Design of an Integrated Process Chain to Manufacture Titanium Components with Micro Features

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Abstract
More and more micro components and micro features have been introduced into diverse types of industrial products and market sectors. Micro features are used in the aerospace and automotive industry and for medical and biomedical applications. There are several micro manufacturing processes but they are quite limited to machine 3D free-form micro structures in a wide range of materials, mainly hard metals. Thus, the integration of processes into a continuous process chain is required. In this paper, the design of an integrated process chain to support the manufacturing of micro features on titanium components using a formal approach is presented.

Keywords:
Process chain design, axiomatic system design, technology data catalogue

1 INTRODUCTION

In the last decade, the use of micro products has significantly increased [1]. A market analysis for the years 2004-2009 shows a clear indication of the scope of the economic sectors that are directly affected by micro technologies with their current investment trends. Investments are expected to keep on growing rapidly with the potential of the market reaching 20 billion € in 2010, with a growth rate of around 20% in micro technology products [2].

Micro components have been introduced into diverse types of industrial products in diverse industries and applications, e.g. the automotive and aerospace industry, and for medical and biomedical applications [1, 3-4].

Micro holes, the most basic micro features of micromachining, with diameters between 200- 300µm are commonly found in several products; for example, mechanically drilled in printed circuit boards. Fuel injection nozzles are also mechanically drilled or machined by electric discharge machining (EDM). Holes with a diameter smaller than 100µm have become the new machining challenge [3].

Figure 1: Instrumentation holes on blisk [5].

In the aerospace industry, micro holes with the functionality of decreasing the temperature of the component surface are designed and machined on combustors and in high pressure turbines. Recently, micro features were also incorporated on stator vanes and rotor blades. This is the most significant application due to the fact that in aero engine manufacturing blades are the only components manufactured in relatively large quantities [4]. Moreover, micro holes are found on blade trailing edges, as micro instrumentation holes on all parts of the engine (see Figure 1), and as oil whizzer holes on compressor discs [5]. There are several technologies to drill cooling holes but their biggest drawback is their achievable machining speed. EDM and electro chemical drilling (ECD) have been the main manufacturing methods because they can make multiple holes at the same time using multiple electrodes [6], all at the same angle with high levels of roundness and taper [7]. ECD and EDM have typical drilling speeds of 1-10mm/min [6]. Although they are slow processes and they can not be used if the blades and vanes are coated with a thermal barrier coating, they are used when the aspect ratio of a hole is so large that laser drilling will not produce the quality level desired [4]. Electron Beam Drilling (EBD) is a fast process, but it is not an attractive technology because it needs a vacuum chamber and is more expensive than a YAG laser [6-7].

According to [1], the integration of processes into a continuous process chain is necessary for the manufacturing of new micro components and micro features; and therefore, the usage of systematic design methods is of relevance. Moreover, the importance of process chains thrust the need to characterise processes not only for their individual capability but also for their suitability for the integration into process chains to satisfy specific functional and technical requirements [8]. Toolboxes are highlighted as solutions to link the design of products and design of processes and process chains to fulfil specific functional and technical requirements [8].

An integrated methodology to generate process chains for the manufacturing of micro features on titanium components was developed using a formal approach [9].

A process chain developer, based on the axiomatic system design, was created to define timed sequence sub-processes. On the other hand, in order to retrieve, to characterise and to share relevant engineering data generated during the manufacturing process, a technology data catalogue (TDC) was developed. While the process chain developer provides the structure of the process chain, the TDC provides manufacturing process scenarios with all of the data needed for the manufacturing of the micro features on the titanium component. A semantic net, part of the TDC, will be utilised as an effective tool to share the final process chain and manufacturing information.

2 AXIOMATIC SYSTEM DESIGN FRAMEWORK

Axiomatic design is a methodology created by N.P. Suh that endows designers with the scientific basis for the design of engineering systems. Additionally, axiomatic design enhances creativity, minimises the iterative trial and error process, and determines the best design, among other advantages. Suh defined design as an activity that "involves interplay between what we want to achieve and how we choose to satisfy the need (the what)" and four domains that delineate four different design activities [10]: the customer domain, the functional domain, the physical domain, and the process domain (see Figure 2). The customer domain is characterized by attributes (CAs) or the needs that the customer seeks in a product, or a process or a system. In the functional domain the needs are defined based on functional requirements (FRs) and constraints (Cs). In the physical domain the design parameter (DPs) that satisfy the specified FRs are described. Finally, in the process domain manufacturing process variables (PVs) are characterized and a process based on the PVs that can produce the DPs is developed. Constraints (Cs) provide the limits on the acceptable design. The difference between Cs and FRs is that Cs do not have to be independent as the FRs do. Axiomatic design starts by identifying and defining the customer attributes or needs, and translating them into functional requirements. That involves a mapping process from the customer domain to the functional domain. Then a mapping process between functional domain and the physical domain follows to satisfy the customer needs. This process is also called a zigzagging method. This method allows hierarchies for FRs, DPs, and PVs to be created in each domain.

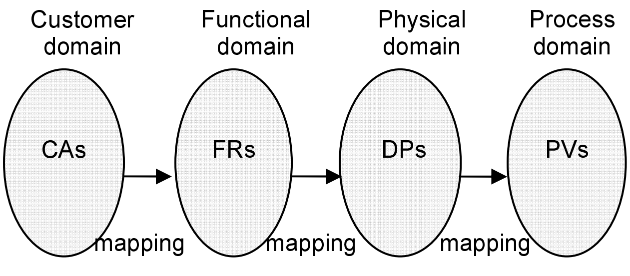

Figure 2: Schematic representation of domains [10].

During the mapping process, many possible DPs can be found; the key DPs are selected for the design according to two design axioms: the independence axiom and the information axiom.

The mapping process can be expressed mathematically in terms of characteristic vectors. A vector of FRs can be related to a vector of DPs according to the following equation:

$$\{FR\} = [AD]\{DP\} \tag{1}$$

The elements of the matrix are represented with a "0" if there is no effect and with an "X" if there is an effect, and later on are substituted by other values. Moreover, when all Aij are equal to zero except those where i=j then the design matrix is defined as diagonal and the design is called an uncoupled design, where each of the FRs can be satisfied independently by means of one DP. And when the upper triangular elements are equal to zero then the design matrix is defined as a lower triangular matrix and the design is called a decoupled design, where the independence of FRs can be ensured only if the DPs are defined in the right sequence. In any other case, the design matrix is defined as a full matrix and the design is called coupled, which is the most undesired design.

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix} \tag{2}$$

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix} \tag{3}$$

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X & X & X \\ X & X & X \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix} \tag{4}$$

Equation (2) shows a diagonal matrix/ uncoupled design, equation (3) shows a triangular matrix/ decoupled design, and equation (4) shows a full matrix/ coupled design.

The independence axiom declares that the independence of the functional requirements must be maintained; the design solution must satisfy each FR without influencing the other FRs. The information axiom defines that the better design is the one with the minimum information content to fulfil the design. The information content is calculated as follows.

The information content Ii for a given FRi can be defined in terms of probability Pi of satisfying FRi

$$I_i = \log_2 \frac{1}{P_i} = -\log_2 P_i \tag{5}$$

where the information is given in units of bits.

As defined in [10], the logarithmic function is chosen so that the information content will be additive in the case of many functional requirements that must be satisfied at the same time. Either the logarithm based on 2 or the natural logarithm may be used. And the total information content or information content of the system (Isys) is calculated as follows.

$$Isys = \sum_{i=1}^{m} I_i = -\sum_{i=1}^{m} \log_2 P_i \tag{6}$$

where P{m} is the joint probability that all m FRs are satisfied. When all FRs are statistically independent, as in the case of an uncoupled design, P{m} is defined as follows.

$$P\{m\} = \prod_{i=1}^{m} P_i \tag{7}$$

Axiomatic design presents many advantages compared with other methodologies such as TRIZ, the Taguchi method, engineering design and systematic design. It provides a good structural foundation based on functional analysis and information minimisation, which lead to robust design [10]. The information axiom provides the criterion for making the decision without the arbitrary weighting factors used in other decision making theories. As stated in [10], when the design range is specifically defined for all functional requirements, the design goal is fully specified, and any design that satisfies the functional requirements within their specified design ranges fully satisfies the design aim. Thus, there is no need for weighting factors.

3 INTEGRATED DESIGN METHODOLODY

The integrated methodology proposed for the design of process chains for the manufacturing of titanium components is shown in Figure 3 [9]. The inputs in the schematic representation are the requested component design, generally provided as 3D-CAD design, and the respective workpiece material, e.g. Ti6Al4V alloy. The output is the optimised machining information. This information is represented in a net in order to guarantee that it is easy to understand and communicate, and to navigate through its information dynamically. The machining information includes the adequate technology, optimal process resources (machine tool, tools and fixtures), and optimised kinematic and cutting parameters to manufacture the component. With them, the tool path and the NC programme can be further generated by the CAM operator. The process chain developer, based on the axiomatic system design, generates timed sequence sub-processes with the aim of enhancing productivity in the manufacturing domain. It translates customer needs into functional requirements which are fulfilled by design requirements. In an acceptable process chain design, the design parameters can be adjusted to satisfy their corresponding functional requirements without affecting other functional requirements. The timed sequence sub-processes provide the necessary guidelines for modelling and planning the manufacturing process. The technology data catalogue is a manufacturing knowledge repository where information (which corresponds to design parameters from the process chain) is characterised and shared in a dynamic way. Moreover, the catalogue includes ontology and a semantic net, for retrieving, structuring, processing and communicating optimal engineering data, such as:

- Properties and limitations of manufacturing processes,
- Properties and limitations of machine tools,
- Material characteristics,
- Geometric data of components,
- Machining performance and productivity parameters.

The development of the ontology assures that the knowledge is extracted (even that which otherwise would remain hidden as implicit knowledge, e.g. operational knowledge) from different sources, and stored in a single database to support the manufacturing process planning. The process chain developer communicates with the technology data catalogue to gain design parameters for the machine setup such as tools, fixtures, coolants and lubricants and the relevant process parameters, such as feed rates and cutting speeds for specific features and machining operations. These process parameters were previously extracted from successful used cases of machined parts and stored in the technology data catalogue after being characterised. The main advantage of the integrated methodology is that precise information exchange is enabled and consequently the time for process planning, machine setup time and cycle time are minimised. The process chain developer and the technology data catalogue will be detailed in the following sections.

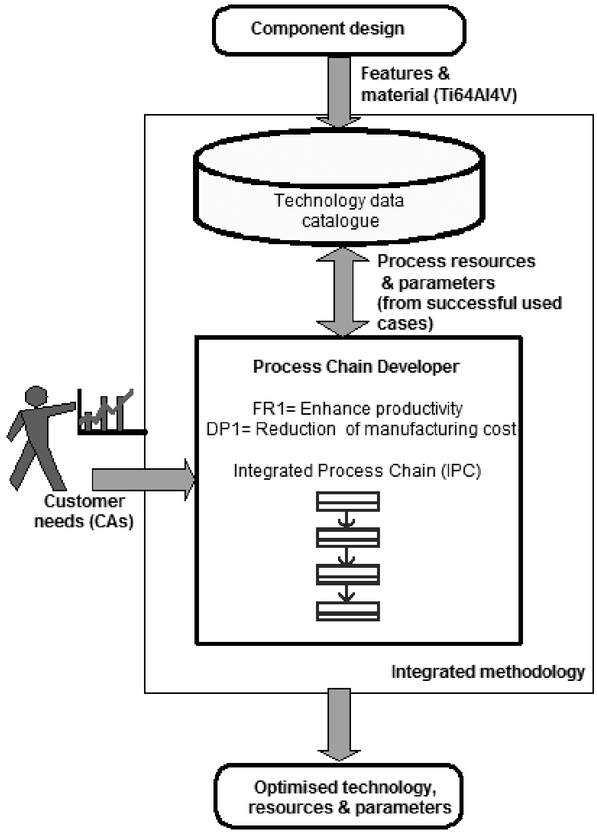

Figure 3: Schematic representation of the methodology.

3.1 Process chain developer

The process chain developer is used to generate a process chain for the machining of a Ti6Al4V alloy with dynamic cutting conditions; this means higher cutting speed and higher axial tool engagement. As an example, the process chain development for the manufacturing of blisks, where large axial depth of cuts result in chatter vibrations and increase in dynamic cutting forces, is presented.

The process chain developer defines the first level functional requirement (FR) and the respective design parameter (DP) as follows:

FR_1= Enhance productivity

DP_1= Reduction of manufacturing costs

The target cost for manufacturing the required component is identified. Then, it is translated into the first constraints of the design. Constraints provide bounds on the acceptable design solutions and they do not have to be independent as the FRs [10].

C_1= Manufacturing target cost

Blisk manufacturing costs can be split into three main categories: the material costs, the airfoiling process cost, and other manufacturing and quality assurance costs. Thus, the process chain developer determines the next decomposition as follows.

FR_{11}= Minimise airfoiling process costs

DP_{11}= Integrated process chain design

FR_{12}= Minimise quality assurance costs

DP_{12}= Steady process to target design specifications

FR_{13}= Minimise material costs

DP_{13}= Optimum material utilization

The design equation representing the interaction between the FRs and DPs is as follows.

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \end{Bmatrix} \quad (7)$$

where [A] is a triangular matrix, thus a decoupled design.

The integrated process chain is designed to reduce the manufacturing process costs, to achieve a steady process and optimise the use of material. On the other hand, a process without readjustments to the target design specifications achieves the minimisation of material wasted.

Since the manufacturing of the disk involves processes where a sufficient amount of experience has been obtained through the manufacturing of the conventional blade assembled disk (e.g. conventional cutting, surface compactness and finishing), the process chain is specifically designed for minimising blisk airfoiling process costs. Three machining processes may be used for manufacturing airfoils: milling, linear friction welding (LFW) or electrochemical machining (ECM).

The selection of the process which better fulfils the design requirements can be selected by applying the second axiom, the information axiom.

The following are the most important functional requirements that the machining process must initially satisfy: dimensional accuracy, surface quality and machining productivity.

FR_1= Machine blisk with (number) airfoils

FR_2= Machine blisk of diameter… mm

FR_3= Accomplish airfoil thickness at the inner annulus in the range of … mm and at the blade tip of … mm

FR_4= Obtain a surface roughness in the range of…µm

FR_5= Achieve the minimum machining time per airfoil

While the above mentioned FRs represent the design range, the current capabilities of the processes represent the system design.

Once the design and system ranges are defined, the areas with a common range between each value from the design and each of the values from the system are identified and the probabilities of satisfying each functional requirement are analysed. Then, the information content for each FR is calculated using the equation (5). The information content of the system is calculated using equation (6).

The information axiom states that the design that has the smallest information content (I) is the best design, as it requires the least amount of information to achieve the design goals.

The process decomposition will be further focused on the integrated process chain for milling, since this process is utilised before the electro chemical machining of the airfoil for rough machining to remove material up to an envelope of 2mm to final shape; and after the linear friction welding of the airfoil to remove the clamp shoulder. Thus it is considered as a representative process to demonstrate the effectiveness of the process chain developer.

The process chain design must integrate a strategy, tools and machine tools to make possible the reduction of manufacturing throughput time and thus, costs. The process chain developer defines FR_{11}/DP_{11} as follows:

FR_{111}= Retrieve surface and dimensional requirements

DP_{111}= Characterised feature from TDC

FR_{112}= Generate the machining strategy

DP_{112}= Machining range and operation definition

FR_{113}= Determine machine tool performance and limitations

DP_{113}= Machine tool selection from TDC and process constraints determination

FR_{114}= Determine type of milling cutter for machining strategy

DP_{114}= Milling cutter type selection

FR_{115}= Maintain cutting zone at stable temperature and lubricated to extent tool life

DP_{115}= Cooling lubricant selection

FR_{116}= Assure that the workpiece is firmly held in place for the machining

DP_{116}= Fixture selection

FR_{117}= Maximise surface finish quality while maximising machining productivity

DP_{117}= Kinematic and cutting parameters

In accordance with the following constraints:

C_2= Manufacturing throughput time

The design equation representing the interaction between the FRs and DPs is as follows.

$$\begin{Bmatrix} FR_{111} \\ FR_{112} \\ FR_{113} \\ FR_{114} \\ FR_{115} \\ FR_{116} \\ FR_{117} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 & 0 & 0 \\ X & X & X & 0 & 0 & 0 & 0 \\ X & X & X & X & 0 & 0 & 0 \\ X & X & X & X & X & 0 & 0 \\ X & X & X & X & X & X & 0 \\ X & X & X & X & X & X & X \end{bmatrix} \begin{Bmatrix} DP_{111} \\ DP_{112} \\ DP_{113} \\ DP_{114} \\ DP_{115} \\ DP_{116} \\ DP_{117} \end{Bmatrix} \quad (8)$$

where [A] is a triangular matrix, thus it is a decoupled design.

From the 3D-CAD design, the manufacturing features are manually retrieved and characterised. After their characterisation, they are stored in the technology data catalogue. The characterised data is further utilised in the design of the process chain in the form of constraints, where workpiece material, raw material dimensions, part dimensional requirements (shape and size), tolerances, and surface requirements are specified.

Once manufacturing features are identified, the machining strategy must be generated. Here, the machining range is defined as rough machining, or semi-finishing or finishing. Then, a machining operation is identified which will assure the generation of the required part shape by removing material from the workpiece in the form of chips. The machining operation can be classified in several categories, e.g. face milling, end milling, slotting, form milling, micro milling, etc. The machining strategy provides the general information for the design of the manufacturing process and the definition of process resources (tool, machine tool, fixtures) and process parameters (speed and feed). On the other hand, the machining strategy is important for determining the tool path, and therefore responsible for lead time, geometry accuracy and surface finishing.

The process chain developer selects a milling machine in accordance with the part dimensional requirements, and determines the machine performance by retrieving data characterised in the TDC, e.g. positioning accuracy (resolution and repeatability), maximum spindle speed, power, machine tilt angles (rotational axes limitation), kinematics limitations in X, Y, and Z axes, physical ability to run simultaneously 5 axis tool paths, and tool holder.

The characterised machine data need to be taken into consideration to define the process resources (tool) and process parameters (spindle speed, power required for the cutting operation, etc,); as well as, to generate the tool path (collision free with respect to the cutter and holder) in the CAM system. Thus, these data are further handled in the form of constraints.

The milling cutter type must be selected in accordance with the machining range and operation, workpiece material, initial block dimensions, the characteristics of the machine tool (tool holder, max. spindle speed). The manufacturing throughput time (where a short throughput time may required faster cutting speeds, thus a better tool performance) and the manufacturing target cost.

In order to select the appropriate milling cutter geometry, the fact that a higher axial depth of cut generates chatter vibration must be taken in account. Thus, the process chain developer defines FR114/DP114 as follows.

FR_{1141}= Assure that the tool is strong and rigid enough to resists cutting forces

DP_{1141}= Cutting tool material for machining high strength part

FR_{1142}= Minimise thermal load on the tool cutting edge and welding between tool and chip (BUE formations) to increase machining accuracy

DP_{1142}= Tool coating or insert type which can resist heat and adhesion

FR_{1143}= Assure dimensional requirements can be achieved

DP_{1143}= Tool diameter and length (L/D ratio)

FR_{1144}= Assure a uniform chip formation/ chip breakability

DP_{1144}= Number of teeth and tool helix angle

FR_{1145}= Minimise self exited chatter vibration

DP_{1145}= Irregular tooth spacing (variable pitch angle)

In accordance with the following constraints:

C_1= Manufacturing target cost

C_2= Manufacturing throughput time

C_3= Workpiece material

C_4= Dimensions of initial block (raw material feature)

C_5= Tool holder

The design equation representing the interaction between the FRs and DPs is as follows.

$$\begin{Bmatrix} FR_{1141} \\ FR_{1142} \\ FR_{1143} \\ FR_{1144} \\ FR_{1145} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & X \\ X & X & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{1141} \\ DP_{1142} \\ DP_{1143} \\ DP_{1144} \\ DP_{1145} \end{Bmatrix} \quad (9)$$

where [A] is a triangular matrix, thus it is a decoupled design.

From the design equations one can realise that the material selected for the tool may also minimise the thermal load on the cutting tool edge and the welding between the tool and chip. Thus, an extra tool coating may be not required.

The fixture must be selected in accordance with the dimensions of initial block (raw material feature). The fixture must anchor the workpiece effectively for the machining operation to avoid vibration due to the generated cutting forces.

The maximisation of the productivity and the surface finish is possible by suppressing chatter vibration and minimising airfoil deflections during the machining process. The tool geometry previously selected is influencing the minimisation of chatter, but the complete suppression will be achieved by selecting the correct spindle speed value. Thus, FR_{117}/DP_{117} is decomposed as follows.

FR_{1171}= Minimise chatter intensity

DF_{1171}= Spindle speed definition (S)

FR_{1172}= Assure a constant cutting force to minimise airfoil deflection

DP_{1172}= Feed rate definition ($V_f=f_z*z*S$)

The design equation representing the interaction between the FRs and DPs is as follows.

$$\begin{Bmatrix} FR_{1171} \\ FR_{1172} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_{1171} \\ DP_{1172} \end{Bmatrix} \quad (10)$$

where [A] is a diagonal matrix, thus it is a uncoupled design.

The spindle speed can be defined based on a stability lobes diagram with variable depth of cut. Once the process is stabilized, milling force modelling can be used to determine the feed rate corresponding to a reference force value (maximum value). The selected speed for the highest depth of cut and the optimised feed rate will determine the maximum material removal rate, while avoiding the effects of chatter vibration like poor surface finish, and dimensional errors on the part.

The tool path must be generated to fulfil dimensional and shape requirements which include airfoil thickness and milling crest geometry tolerances; and in accordance with the machine limitations and the milling cutter type and geometry. On the other hand, the tool path must be determined considering the kinematics of the tool exits from the workpiece to avoid burr formations by following these criteria: avoiding exits of inserts, controlling exit order sequence and sequencing process steps to create any burrs on a less significant edge, etc.

FR_{12}/DP_{12} is specified as follows:

FR_{12}=Minimise quality assurance cost

DP_{12}= Steady process to target design specifications

The manufacturing process stability has influence on the cost and delivery time of compressors and turbines. The quality of the machined surface is useful in diagnosing the stability of the machining process, where a poor surface quality may indicate tool wear, burr formations, chatter vibrations, etc. The integrated process chain determines the required process resources and parameters to assure the surface quality and minimise further process adjustments, thus assuring that the part is delivered on time and meets the design specifications.

Finally, FR_{13}/DP_{13} is defined as follows:

FR_{13}=Minimise material costs

DP_{13}= Optimal material utilisation

The characterisation of titanium alloys allows the material data quality and machining productivity to be increased. The material data will be characterised in the technology data catalogue (TDC) to facilitate their retrieval when designing the integrated process chain. The structuring of knowledge and precise knowledge exchange is enhancing effective optimization of a process chain for manufacturing Ti6Al4V components.

The first timed sequence sub-processes for machining the macro component have been designed. Further sub-processes for machining micro features can be designed in a similar way; since tool wear and machining accuracy were already defined as relevant functional requirements. On the other hand, the material data are identified as design parameters, thus the fact that the material for micro machining is heterogeneous will be taken in account during the design of the process chain. The design of a process chain for micro features is illustrated in the case study presented in section 4.

3.2 Technology data catalogue

It is proposed that the design and development of a technology data catalogue (TDC) is a key component of the integrated methodology. The main aims of the TDC are gathering, retrieving, structuring, processing and sharing relevant engineering knowledge in an intelligent way. The TDC will also provide structured information about the best practice settings of the manufacturing system. Data sources are defined and a suitable knowledge ontology is created in order to store the relevant implicit and explicit knowledge generated at the different levels in the manufacturing domain. The definition and use of ontologies will eliminate conceptual and terminological confusion and lead to a shared understanding [11], solving problems of semantics; while the use of semantic nets will ensure the effective sharing of the final process chain and manufacturing information. Further, they will facilitate the dynamic navigation through the information, the information visualization and the sharing of information through formal procedures. Moreover, the advantages of the TDC are:

- Facilitate the extraction of information selectively about process resources (machine tool, tools, etc.), process parameters (feeds and speeds) and process constraints (spindle power).
- Improve and increase information by recording relevant operational knowledge avoiding that this knowledge remains as personal hidden knowledge; and by documenting information from successful used cases.
- Ensure consistency of the information and avoid redundancies.

The technology data catalogue, defined as a knowledge platform, consists of an ontological system and a database. In the ontological system, the manufacturing ontology and the semantic nets are built. The ontology development follows the design criteria defined by [12], and the design process suggested by [13]. The semantic nets provide external data access to the TDC. Thus, the fast heterogeneous information access for handling process requirements is enabled. Moreover, the development of semantic nets further the use of a platform for knowledge processing which allows the integration of various data sources, the development of tacit knowledge, and the flow of information into tasks and processes. The shared terms collected in the database include:

- Manufacturing operations (applicability of parameter settings for manufacturing setups and relevant measuring parameters),
- Machining processes or technologies,
- Process resources (material properties, machine tools, tools, fixtures, etc.),
- Process kinematics (tool access direction),
- Process constraints,
- Manufacturing productivity parameters,
- Manufacturing performance parameters.

As a pull mechanism to fulfil the TDC, interviews of shop floor operators will be part of a formal procedure to avoid the possibility that operational knowledge will remain personal hidden knowledge. Another way of filling up the TDC is by extracting and modelling the relevant information from successful used cases. To enhance the applicability and dissemination of the gathered information, the exchange of data from TDC via web portal is functional.

4 CASE STUDY: MANUFACTURING OF MICRO FEATURES

Micro machining experiments on a Ti6Al4V alloy were conducted. The machining information obtained from the experiments was characterised in the TDC. Then, the characterised data was retrieved and used for the determination of the suitable technology to fulfil multiple functional requirements simultaneously. Three experiments were carried out on the Ti6Al4V alloy utilising three different technologies: drilling, laser, and electric discharge machining (EDM). The necessary machining operations are defined to generate micro holes of three different diameters Ø=1, 0.5 and 0.3mm, and depth range from ≈ 1 to 10mm. Micro holes were chosen as these micro features have applicability for complex components manufacturing in several industries, e.g. the automotive and aero space industries. The diameter accuracy, the roughness of the hole walls and the roughness of the part surfaces were measured. From the measurements, it can be highlighted that the best diameter accuracy was obtained from the laser drilling experiments; dimensional deviation on the EDMed holes was mainly produced by the spark gap, while deviation on the drilled holes was generated by the tool diameter. Laser was the fastest technology compared with milling and EDM, as it may machine the three holes diameters at the same time; also less non productive time was observed due to no tool requirements, and thus no tool changes. In contrast, drilling requires the use of four different tools to pre-drill and drill three different diameters. Tool wear of 7-8% was observed when machining the holes with a diameter of Ø=1mm. Moreover, big aspect ratios (e.g. aspect ratio=16) had higher cutter bending. This bending causes an eccentric movement of the tool and tool breakage. However, this technology provided better surface quality on the walls of the holes (e.g., Ra pin 1mm= 0.231µm) compared with the surface quality obtained from EDM (e.g., Ra pin 1mm= 0.460µm). This may be of crucial importance when drilling for instance cooling holes on turbine blades where the roughness may influence the air flow. On the other hand, drilling and EDM machining do not affect the surface around the machined holes as lasers do; the surface roughness increased from 0.2 to 0.4µm. This requires extra processes where a kind of protection (e.g. wax) is applied around the zone where holes will be machined, and then it is cleaned after the machining. In summary, the advantages and disadvantages of the three technologies have been highlighted; while laser experiments provide better accuracy, drilling experiments presented better surface quality on the hole-walls. When the machining information generated from the three technologies is characterised in the technology data catalogue, different scenarios are created. If only one functional requirement was defined by the process chain developer, e.g. maximising dimensional accuracy, then the machining information from the laser process must be retrieved from the TDC. If the functional requirement was defined as the minimisation of the surface roughness on the hole-walls, then the machining information from drilling experiment must be retrieved from the TDC.

But if two functional requirements must be simultaneously fulfilled by the machining process, e.g. dimensional accuracy and surface quality when machining micro holes of different aspect ratios, then a tool to facilitate the selection of the adequate machining process is required.

Such a tool is provided by the process chain developer, through the information axiom.

Assume that the functional requirements for the machining of features of Ø= 1mm were defined as follows.

FR1= Diameter deviation from nominal<0.01mm

FR2= Hole-wall roughness<0.30microns

FR3= Change on surface roughness around holes< 0.01microns

While these functional requirements specify the design range, the capabilities of the technologies summarized in Table 1, represent the system design.

Once the design and system ranges are defined, the areas with a common range between each value from the design and each of the values from the system are identified, and the probabilities of satisfying each functional requirement are analysed. Then, the information content for each FR is calculated using the equation (5), as shown in Tables 2-4.

The information content of the system is calculated using equation (6), as shown in table 5.

It can be concluded from tables 2-5, that the laser machining satisfies the first functional requirement, achievement of minimum diameter deviation from nominal, when the diameter of the hole is 1mm. Drilling satisfies adequately the second functional requirement, achievement of good surface quality on hole-wall, when the diameter of the hole is 1mm.

Machining technology	**Diameter deviation (mm)**	**Hole –wall roughness (μm)**	**Surface roughness (μm)**
Drilling	0.013	0.23	0.011
Laser	0	No information available (NA)	0.245
EDM	0.03	0.46	0.008

Table 1: Technology capabilities obtained from experiments for micro holes of Ø= 1mm.

Option	**Design range**	**System range**	**Area with common range**	**Prob. of satisfying FR_1 (P_1)**	**Information content (I_1)**
Drilling	<0.01	0.013	0.01	0.77	0.38
Laser	**<0.01**	**0**	**0.01**	**1**	**0**
EDM	<0.01	0.03	0.01	0.33	1.60

Table 2: Calculation of the information content for FR_1.

Option	**Design range**	**System range**	**Area with common range**	**Prob. of satisfying FR_2 (P_2)**	**Information content (I_2)**
Drilling	**<0.3**	**0.23**	**0.23**	**1**	**0**
Laser	<0.3	NA	0	0	*Infinite
EDM	<0.3	0.46	0.3	0.65	0.62

Table 3: Calculation of the information content for FR_2.

Option	**Design range**	**System range**	**Area with common range**	**Prob. of satisfying FR_3 (P_3)**	**Information content (I_3)**
Drilling	<0.01	0.011	0.01	0.91	0.14
Laser	<0.01	0.245	0.01	0.04	4.61
EDM	**<0.01**	**0.008**	**0.008**	**1**	**0**

Table 4: Calculation of the information content for FR_3.

Option	**I_1 (bits)**	**I_2 (bits)**	**I_3 (bits)**	**Isys (bits)**
Drilling	**0.38**	**0**	**0.14**	**0.52**
Laser	0	Infinite	4.61	*Infinite
EDM	1.60	0.62	0	2.22

Table 5: Calculation of the total information content.

*Infinite= it cannot satisfy FR / The design range and the system range do not overlap.

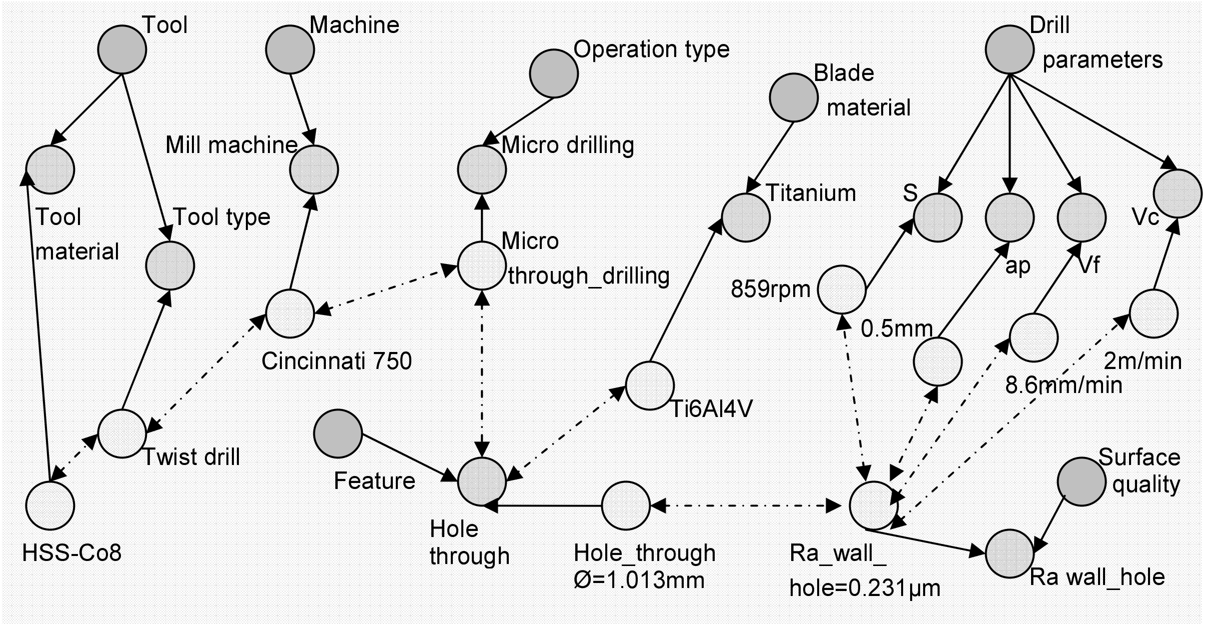

Figure 3: Semantic net for drilling a hole through of diameter=1.01mm and hole wall roughness= 0.23µm.

EDM satisfies the third functional requirement, minimisation of the change on surface roughness around holes before and after the machining. But, drilling is selected as the best technology since it has the highest probability for satisfying all functional requirements simultaneously, with the least amount of information. The semantic net retrieved from the TDC for drilling the micro holes is shown in Figure 3. It provides structured information about the best practice settings of the manufacturing system (tool, machine, parameters) to be used by the machine operator at the workshop.

5 SUMMARY

The integrated methodology, proposed in the previous sections, was successfully validated. It was demonstrated that the integration of the process chain developer and the TDC assures that the adequate technology is used for a specific micro machining operation. Micro features were machined on a Ti6Al4V alloy utilizing three different technologies: drilling, laser drilling, and electric discharge machining (EDM). The necessary machining operations were defined to generate micro holes of three different diameters Ø=1, 0.5 and 0.3mm, and depth range from ≈ 1 to 10mm. It was observed in micro machining that the tools have greater influence on the features accuracy than in conventional size machining. The three technologies present advantages and disadvantages; e.g., while laser experiments provide better accuracy, drilling experiments presented better surface quality. Different technologies with different parameters fulfil different requirements. If these parameters are characterised in the technology data catalogue many scenarios will be obtained which will not facilitate making the decision of which technology is the best for the process chain. Therefore, the technology data catalogue requires an approach to define systematically the process requirements (design range) and the actual process performance (system range) and find out methodically the best process without arbitrary weighting factors. The process chain developer provides such a decision tool, by applying the information axiom.

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