A system for presenting manufacturing knowledge on the design level in toolmaking

J. Valentincic\textsuperscript{1}, D. Brissaud\textsuperscript{2} and M. Junkar\textsuperscript{1*},

\textsuperscript{1} University of Ljubljana, Faculty of Mechanical Engineering, Aškerceva 6, SI-1000 Ljubljana, Slovenia, e-mail: lat@fs.uni-lj.si
\textsuperscript{2} Institut National Polytechnique de Grenoble, Laboratoire 3S, BP 53, 38041 Grenoble cedex 9, France, e-mail: daniel.brissaud@hmg.inpg.fr

Abstract

A novel approach to avoid the knowledge gap between the design and the manufacture is presented in this paper. The main idea is to build the system in the form of computer program, which core is the manufacturing expert system, to be used by the product designer. The system reveals critical features of the newly designed product from the manufacturing point of view and points them out to the product designer. According to critical features of the product design, the product designer can decide whether to change the critical part of the product or not—he is the only one who may make changes in the design of the product. The system presented in this paper is prepared for the toolmaking industry, where a lot of relatively cheap products are made by one relatively expensive tool. Since the shape of the cavity in the tool is the negative shape of the product, small changes in the product design can significantly reduce the manufacturing costs of the tool. A design adaptation system for machining in toolmaking (DASMT) reveals features, which are critical for machining and makes suggestions to the product designer to alter the features by keeping the overall functionality of the product.

Key words: DFM, electrical discharge machining, expert systems, toolmaking

1. Introduction

From hundreds of product concepts, only five up to twenty will merit serious consideration [1]. This is due either to an inadequate exploration of all feasible alternative concepts or to an ineffective integration of the product design concepts with evaluation criteria such as ease of manufacture and production cost [2].

Design for manufacture (DFM) philosophy is characterized by simultaneous design of a product and its manufacturing process in order to achieve the best outcome and consequently optimise the overall costs. The manufacturability concept has been developed to measure the degree of integration between the product and the process; manufacturability implies easy production and can be approximated by the capacity to achieve the desired quality and productivity while optimising costs.

* Corresponding author
An extensive work has been done within last ten years in the field of design, driven by manufacturing issues of tools. DFM needs a lot of expert knowledge of the manufacturing process itself. For example, knowledge on the wear process of an electrode machining of a tool is proposed in Mohri et al. [3], a process planning system for EDM operations is proposed by Lauwers and Kruth [4] and knowledge about comparison and selection of competitive technologies, such as sinking electrical discharge machining (EDM) and high speed milling (HSM) in tool manufacturing is the topic of Alam et al.’s article [5]. The second part of the latter work deals with the basic DFM techniques such as rules advising the designer, guidelines assisting him throughout methodology, simulation software to detect problems in shape, quality or productivity and cost calculation software to control manufacturing costs. An overview of this field is given in Boothroyd and Dewhurst [6,7] and in [8].

For DFM implementation Lee et al. [9,10] are suggesting the rationalization of the design process. Chin and Wong [11] proposed a system for rationalization of the design process of tools for plastic injection and Ding et al. [12] for the EDM electrode design process.

What becomes the most significant topic in DFM system is the management of the whole body of knowledge and data. Chen and Hsiao [13] proposed a collaborative data management system. Young et al. [14] proposed a system providing high-quality information on which designers can base their decisions on-line. Most authors proposed to embody information into knowledge bases and expert systems [10,11].

The last portion of knowledge needed in a DFM system is related to the design methodology. Literature proposes classical methodology based on seven steps [8,15]: (1) product analysis to collect and clarify information, (2) manufacturing process analysis concerned with the collection, processing and reporting of process-specific and resource-specific data, (3) measurement of the interactions between product and process information in terms of the relevant performance indicators, (4) highlight of problems, (5) diagnosis for effects and causes, (6) advices in redesign, and (7) prioritising changes in the design procedure, if necessary.

In this paper, an integrating system for the design of the product and its simultaneously adaptation to the tool manufacturing is proposed. The system is to be used by the product designers. Based on the main principles of DFM techniques, its originality comes from both the adaptation methodology and the implementation of the professional knowledge. The design adaptation system for machining in toolmaking (DASMT) aims to address the embodiment and detail design phases of the product definition, as well as the conceptual design phase of the die definition at an early stage, when there is still time to make significant changes. This methodology is extremely useful, as it enables evaluation and optimisation of the design and avoids designers’ time-consuming iterations.

The paper is organised as follows: the design for manufacturing was introduced in the first section. In the second section, an overview of Slovenian toolmaking industry from the DFM point of view is given. In the second section, the originality of our method is presented. The
description of the DASMT is given in the third section. The modules of the DASMT are described in the fourth section, where the detailed insight into the expert system for tool design adaptation for machining by EDM is given. Finally, the conclusions are drawn in the fifth section.

2. Methodology of the design adaptation system for machining in toolmaking

The relation between the design and the manufacturing of the products made in the mass production is complex since the tool for mass production of the product has to be made. The tools are made in toolmaking and they are intermediary products by which the basic products or their components are produced, such as casings, plastic bottles, etc. In general, tool consists of one or more cavities. The shape of the cavity depends on the product design, and is usually extremely complex. Therefore it is important to decompose it to individual features regarding the requested shape, tolerance and surface roughness of the cavity. A manufacturing feature can be defined as a geometrical form of the workpiece to which manufacturing properties are associated and for which a manufacturing process is known. In the case of EDM process, a feature is a part of the tool, which can be machined by an electrode or a set of electrodes for rough and fine machining on a given EDM machine.

Electrical Discharge Machining (EDM) and High Speed Milling (HSM) are the two processes generally applied for machining of tool features. In most cases, both processes are applied sequentially for the production of a given tool. When EDM has been selected the electrode has to be made, which shape is transferred into the workpiece, i.e. tool. The entire design process consists, namely, of the design of the product, the tool and the electrode. The tool has to be designed according to the product design by taking into account all properties of the manufacturing process of the product (forging, moulding, etc.) and the manufacturing processes of the tool (EDM, HSM). The electrode itself is defined by the tool features and is generally machined by either wire-EDM or milling process. Consequently, the entire production process includes the simultaneous design of the product, the tool(s), the electrode(s) and the associated manufacturing processes. All these activities should be done simultaneously, but unfortunately in practice this is still impossible.

As mentioned before, the DASMT aim is to adapt the product design, which will be made in the mass production, to the tool manufacturing. The system, which presents the toolmaking knowledge on the design level, was developed by integration of the results from the literature and our knowledge. If the properties or demands for the product are denoted as \( D^* \) and properties or demands for the tool manufacturing are denoted as \( M \), then:

\[
M = F(D^*),
\]

where \( D^* \) and \( M \) are vectors of the attributes, which are describing design and manufacturing properties respectively: \( D^*=(d_1^*,d_2^*,...,d_p^*,...d_P^*) \), \( M=(m_1,m_2,..,m_q) \). Function \( F \) embarces several functions, which are describing the relations between the attributes \( d_p^* \) and \( m_q \). The adaptation problem deals with the inverse problem to derive design vector \( D^* \) from manufacturing vector \( M \):
\[ D = F^{-1}(M). \] (2)

For each manufacturing attribute \( m_q \) it is necessary to define all mapping functions \( f_r \) with other manufacturing attributes \( m_{q'} \) and design attributes \( d_p \):

\[ m_q = f_r(d_p, m_{q'}): \quad p \in \{1, 2, ..., P\}; \quad q, q' \in \{1, 2, ..., Q\}, \quad q \neq q'; \quad r \in \{1, 2, ..., R\}. \] (3)

The mappings from the design to the process planning level are better defined than the mappings from the process planning to the design level. Thus, function \( F \) is easier to describe than the inverse function \( F^{-1} \), which is needed for design adaptation of the product to the tool manufacturing. Function \( F \) is represented in the form of computer algorithms, which are assembled into three expert subsystems (modules) for each field. The inverse function \( F^{-1} \) is obtained by including the product designer into the interaction between the three expert systems. Such a system was named as DASMT.

3. The Design adaptation system for machining in toolmaking

The expert systems included into the DASMT manage manufacturing knowledge to provide the designer only with the critical information on the product (critical from the manufacturing point of view). The decision about the design adaptation is only up to the designer, by considering the demands for the product and the demands for the tool. The latter are presented to the designer by DASMT as a critical parts of the product design from the tool manufacturing point of view. Thus, the basic idea of the system is to determine the critical design attributes; the determination is based on the network of dependencies between the design and the manufacturing attributes. Manufacturing attributes of the tool were established according to the given product design attributes by considering engineers’ knowledge, expert and scientific knowledge about the machining processes and case studies.

First, the dividing plane of the tool is defined by the DASMT and both parts of the tool are segmented into several features according to the design data of the product. Further on, the appropriate machining process is defined for every feature and critical parts of the features are revealed. If the demands for the product enable the adaptation of the critical parts, the designer adapts those parts to the ease of tool manufacturing. Once the designer changes the design configurations and the attributes, the DASMT makes changes of the tool design and adapts the machining processes and its machining parameters to the new, altered design. Adaptations are driven by improvements of product and tool definitions, minimising the overall production costs and maximising productivity. Substantial increases in ease of tool production can be achieved by slight alterations of critical product design attributes, which should however not deteriorate its functionality. The designer tunes the critical attributes of the product to the process attributes of the selected machining process of the die throughout the iterative process. Thus the number of iterations between the designer and the die engineer is significantly reduced.

The general concept of DASMT is presented in Fig. 1. The upper part of the figure presents
the information flow between the product designer, the tool engineer and the operator of the machine, who actually makes the tool. The lower part of the given figure shows the information flow between the designer and the modules of DASMT. These are: system for die segmentation and determination of the machining process (MSaSMP), design adaptation modul for EDM (DAM-EDM) and design adaptation modul for HSM (DAM-HSM).

Figure 1: Scheme of DASMT

The product design attributes $D^*$ are introduced to the MSaSMP as shown in Fig. 1. The modul defines the dividing plane and segments each part of the tool into several features and for each feature it determines the appropriate machining process. Further on, a set of tool design attributes $D$ is generated. The mapping is relatively simple, since the tool has a negative shape of the product. The product dimensions differ from the tool dimensions for the contraction of the product material due to the temperature dilatation. The MSaSMP modul was build by Nardin [17] and up to now it works as an autonomous system.

The machining process is selected for each feature described by tool design attributes $D$: the selection is made between EDM and HSM. According to this selection, each tool feature is presented to the appropriate design adaptation module: DAS-EDM or DAS-HSM to be examined from the manufacturing point of view. In this process, the design attributes, which are the most problematic from the manufacturing point of view are established. They are named critical design attributes, denoted as $D_{cr}$, and they are identical to the critical product design attributes $D^*_{cr}$, that are introduced to the designer. The designer then tries to adapt the design focusing on the given critical product design attributes. The system is interactive: every product design adaptation reflects in the establishing of new critical product design attributes that are describing certain product parts. Of course, the critical design parts can not be avoided. The most convenient is that all parts of product are critical. In such case, the selected machining parameters hardly achieve the demands for the product and tool design—the machining of the tool is the cheapeast and the fastest.
4. Functioning of the modules

The whole DASMT, which consists of three modules is presented in Fig. 1. Nardin presented MSaSMP in [17] and thus it will not be presented in detail here. Since both other modules, namely DAM-EDM and DAM-HSM have not been presented in the literature yet, they are presented here.

DAM-EDM and DAM-HSM can work also as autonomous system, which solves specific problems such as tool design adaptation to the specific machining process that is determined in advance. Such an autonomous system is to be used by tool designer who makes tool design for the given product and checks and optimizes the shape of tool features according to the selected machining process of the given feature. Since the tool designer is not familiar with the demands of the product, such optimization requires also the presence of the product designer.

The conceptual scheme is equal for both modules and is shown in Fig. 2. Design attributes of the tool are established by MSaSMP, where also the most appropriate machining process is selected for each feature of the tool and the attributes are sent to the corresponding module; if a feature is machined by EDM process, the design attributes of the feature will be send to the DAM-EDM, in the case that HSM process is determined to machine the given feature, the design attributes will be send to the DAM-HSM.

The kernel of each module is an expert system which chooses appropriate machine for the given feature machining. The content of the machines database depends on the toolmaking company, where the tool will be manufactured. Each machine has its own machining parameters database. The EDM machines use different machining parameters to achieve the same machining results. Not all of the HSM machines have the same performances and the same tools available in the given toolmaking company. Thus, the dashed line in Fig. 2 indicates that the machining parameters database depends on the selected machine. Algorithms of the machine selection and the machining parameters selection strongly depend on the selected machining process. Further on, the DAM-EDM will be described.
4.1 Detailed insight into the DAM-EDM

The description of the tool design has been formalised into design attributes, which all together describe the tool to determine its manufacturing. According to the literature, industrial experience and our own experience, 10 tool design attributes have been selected to determine the EDM manufacturing attributes and thus to define the tool manufacturing. The design attributes are in general vectors and noted as \(d_i\). Two attributes characterise the whole tool: \(d_1\) represents the maximum dimensions of the tool \((x, y, z)\), and \(d_4\) represents the tool material. Each tool feature is characterised by 7 attributes; the main one is the attribute \(d_2\) characterising the shape of the feature. The rest attributes are: \(d_3\) surface area, \(d_6\) machining depth, \(d_7\) surface roughness, \(d_8\) heat affected zone, \(d_9\) roundness of edge, and \(d_{10}\) slope of flank surface. The attribute \(d_3\) is a global attribute characterising the tolerances of dimensions, shapes and positions.

Most of the presented design attributes is well defined by its name, and their values are numbers. Thus, their detailed description is not required. Attribute \(d_2\) describes the shape of the feature and it requires detailed description. In general there are many features on a tool, thus there are more than one instance of attribute \(d_2\) for each tool.

To describe the characteristics of EDM machines and the performances of the machines when certain machining parameters are used, two databases were build. First database consists of the EDM machines data, which are available in the given toolmaking. The important data are: the working area size in \(x, y, z\) axes \(m_1\), the list of the axes that can operate on the particular machine \(m_2\) and the precision of the machine in each axis \(m_3\).

The second database consists of machining parameters and their performances. A group of set-up parameters, denoted as \(m_4\), includes free voltage, electric current amplitude and pulse-on time. Each group of parameters is limited by the smallest eroding surface size that can be machined by the given values of the set-up parameters. For each group of the set-up parameters, the following performances are given: the relative corner wear of the electrode, the achieved surface roughness, the achieved depth of the heat affected zone and the requested machining allowance, which should be taken into account also when changing from rough set-up to fine set-up. This database is a direct copy of the technological tables, given by machine manufacturer as assistance to the machine operator.

In order to present all the manufacturing attributes, it is necessary to mention the electrode material \(m_4\) and required number of electrodes for machining of the given feature of the tool \(m_6\). These attributes are directly determined in DAM-EDM by the design demands for the tool and they are established according to the mappings of the design to the manufacturing attributes.

Mappings from design to the manufacturing level are presented in Fig. 4, where the design attributes that are required to establish manufacturing attributes for tool machining. Some of the mappings are very simple, e.g. the machine working area size, which DAM-EDM selects for the machining of the given tool, must be larger than the size of the tool. More
sophisticated problem is to determine the suitable machining parameters. It can be solved by computer algorithm, which takes into account the selected EDM machine (database of the machining parameters and process performances is known – mapping \( f_7 \)) and design attributes of the given feature – mapping \( f_5 \). When databases of process parameters was selected, the electrode material, which is defined by the tool material and the eroding surface size, plays an important role (mapping \( f_4 \)).

![Diagram](image)

Figure 4: Mappings of the design attributes of the tool to the manufacturing attributes for tool manufacturing. Denotations of the design attributes: \( d_1 \) size of the tool, \( d_2 \) shape of the feature, \( d_3 \) given tolerances, \( d_4 \) tool material, \( d_5 \) eroding surface size, \( d_6 \) feature depth, \( d_7 \) surface roughness of the element, \( d_8 \) allowed heat affected zone, \( d_9 \) edge roundings, \( d_{10} \) slope of the flank surface. Denotations of the manufacturing attributes: \( m_1 \) working area size of the machine, \( m_2 \) number of axes, \( m_3 \) precision of each axis, \( m_4 \) electrode material, \( m_5 \) setup parameters, \( m_6 \) number of electrodes required to machine given feature.

Since the purpose of this paper is to present the novel approach to manufacturing knowledge presentation on the design level, the algorithms for mapping from design to manufacturing level will not be presented here. They are presented in [16]. From Fig. 4 one can observe that the mappings are made from design to manufacturing level, i.e. following function \( F \). The inverse function \( F^{-1} \) is obtained through the user of DASMT, i.e. product designer.

5. Conclusions

In this paper the DASMT system has been described. It belongs to the group of DFM systems, but it differs from other DFM systems as it leaves the best design solutions to the
designer itself, who has the best knowledge about the demands for the product characteristics. His knowledge incorporates also the knowledge about aesthetics, ergonomics, etc. In such a way the designers’ creativity is fully supported: instead of leading the designer through the process of design, the DASMT system only points out the weak parts of the product design from the manufacturing point of view and leaves full freedom to the designer to adapt it. The weak points of the design are revealed by expert systems DAM-EDM and DAM-HSM.

The design adaptation for the ease of manufacture is a complex task, particularly in toolmaking industry where plenty of decisions have to be coordinated. Thus, the modular approach to system building is very suitable. Up to now two problem solvers of DASMT system have been developed separately and each of the problem solver works autonomously. The MSaSMP was presented in [17] and DAM-EDM is briefly presented in this paper. The future work will be focused on the development of the DAM-HSM for adapting features that will be machined by HSM. The DAM-HSM will follow the same philosophy as the DAM-EDM. Later, all three modules will be included into the general system—DASMT, which functionality is described in this paper.

References


