable to generate strip-layout automatically, conduct design checks for various die components, and generate the assembly views and bill of materials for the blanking die. This system is developed by interfacing AutoCAD with AutoLISP. Cheok et al. [36], [37] from National University of Singapore have reported to develop an intelligent progressive die (IPD) design system. They used various AI techniques such as feature-based modeling , rule-based approach and spatial reasoning to work-piece shape representation, shape recognition and decomposition, and die component representation for die design automation. Ismail et al. [1] worked on design automation for progressive piercing and blanking dies. Their work is based on applying a coding technique to characterize the stamped part geometric features, which is subsequently used to generate the type and layout of the die punches, and then developed the strip layout automatically. Esche et al. [38] explored knowledge-based system to design intermediate tooling conditions and determined minimum drawing steps of axisymmetric deep drawing problems and two-dimensional forming problems. Huang et al. [39] developed UNIX based expert system for planning and design of metal stamping dies for piercing and blanking operations. The system is developed using integrating AutoCAD with Kappa and some C programs. Park [11] developed an expert system for electronic gun grid parts. This system is coded in C under UNIX platform and CIS customer language of the EXCESS CAD/CAM system. Ong et al. [40] developed a system using an algorithm for automatic generation of bending sequence for progressive die. It consists of several modules, namely feature recognition, strip layout and die design. Choudhary and Allada [41] developed an integrated PC based CAD/CAM system for design of precision punches and die for small scale manufacturer. Singh and Sekhon [42] developed a low cost expert system for small and medium sized enterprises to assist sheet metal planner in making an intelligent selection of press machine from alternative machines available. The system is coded using AutoLISP programming language. Pilani et al. [2] proposed a neural network and Knowledge-based, hybrid intelligent system approach for generating an optimal die face for forming dies. Caiyuan et al. [43] reported to develop a knowledge-based CAD/CAM package labeled as HPRODIE for progressive dies for small-size metal stampings using feature mapping, rule based reasoning and case-based reasoning techniques. Kim et al. [44] developed a computer module, production feasibility check module, strip layout module, die layout module and post processing module.

Shi et al. [45] developed a process planning system for an auto panel. Tor et al. [3] used case based reasoning (CBR) and graph-based approach for progressive die design and process planning. It combines the flexibility of blackboard architecture with case-based reasoning. This system is capable of managing heterogeneous Knowledge sources. Vosniakos et al. [46] presented logic programming paradigm for checking part design, configuration of press tools and planning process for U shape bend part. This system is coded using Prolog. Kumar and Singh [47] developed an intelligent system for selection of progressive die components. The system modules are capable to determine type and proper dimensions of progressive die components namely die block, die gages (front spacer and back gage), stripper, punches, punch plate, back plate, die-set and fasteners. This system is developed using rule-base approach of AI and it is coded in AutoLISP language. Dequan et al. [48] presented a comprehensive review of knowledge-based system used in stamping planning. They presented a framework of CAD system that carries out automated process planning for piercing operation of precision work at a high speed. Chan et al. [49] developed an integrated system using FEM simulation and artificial neural network (ANN) to approximate the functions of design parameters and evaluate the performance of die designs before die tryout. Chi [50] proposed the fuzzy classification and rough set approach for mining the die design knowledge from various resources. These mined rules guide the designer in stamping die design. Zhibing et al. [51] developed a multi-step unfolding method (MSUM) for blank design and formability prediction of complicated progressive die stamping part. Chu et al. [52] used graph theoretic algorithm for automatic operation sequencing for progressive die design. The algorithm is implemented in C++ and is fully integrated with SolidWorks CAD system. Ghatrehnaby and Arezoo [53] developed algorithm for an automated nesting and piloting system for progressive dies. Their work is concentrated on geometrical optimization of nesting and piloting in CAD system. A summary of salient features of various systems developed by worldwide researchers using AI techniques in the area of metal stamping dies is presented in Table II.

TABLE II
SALIENT FEATURES OF SYSTEMS REPORTED IN LITERATURE IN THE AREA OF AI APPLICATIONS TO METAL STAMPING DIES

Ref. No	Researchers	System Details	Remarks
[32]	Lin et al. (1989)	Developed PC based expert system KBS using FORTRAN, Micro Expert and AutoCAD for progressive die.	Developed for simple blanking and Piercing of 2D parts with simple geometrical profile.
[33]	Sitaraman et al. (1991)	Knowledge based system for process sequence design in axisymmetric sheet metal forming.	Limited to certain phases of process planning of forming die design process.
[9]	Duffey and Sun (1992)	Used concept of KBS to model die components and assemblies for hinge part. Implemented in ICAD design language.	Developed for design of door hinges. Requires an experienced die designer to operate the system.
[34]	Li et al. (1992)	Developed a rule based KBS for small size electronic part using graph theory.	Limited to specific application.
[10]	Prasad and Sundaram (1992)	Developed KBS using AutoCAD with FORTRAN 77 and AutoLISP for Automatic generation strip layout, die layout, bill of materials.	Developed for blanking operations and for simple parts.
[35]	Nee and Foong (1992)	Punch shape design automation for progressive dies, using heuristic rules.	Limited to punch shape design and not capable of checking design features of sheet metal part.
[21]	Lee et al. (1995)	Developed IKOOPS for process planning. Used object-oriented schema together with production rules and heuristics.	Developed for the planning of progressive die plates.
[20]	Tizsa (1995)	Developed KBS for generation of process sequences & designing tools for deep drawing of axisymmetric & rectangular part.	Required inputs from the die designer to operate the system.
[22]	Mantipragada et al. (1996)	Developed a feature based KBS to alert die designers for potential production problems, defects and failures.	Developed for simple and specific part for checking manufacturability of sheet metal parts.
[38]	Esche et al. (1996)	Developed Rule based KBS for generation of forming process outlines system for round shaped parts.	Inputs from die-designer required. Experienced die designer required to operate the system.
[39]	Huang and Ismail (1996)	Used rule based object oriented and feature base concept to develop KBS for punch shape selection, number of staging and size of die components.	Developed for straight edge sheet metal parts of blanking and piercing operations.
[36]	Cheok and Foong (1996)	Linking together a CAD system, a knowledge-base system and library of numerical routines for design of progressive die.	Not capable of checking design features of sheet metal part.
[40]	Ong et al. (1997)	Described a methodology to determine the optimal set-up and bending sequences for the brake forming of sheet metal components.	Limited to specific application.

Ref. No	Researchers	System Details	Remarks
[37]	Choke and Nee (1998)	Developed intelligent KBS for progressive die design using various AI techniques.	Unable to check design features of sheet metal part, Designer is expected to generate the assembly views and bill of materials interactively.
[11]	Park (1999)	KBS approach is used to developed CAD/CAM system for deep drawing die using object-oriented techniques.	Developed for blanking die set and simple deep drawing press.
[41]	Choudhary and Alled (1999)	Developed a rule based KBS for design of precision punches and die, written in AutoCAD platform using AutoLISP programming language.	Developed for a specific applications and small parts.
[42]	Singh and Sekhon (1999)	Used rule base KBS approach for optimum selection of press.	Need user interactions and die design knowledge.
[2]	Pilani et al. (2000)	Developed a hybrid system using ANN and KBS approach to optimal design the die faces of forming die.	Experience die designer is required and developed for specific applications.
[12]	Choi and Kim (2001)	Used knowledge base system approach, developed by embedding algorithms in AutoCAD, used AutoLISP language for programming.	Developed for mainly blanking or piercing operations of irregular shaped sheet metal parts.
[45]	Shi et al. (2002)	Developed a KBS for processing planning for auto-panel using rule base and case base.	Concentrate on specific problem.
[3]	Tor et al. (2003)	Used CBR to develop KBS for design of progressive die.	Need initial cases as database, also indexing and retrieving of cases from database makes design process slow.
[28]	Ramana and Rao (2005)	Rule based KBS for checking the manufacturability of sheet metal parts.	Need to focus on the effect of change in design parameter on functionality of part.
[46]	Vosniakos et al. (2005)	Used logic programming paradigm to assess part and tool design, as well as to suggest process plans.	Covered only U shape parts, cutting and piercing operations only.
[48]	Dequan et al. (2006)	Developed a KBS for Process planning for stamping die using Object-orient techniques.	Limited to specific problem need to focus on optimization material utilization.
[47]	Kumar and Singh (2007)	Used rule base KBS approach for modeling strip-layout, and selection for die components.	Developed for progressive die.
[49]	Chan et al. (2008)	Developed an integrated methodology using ANN and FEM to address the uncertainties in design of metal-formed part.	Experience designer required, also FEM takes long time for computation.
[51]	Zhibing et al. (2008)	Finite element model is developed using AI for blank design and formability prediction of complicated progressive die stamping part.	Finite element analysis calculation consumes lot of time

IV. Some Comment on Reviewed Literature

Most of the systems developed for manufacturability evaluation for sheet metal take part information interactively, while others used feature extraction approach to extract CAD data as input. Some limitations in using these approaches are Imprecision/fuzziness of extracted data; inflexibility of type of data; and difficulty in interpreting relationships between various features of the part. Therefore, there is a need to explore for combining data input mechanisms and manufacturability assessments/reasoning tools, and more interactive format for output. Similarly most of the metal stamping die design automation prototypes reviewed are rather restricted to specific application domain, or still needed considerable interactive inputs from experienced designers to develop strip layouts, design of die components and die modeling. This is because these systems still have the disadvantages of the conventional architecture of knowledge based expert systems, which are incapable of managing heterogeneous knowledge sources effectively. Also, these systems require skilled and experienced die designers to input data, and finally to take appropriate decisions.

V. Conclusion and Scope of Future Work

Earlier, the process of die design was considered an art rather than the science. Traditionally, checking the manufacturability of sheet metal parts and process of die design require experienced die designers, involve numerous calculations, and hence time-consuming tasks. But with the advancement in the field of AI around 1980s, these are being carried out using various AI techniques. But most of the systems developed using AI techniques are having limitation in extraction and representation of part feature data in more interactive format for displaying output. Further, most of the systems are developed for single-operation stamping dies using production rule-based approach of AI. Very few systems are developed for design of multi-operations dies and even these are not capable to fully automate the die design process.

Therefore, there is need to develop an intelligent system by combining some suitable AI technique and CAD system for manufacturability assessments/reasoning, concurrent planning and quick design of multi-operation dies. The system must have rich knowledge-base comprising knowledge of experienced die designers and process planners, must be interactive and user friendly and have low cost of implementation. The system finally must give its output in form of drawings of strip-layout, die components and die assembly. The authors are applying their research efforts in this direction to assist process planners and die designers of small and medium scale sheet metal industries.

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