I, Anish Dantale, hereby submit this original work as part of the requirements for the degree of Master of Science in Mechanical Engineering.

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A Group Technology Based Approach for Application of Design for Manufacturability (DFM) Rules

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A Group Technology Based Approach for Application of Design for Manufacturability (DFM) Rules

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Abstract

As the industry moves towards a lean manufacturing and product development paradigm, manufacturability tools need to evolve. The various stages of product development need to be streamlined to ensure cost reduction and reduced time to manufacture. Traditional approaches for applying design for manufacturing and assembly (DFMA) have relied on the knowledge and intuition of the designer resulting in sporadic application of the DFMA process. This research is an effort to apply Group Technology (GT) based part classification and coding system to identify geometric features of the part and map them to appropriate Design for Manufacturaibility (DFM) rules. This mapping and subsequent development of GT Classification was performed specifically to be used with existing CAD packages. To start with, a consolidated set of all DFM rules for parts manufactured by machining process were collected from literature and combined with additional rules developed in house. Next, appropriate correlations between these DFM rules and the geometric and material features of the parts were made. A new GT based part coding system was then developed to map the specific geometric features of machined parts to the DFM rules. The system was implemented as an add on within the Solid Edge CAD package and two example parts were demonstrated using the system.
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Chapter 1: Introduction

1.1 Motivation for the Thesis

Decisions made during early design process have a significant impact on the manufacturability and the cost of the part. Traditionally, the approach for product development has been what is called the “over the wall approach” [1] as illustrated in figure 1.

The attitude of the designer was “We design it, you build it” [1] when referring to the manufacturing department. Traditionally, there was very little communication between the design and the manufacturing departments during the design phase of the product development. This led to multiple design iterations increasing the time to market. Recently, several approaches have been proposed by researchers [2-4] based on concurrent engineering, concurrent design, and design for manufacturing and assembly to expedite the early stages of product development cycle.
To address the gap between design and manufacturing stages, the National Research Council [5] made several recommendations in their report to address this problem. The two salient recommendations are

“Engineering Design: The Department of Defense should develop interoperable and composable tools that span multiple technical domains to evaluate and prioritize design alternatives early in the design process”. [5]

“The creation of tools for automated analysis of design alternatives”. [5].

These suggestions from the report highlight the lack of tools that span multiple domains of product development process.

1.2 Objective

This research is an effort to apply GT based part classification and coding system to identify geometric features of the part (design stage) and map them to appropriate DFM rules (manufacturing stage). To start with, a consolidated set of all DFM rules for parts manufactured by machining processes were collected from literature [6]. Next, appropriate correlations between these DFM rules and the geometric features of the parts were made. The digits or the combination of the digits in the proposed GT code were then mapped to each of the DFM rules.

The flow of the process is as follows: given a part design, the proposed GT code is assigned based on its geometric features. This assigned code is used to retrieve the relevant DFM guidelines specific to the part. The designer determines which identified DFM guidelines have been violated and makes modifications to the design of the part in question without the need for an extensive design review phase. The GT code for the redesigned part is once again verified for violations until the designer is satisfied. It should be noted that this is a proof of concept only and
takes into consideration only a defined set of DFM guidelines and associated mapping with GT codes. As the scope increases to include more DFx guidelines, the coding and the subsequent mapping should be revisited to avoid any contradictory guidelines.

1.3 Scope of the Thesis

For this study, the scope is limited to machined components (Rotational and Prismatic). It provides a good subset of DFM guidelines to be reviewed yet provide the most variety in terms of the features that can be manufactured. Automation of GT code assignment to the part is not included in this research.

1.4 Overview of the Thesis

The Thesis is organized in 6 chapters. Chapter 1 introduces the problem statement, discusses the motivation behind it, and introduces the need for the research. Chapter 2 reviews the literature of GT and DFM and discusses the aspects of GT coding and classification structure. Chapter 3 explains the methodology of mapping the reviewed DFM guidelines to an appropriate GT coding system and elaborates on the details of the coding structure. Chapter 4 gives a description of the DFM Guidelines Advisory Macro. This chapter presents the workflow of the application, the instructions to use it and the results obtained for the application. Chapter 5 presents the application of the GT based DFM analysis on three examples of different types of parts where GT based DFM violations and possible mitigations are identified. This also forms the results section of the thesis. Finally, Chapter 6 states the conclusions from the current work and presents the scope of future work. Appendix has a list of the DFM guidelines used for this thesis and their mapping with the GT Codes.
Chapter 2: Literature Review.

2.1 Group Technology

Group technology is a manufacturing philosophy for segregating parts, tools, assemblies having similar geometric, functional or part specific characteristics [7-10]. Parts are classified based on their shape, function, size or materials and are grouped together to take advantage of similar production requirements. With the keynote publication by Mitrofanov [10], GT was widely accepted across Russian industries, and later throughout Europe after a translation in English. Thereafter, Burbridge [11] expanded on the production flow analysis aspect of GT. Ham [12] performed similar research in production flow analysis and concurrent manufacturing applications of GT.

A GT code is usually a string of numbers and letters, each of which represents a distinct characteristic about the part in a concise way [8, 9, 13]. A GT coding system allows the classification of parts into groups based on the similarities of geometric attributes, designs and process plans [14]. This in turn allows the user to search the database for parts with similar designs and attributes and generate new designs using a knowledge-based system [14]. The GT code can be also used to evaluate manufacturability of the part design.

2.2 Classification and coding

For an efficient GT system, classification and coding provides an essential and effective tool to form part families based on specific parameters and code digits. Classification means “sorting parts into groups thus separating parts with similarities and/or dissimilarities based on some
predetermined parameters” [12] whereas coding refers to numbers, letters, or a combination assigned to a part to identify its part family.

Most GT systems are “Home Grown” to suit the needs or purposes of a localized environment. A well designed and properly adapted classification and coding system provides a foundation for an efficient design retrieval system. The purpose of a good coding system should be to:

1. Determine the critical attributes that reasonably characterize the part.
2. Partition the part database in a manner consistent with the frequency distribution

2.2.1 Code Structures

The heart of a GT system is the development of a coding structure that will capture part information specific to the application. There are three basic types of GT coding systems: (1) Hierarchical (2) Chain, and (3) Hybrid [13, 18]. In a hierarchical structure, each character in the code has a unique relation with the preceding characters. In case of a chain structure [8], each character is a distinct representation of critical information without depending on the previous digit of the GT code. Lastly, the hybrid structure incorporates attributes of both, hierarchical and chain structures. Most of the developed GT coding systems adapted hybrid structure to leverage advantages of both structures.

In general, part similarities can be divided into 2 types: (1) Design attributes- consisting of geometry, size, and shape of the part; (2) Manufacturing attributes-e.g. sequence of processing, manufacturing process, and machine used [15]. GT coding efficiently categorizes the parts into part families based on geometric or processing similarities or both. [19]

Two major and influential classification and coding systems are reviewed.
1. Opitz system [16]
2. MICLASS system [17]

2.2.2 The Opitz classification system

The classification system developed by H. Opitz [16] at the University of Aachen in Germany is a keynote effort and one of the most well-known of the in GT classification and coding. The Opitz system uses a sequence of numbers and letters e.g. 12345 6789 ABCD. The base code is 9 digits, which can be extended by 4 digits. The root code conveys design and manufacturing information. The interpretation of the nine digits is illustrated in figure 2. The first 5 digits of the base code are the form code (design attributes). The next 4 comprise the supplementary code which describes the manufacturing attributes. The extra 4 digits, the secondary code, identify the production operation code and sequence.

![Figure 2: Structure of the Opitz System [16]](image)
2.2.3 The MICLASS System

MICLASS stands for Metal Institute Classification System. It was introduced in Europe and later in the United States in 1974 [17]. The MICLASS system is used to automate design production and management functions such as drawing standardization, drawing retrieval, process routing standardization, process planning, tool selection for a part, and for machine tool investment analysis. The MICLASS is flexible, ranging from 21 to 30 digits, and adaptable to a specific organization. The first twelve digits represent the following attributes 1: Main shape; 2-3: Shape elements; 4: Position of shape elements; 5-6: Main dimensions; 7: Dimension ratio; 8: Auxiliary dimension 9-10: Tolerance 11-12: Material.

Figure 3: MICLASS Classification Structure Overview. [17]
2.3 Design Applications of GT

It is often difficult to retrieve similar parts in large manufacturing organizations which have not incorporated GT, although legacy products exist in their database. This leads to design duplication where a new part is designed from scratch even though similar legacy parts already exist in the part database. GT coding of parts can be utilized to avoid this duplication by efficiently retrieving legacy designs from the part database. GT also assists in standardization of designs as mentioned in the research by Dowlatshahi and Nagaraj [15]. These attributes of GT help in speeding up the overall design process of a part and to reduce the possibility of design proliferation. An efficient GT system addresses this issue [15] resulting in reduced time and effort required for a new design.

2.4 Design for Manufacturability

The concept of DFM was developed over the years to bridge design and manufacturing. Several similar approaches have been utilized by numerous organizations. Bralla [6] points out that the terms producibility and manufacturability indicate the ease with which a component can be manufactured. He defined DFM as

“In a broad sense, DFM includes any steps, methods, or systems that provide a product design that eases the task of manufacturing and lower the manufacturing cost” [6]  

“In a somewhat more specific sense, design for manufacturability is primarily a knowledge based technique that invokes a series of guidelines, recommendations or rules of thumb for designing a product so that it is easy to make” [6]
With these definitions in mind, the process of developing DFM in any design system has to follow certain techniques. Zhao and Shah [20] looked into the three ways in which DFM can be applied:

1. Cross functional teams

2. Design /DFM manuals

3. Software tools.

Software tools (CAD/CAM) tools are the most efficient methods of the three. Tools are the least time consuming and require minimal effort compared to the other two methods. Recently, Chiu [21] looked into a detailed literature review of the DFM research and categorized focus areas as 1. Guidelines 2. Checklists 3. Matrices 4. Mathematical model 5. Methods. Checklists and matrices are manual processes and have to be revisited to get the complete results, thus resulting in a longer time to get the results. Use of guidelines and mathematical models facilitate ready results that can be quickly implemented. The set of typical DFM guidelines are either generic, applicable over a broad range of products, or formulated with a specific type of manufacturing process/part family in mind. Phal [22] and Hegde [23] created rules primarily for sheet metal parts. Anderson [24] formulated rules for DFM and then later expanded to include design for high quality, lean manufacturing, and design for low cost and design for quick and fast production. Similar DFM rules and guidelines were suggested by Corbett [25], Edwards [26] and Hamidi [27] each adding their variations of the rules and guidelines. But of all these, the one that provides the most comprehensive and detailed guidelines are the once compiled by Bralla [6]. He explained every manufacturing operation in detail and provided guidelines, rule of thumbs, detailed analysis of manufacturability related to each individual operation based on the
recommendations of subject matter experts. Turek [28] in his dissertation compiled a comprehensive list of DFx rules based on the research.

2.5 Role of GT and DFM in Product development:

A design project, whether a new product development or an existing design modification, follows a set of guidelines and principles that are aimed at improving the manufacturability of the components. These guidelines, though not universally followed across different organizations, have some basic elements [23, 29].

- Design guidelines and objectives.
- Modeling and simulation
- Informal design review
- Design tools and CAD
- Formal design Reviews
- Manufacturability test.

The elements that have the most impact on the final manufacturing costs are the Design guidelines and objectives, modeling and simulation and informal design review. These stages offer the most design flexibility and influence the subsequent design costs [29].

With the importance of design guidelines established, maximum effort is invested in in this stage to ensure good product design. To achieve this, a set of guidelines and rules are to be followed to ensure the manufacturability of final product at low cost. DFMA is a tool that can be used to ensure the manufacturability.
Design rules are developed by the combined effort of the manufacturing and the design departments. Once the set of rules are finalized, these rules are guidelines for the design department. Any variation from these design guidelines are flagged and design modified to fit them. This is the stage where the design tools and the CAD software play an important part. Using these as preemptive tools to follow and implement the design rules and guidelines, the tools can prevent mistakes and prevent costs from adding up downstream.

CAD workstations as a design tool offer an important early intervention point for enforcing the design rules and guidelines. The DFM Guidelines and the overall DFM analysis of the product development cycle can be performed using these CAD tools.
Chapter 3: Methodology

3.1 Need for a new GT Coding system

A DFM based GT coding system is required primarily due to the following reasons:

1. The current systems that are based on the part features do not provide sufficient feature information to integrate DFM rules and flag violation.
2. The existing GT coding systems are suited for a specific purpose (e.g. feature based). Most of the systems are developed in house by the industries catering to their specific product lines.
3. Existing GT systems only provide a high level classification with little to no consideration of the relationship between the features or their measurable attributes.

The new classification and coding system presented here is designed to overcome these limitations and allow for a robust and accurate mapping with the DFM guidelines. The OPITZ [16] system provides the basic framework to build upon the fundamental features.

3.2 A DFM based GT coding system

The focus of this research is to bring together and correlate the functionality that a design engineer has in mind to the features that are to be manufactured. Because part functions are related to the part features of the product, design for manufacturability guidelines strive to provide the connectivity between the functional requirements of the designer and the manufacturability requirements of the manufacturing engineer.
Each feature, in turn, is produced by a manufacturing process. Figure 4 is an example of a flanged mount with a slit for supporting a shaft and the associated manufacturing processes for each feature. With features as a common platform for relating the design and manufacturing stages of the part, the new GT classification and coding system is developed to describe the features that define the manufacturability of the part.

<table>
<thead>
<tr>
<th>Design Function</th>
<th>Feature</th>
<th>Manufacturing Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tighten Shaft</td>
<td>![Image]</td>
<td>Milling</td>
</tr>
<tr>
<td>Clamp Shaft</td>
<td>![Image]</td>
<td>Drilling; Boring</td>
</tr>
</tbody>
</table>

Figure 4: Relation between functional design and manufacturing process (adapted from [30])

3.3 Review of DFM Guidelines

The first step in the process of creating a mapping system and developing a DFM based GT coding system was to undertake a comprehensive review of the DFM Guidelines. DFM guidelines are grouped by either the manufacturing process, such as forming, machining, and stamping, or by the characteristics of the part e.g. metallic vs nonmetallic.[6] This gives only a partial view of what these guidelines represent. A closer examination reveals secondary
classification of the DFM guidelines based on the auxiliary characteristics they represent. The DFM guidelines reviewed, in general, fall under the following categories where the top level is classified by features, which can be broken down further into the following attributes.

- Features
  - Measurable attributes
  - Characteristics
  - Arrangement
  - Minimization of operations
  - Absolute position
  - Relative position
  - Hierarchy

3.4 Mapping

The process of mapping is the critical component in ensuring the efficient correlation between the DFM guideline and the GT classification and coding. As previously stated, the Opitz [16] system was the basis for developing the new system. To create the mapping, the iterative process described in figure 5 was followed for all the DFM guidelines reviewed.

![DFM and GT mapping Process](image)

Figure 5: DFM and GT mapping Process
Once the mapping is complete for all the guidelines, a database of the GT Codes mapped to the DFM guidelines is created. This database acts as the primary rules engine to fire the DFM appropriate guidelines based on the input of the GT codes associated with the part. To elaborate the process of how relevant DFM rules are fired, consider the example shown in Figure 6.

![Figure 6: Mapping Procedure](image)

The first step in the process is to assign a GT code to a part as illustrated in Figure 6. This is performed by identifying individual features of the part starting from the primary shape. Subsequently, the assigned GT code “2-3100-10004-7-0-00-’7’-100-‘M24X1.5’-0 ’20’ ’3’ ’1.55’-60” is associated with the part number. To an end user, this is the GT code for the part. But in order to identify the DFM guidelines, internally, each digit at each position has its unique CODE ID, which maps to the unique Rule ID of the DFM guideline in the database. The unique CODE ID
identifies the 1) position and 2) the value of the code at that position. For example, consider code “2” at position 1 has a unique CODE ID 2; code “3” at position 2 had a CODE ID 8; code “1” at position 3 had a CODE ID 15 so on and so forth. The detailed unique identifiers for each CODE ID corresponding to the digit are available in Appendix 1.1. The CODE IDs are not visible to the end user but are critical in order to understand the mapping as the lookup in the database is based on it. All the Rules with their RULE IDs are described in Appendix 1.2. Appendix 1.3.1 presents the mapping of all CODE ID to the RULE IDs, and Appendix 1.3.2 has the mapping of all RULE IDs to a CODE ID. Thus we see there is a many to many relational mapping between CODE ID and RULE ID.

Coming back to the example in Figure 6, the GT Code “2-3100-10004-7-0-00-’7’-100-’M24X1.5’-0 ‘20’ ‘3’ ‘1.55’-60” is interpreted by the system as a string of CODE IDs as follows:

```
 2  8  15  18  28  43  52  62  65  83  91  94  100  105  107  129  130
```

During the database lookup, these CODE IDs identify the guidelines that are applicable for the given input. There is also a check to see if there are any conditional guidelines that have to be triggered only when a particular ID is entered in the string. For the instance in figure 6, the RULE ID is listed under the CODE ID and the mapping is described in Table 1 and illustrated in figure 7.

<table>
<thead>
<tr>
<th>CODE ID</th>
<th>RULE ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>106</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>18</td>
<td>7</td>
</tr>
<tr>
<td>28</td>
<td>62</td>
</tr>
<tr>
<td>43</td>
<td>72</td>
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<td>52</td>
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<td>58</td>
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<td>72</td>
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<td>74</td>
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<td>91</td>
<td>55</td>
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<td>94</td>
<td>75</td>
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<td>100</td>
<td>57</td>
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<tr>
<td>105</td>
<td>76</td>
</tr>
<tr>
<td>107</td>
<td></td>
</tr>
<tr>
<td>129</td>
<td></td>
</tr>
<tr>
<td>130</td>
<td></td>
</tr>
</tbody>
</table>
The guidelines associated with this Rule IDs are presented to the designer as an output. After reviewing the guidelines and making appropriate changes to the part, the GT code is updated which in turn changes the code in the database. The next time the GT code is used to obtain guidelines, since some violations may have been rectified, the number of guidelines presented will be typically smaller than the previous instance.

### 3.6 Structure of the new coding system

A hybrid coding structure is best suited for a DFM based GT system. The proposed system uses design features as the basis for classification of the parts. Because design features are built upon the basic shape, the principal shape and size of the part form the core of the new system. The Opitz [16] system is one such coding system which accurately describes the parts based on their preliminary shape. This system is robust and after various iterations has proved to be a good reference point to several other GT classification and coding systems that have been developed since. The proposed system in this research is derived from and based on the Opitz [16] coding system. The coding system is developed in a way that it can be easily scaled, altered or modified.
based on the additions or deletion of DFM Guidelines. The mapping to DFM rules needs to be evaluated after every alteration.

The idea of using manufacturability knowledge in the early design stages is accomplished by identifying the design features using the GT code. The GT code in turn is mapped to a DFM guideline for that feature.

A total of 136 DFM guidelines for prismatic and rotational machined parts were reviewed and categorized from the relevant literature. Each of these rules were correlated with geometric manufacturing features of the part and subsequently mapped to the digits of the developed GT code.

The GT code developed is a sequence of alphanumerical characters, diverging from a primary root structure based on Opitz [16]. The root or the first digit of the GT code determines which category the part belongs to i.e. rotational or prismatic. All the subsequent digits are based on the initial digit. Using this approach, a new GT code system is developed for a cylindrical part comprised of 25 digits and a prismatic part described using 11 digits encompassing all the possible features that can be available on a given part. In the proposed GT coding system, each category is separated by a hyphen (“-“).

3.7 Coding Structure- Cylindrical Parts

The structure gives an overview of the different categories such as shape category, external features, internal features etc. for each digit position in a GT code. The new coding structure expands on the primary root structure of the Opitz classification system [16].
The new classification has 25 digits for rotational and 11 for prismatic parts compared to 9 in the original Opitz classification. It also expands on the original digit to describe more categories for each digit. The first digit is the same as the Opitz system used to classify the part class based on main shape with only minor changes to suite the current classification. From the second digit on, the new classification expands on the base system and tries to describe the part in more details. For instance, Digit 2 in the Opitz classification describes the external shape of the part. The new classification uses 4 digits to describe the main external shape of the part compared to 1 for Opitz classification illustrated in figure 2. The first digit of these 4 uses the mostly same as Digit 2 in the original but adds some more categories. The rest of the 3 are external shape details not present in the original. Same is the case with digit 3 (internal features) in the Opitz classification that expands to digit 6-10 in the new classification thus significantly expanding on the details described by the GT Code.

Each digit position in the new classification has a range of possible options that will describe the feature in detail. For instance, if the first digit in a GT code is 2, the part is rotational with an L/D ratio less than ‘3’. The second digit defines principal shape from 0-8, with 0 being no features; 1-stepped part with straight edges and so on. The third digit describes the corner specification of an external feature from a range of 0-4 and so on. For features with greater than 9 options for their description, the range continues with alphabets starting from A onwards (i.e. 0-9, A-Z etc.). The coding structure specifies the major categories of features, description of its place holder and the possible range of values of a cylindrical part.

- Shape Category
  - Digit 1 (1-4)
• L/D Ratio < 0.5 (Thin Disks)
• 0.5 < L/D Ratio < 3 (Medium Length)
• L/D Ratio > 3 (Long Components, Shafts)
• Components with Axis Deviation

• External Features
  • Digit 2 (0-8) - Principal Shape
  • Digit 3 (0-4) - Corner Description
  • Digit 4 (0-8) - Groove/Keyway Details
  • Digit 5 (0-D) - Surface Finish

• Internal Features
  • Digit 6 (0-9) - Principal Shapes (Internal)
  • Digit 7 (0-5) - Corner/Bottom description
  • Digit 8 (0-2) - Groove Details
  • Digit 9 (0-D) - Surface finish
  • Digit 10 (0-4) - Internal Hole Ratio

• Milling/Surface Features
  • Digit 11 (0-9) - Milled/Shaped Surface features

• Auxiliary Holes/Features
  • Digit 12 (0-5) - Auxiliary Features
  • Digit 13 (0-2) - Auxiliary feature intersection details

• Thread Details
  • Digit 14 (value) - Thread length
  • Digit 15 (0-2) - Thread Clearance
  • Digit 16 (0-2) - Edge Finishing
  • Digit 17 (0-3) - Interruptions
  • Digit 18 (value) - ISO Specs

• Key Details
  • Digit 19 (value) - Type of Key
  • Digit 20 (value) - Shaft Diameter
  • Digit 21 (value) - W Value (Key Width)
  • Digit 22 (value) - H Value (Key Height)
  • Digit 23 (value) - Length of Keyway

• Stock
  • Digit 24 (0-6) - Stock Type

• Surface Coating
  • Digit 25 (0-8) - Surface Coating
3.8 Coding structure- Prismatic parts

Similar to the cylindrical parts, prismatic classification is elaborated using the same structure; place holder and possible range of values given in brackets.
• Non Rotational Components (Long)
• Non Rotational Components (Cubical)
• Overall shape
  • Digit 2 (0-3) Principal Shape
• Bores
  • Digit 3 (0-5) Bores
  • Digit 4 (0-2) Bore Ratio
  • Digit 5 (0-4) Bores Details
• Corner Specifications
  • Digit 6 (0-2) Corner details
• Groove
  • Digit 7 (0-2) Groove
• Surface machining
  • Digit 8 (0-7) Surface Machining
• Auxiliary holes
  • Digit 9 (0-4) Auxiliary Holes Axis and Classification
• Surface Finish
  • Digit 10 (0-D) Surface Finish
• Stock
  • Digit 11 (0-3) Stock Type
Chapter 4: DFM Guidelines Advisory Macro

In this chapter, the GT code associated mapping and the DFM violations are demonstrated using Solid Edge® modeling system. The idea, however, can be implemented using any CAD platform and is not tied specifically to Solid Edge®. Although the mapping of the DFM guidelines and the associated GT code is relevant to the part model, it should be noted that this is just a proof of concept and the database is in no way all-encompassing and ready for final production implementation.

The tool used to demonstrate the working of the proposed GT and DFM system has been developed as a Solid Edge® (SE) macro. Solid Edge® provides a flexible framework to include external tasks and detailed applications in the main application. The Solid Edge® [30] API for .NET framework uses core COM APIs to interact with the object. These COM libraries are available to automate Solid Edge®. The API’s provide detailed geometric information about the part that is useful in feature extraction. For this thesis however, only basic part geometry information is extracted and feature recognition algorithms are not considered while developing the GT code.

Currently the GT code is being assigned manually by selecting individual features and digits in the interface of the macro. The user selects individual digits based on the feature category and proceeds to the next available feature. While it would be ideal to have an automated assignment of GT code based on the feature recognition, automated feature extraction is beyond the scope of this research and is a part of future work and extension of the research.

The Code assignment process is made simple enough to minimize variation in the final GT code assigned to a part by different individuals. That being said, there may be some variations and
these can be rectified only by exposing it to a large user base and making incremental changes to the assignment process. The SE macro execution has two workflow components. Figure 10 explains the steps involved in assigning a GT code to an existing part.

**Figure 10 : GT Code Assignment**

Based on the part CAD geometry, the user identifies and selects the feature from the feature GT code library associated with the digit. Based on the selection, an appropriate GT code digit is assigned to the feature. Along with the digits, feature specifications, such as thread length, length of the keyway, diameter of the shaft etc. are also required to be entered by the user based on the features previously selected. Once the selection of features is completed, the final GT code is assigned to the part. The application interface used to assign a GT code to a part is explained in the following section.
4.1 Application Interface

The user interface developed as a Solid Edge® macro is available when a new part is opened in the SE application. The part opened will provide attributes such as part name and associated GT code. If it exists, the macro will display the existing GT classification code. If not, the designer has an option to assign a new GT code to the part based on the various geometric features and onscreen library templates for each digit. Based on the part type, corresponding detailed options will be available to the user as shown in figure 11.

![Figure 11: Manual Selection of each digit based on feature types.](image)

After a GT code is assigned to the part, the next step is to extract DFM rules and guidelines applicable to the part based on the mapping. The macro internally uses the digits in the assigned GT code to identify the geometric features of the part and associates them with relevant guidelines. With the guidelines as suggestions, the designer now makes appropriate decisions to determine which guidelines have been violated and incorporate modifications to the part design accordingly as illustrated in 12. The rule advisory screen as shown in figure 13 is presented to the user for design review and possible design violations.
If a GT code is already assigned to the part, a designer can obtain DFM guidelines that are deduced from the classification code. The guidelines are displayed within the SE environment and also available to export as a report. Figure 13 shows the sample GT code along with the associated DFM guidelines available for design review.
Chapter 5: Examples of GT based DFM advisory applications

This chapter presents the application of the GT based DFM analysis on three examples that demonstrate DFM violations. The violations are analyzed and used to make mitigations to the design and update the part. The mapping for the rules to guidelines is also shown for each example.

Example 1: Purchase part, commercially available.

This example in figure 14 is a cantilever shaft, stepped on both sides, threaded, with retaining ring groove.

Figure 14 : Example 1 - Purchased part [30]

Part name: FXBA3-7-F3_body.par

Source: Misumi USA. [30]

GT Code: 2-7213-00000-200-'2.78'221'M3x0.5'-''''''''''-11
### Figure 15: Mapping Example 1

### Table 2: DFM Guidelines, Example 1

<table>
<thead>
<tr>
<th>Sr No.</th>
<th>Feature</th>
<th>Rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stepped on both sides’ straight sidewalls/faces -With Screw threads.</td>
<td>Sidewalls and faces should have a draft to prevent tool markings while the tool is withdrawn. [6]</td>
</tr>
<tr>
<td>2</td>
<td>Stepped on both sides’ straight sidewalls/faces -With Screw threads.</td>
<td>Design Screw machine parts to be made to be cut off directly from the stock with the least operations. [28]</td>
</tr>
<tr>
<td>3</td>
<td>Stepped on both sides’ straight sidewalls/faces -With Screw threads.</td>
<td>Design screw machine parts so that they can be machined without any additional operations. [6]</td>
</tr>
<tr>
<td>4</td>
<td>Stepped on both sides’ straight - sidewalls/faces -With Screw threads.</td>
<td>Design parts to be made in the least number of steps. [25]</td>
</tr>
<tr>
<td>5</td>
<td>Stepped on both sides’ straight sidewalls/faces -With Screw threads.</td>
<td>Cast/forged parts with large shoulders should have surfaces that are $2^\circ$ to $3^\circ$ from the plane normal to the axis. [6]</td>
</tr>
<tr>
<td>6</td>
<td>External plane surfaces Related to one another (Dia Opposite)</td>
<td>Design parts to be gripped tightly and firmly to withstand machining forces in planning and shaping processes. [1,25]</td>
</tr>
<tr>
<td>7</td>
<td>External plane surfaces Related to one another (Dia Opposite)</td>
<td>Put machine surfaces on one plane to minimize number of setups and operations. [6]</td>
</tr>
<tr>
<td>8</td>
<td>External plane surfaces Related to one another (Dia Opposite)</td>
<td>“If possible, restrict plane surface machining (slots, groves etc.) to one surface of the component” [1].</td>
</tr>
<tr>
<td>9</td>
<td>External plane surfaces Related to one another (Dia Opposite)</td>
<td>Allow stock for stress relief between roughing and finishing operations for surface machining of thin, flat pieces. [6]</td>
</tr>
<tr>
<td>---</td>
<td>-----------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>10</td>
<td>External plane surfaces Related to one another (Dia Opposite)</td>
<td>Provide for large square clamping surface if the finish of the machined surface is of paramount importance. [29]</td>
</tr>
<tr>
<td>11</td>
<td>External plane surfaces Related to one another (Dia Opposite)</td>
<td>Designs that requires interrupted cutting actions should be avoided as much as possible. [25]</td>
</tr>
<tr>
<td>12</td>
<td>Chamfered Corners.</td>
<td>Make fillets as large as possible. For grinding, machine a relief in the work piece where two ground surfaces meet. [6]</td>
</tr>
<tr>
<td>13</td>
<td>Stepped on both sides straight sidewalls/faces -With Screw threads.</td>
<td>Interrupted surfaces cause vibrations and thus affecting final surface finish. They should be avoided as much as possible. [6]</td>
</tr>
<tr>
<td>14</td>
<td>0.5&lt; L/D Ratio &lt; 3 (Medium length)</td>
<td>Ensure parts are short and stubby, yet not very long or thin. [1,6]</td>
</tr>
</tbody>
</table>

**Example 2: Tube Stock, Turning and Threading.**

The example in figure 16 is a cylindrical part with tubular stock, threaded with a key made of low carbon steel.

![Figure 16: Example-2: Tube Stock Part with Thread](image)

**Part name:** Pipe_Extention.par

**GT Code:** 2-3100-10004-7-0-00-’7’-100-’M24X1.5’-0 ‘20’ ‘3’ ‘1.55’-60
Table 3: DFM Guidelines, Example 2

<table>
<thead>
<tr>
<th>Sr No.</th>
<th>Feature</th>
<th>Rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stepped on one side, straight sidewalls/faces - With Screw threads.</td>
<td>Sidewalls and faces should have a draft to prevent tool markings while the tool is withdrawn. [6]</td>
</tr>
<tr>
<td>2</td>
<td>Stepped on one side, straight sidewalls/faces - With Screw threads.</td>
<td>Design screw machine parts so that they can be machined without any additional operations. [6]</td>
</tr>
<tr>
<td>3</td>
<td>Sharp Corners Essential Features.</td>
<td>Sharp corners should be avoided to prevent tool breakage. [25]</td>
</tr>
<tr>
<td>4</td>
<td>No Thread Clearance</td>
<td>Allow sufficient thread relief at the end of the thread. [28]</td>
</tr>
<tr>
<td>5</td>
<td>Sharp Corners</td>
<td>Use chamfers and countersinks at the ends of threads. Use a standard angle of 45° when using a chamfer.[6]</td>
</tr>
<tr>
<td>6</td>
<td>Internal Plane surface or Groove</td>
<td>Part to be broached should be designed to be easily held by clamping surface.[6]</td>
</tr>
<tr>
<td>7</td>
<td>Internal Plane surface or Groove</td>
<td>Design parts so that a group of parts that require a similar broaching operation can use the same broaching tool.[6]</td>
</tr>
<tr>
<td>8</td>
<td>Tube Stock</td>
<td>Avoid thin walls on components as they have a tendency to distort during machining. [32]</td>
</tr>
</tbody>
</table>
Redesign:

For the part shown in figure 16, increasing the wall thickness of the tube will allow easy machining (rule 8), allowing chamfered corners will increase safety and ease machinability (rule 5, 3). Use of standard broach size will reduce subsequent machining and setups (rule 7). The redesigned part incorporating the suggestions from the DFM advisory is shown in figure 18.

![Figure 18: Revised Cylindrical part sample](image)

**Example 3: Support_Motion_Tray**

The example in figure 19 is a support motion tray, a prismatic part. The part has one primary bore, with auxiliary holes on multiple planes.

![Figure 19: Example 3; Prismatic part](image)
Part name: Support_Motion_Tray.par

Part Description: Flat part, one primary hole, auxiliary holes, low carbon steel.

GT Code: 5-1-113-20-336

**Figure 20 : Mapping Example 3**

**Table 4 : DFM Guidelines Example 3**

<table>
<thead>
<tr>
<th>Sr No.</th>
<th>Feature</th>
<th>Rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Non Rotational Components - (Flat Components)</td>
<td>Allow stock for stress relief between roughing and finishing operations for surface machining of thin, flat pieces.[6]</td>
</tr>
<tr>
<td>2</td>
<td>L/D &lt; 3</td>
<td>Avoid very small auxiliary holes. A diameter of 3 mm should be a minimum. [1]</td>
</tr>
<tr>
<td>3</td>
<td>Drilled holes/Multi direction</td>
<td>To facilitate fixturing, dimension all holes from a common datum if multiple drilling holes are required.[1]</td>
</tr>
<tr>
<td>4</td>
<td>Drilled holes/Multi direction</td>
<td>To simplify tooling, holes should be designed such that they can be drilled from the least number of sides. [28]</td>
</tr>
<tr>
<td>5</td>
<td>Drilled holes/Multi direction</td>
<td>In order to minimize drill changes, use standard size holes, fasteners and threads.[6]</td>
</tr>
<tr>
<td>6</td>
<td>Drilled holes/Multi direction</td>
<td>For large production quantities requiring multiple drill arrangements, drill holes should be spaced to ease simultaneous drilling. [6]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---------------</td>
<td>-----------------------------------------------------------------</td>
</tr>
<tr>
<td>7</td>
<td>Drilled holes/Multi direction</td>
<td>Locate all holes from one surface. [6]</td>
</tr>
<tr>
<td>8</td>
<td>One Principal Bore</td>
<td>There should be sufficient room for drill bushing which are close to the surface. [6]</td>
</tr>
<tr>
<td>9</td>
<td>Machined surface /multiple planes</td>
<td>Put machine surfaces on one plane to minimize number of operations. [6]</td>
</tr>
<tr>
<td>10</td>
<td>Machined surface /multiple planes</td>
<td>Provide for large square clamping surface if the finish of the machined surface is of paramount importance. [29]</td>
</tr>
<tr>
<td>11</td>
<td>Machined surface /multiple planes</td>
<td>Design a part so that the manufacturer has the freedom to include the most appropriate radius between the milled surfaces. [6]</td>
</tr>
<tr>
<td>12</td>
<td>Machined surface /multiple planes</td>
<td>A small step or incline on the perpendicular milled surface provides a relief for the milling cutter. [6]</td>
</tr>
<tr>
<td>13</td>
<td>Machined surface /multiple planes</td>
<td>It is preferable to keep all surface machining operations in one plane. [6]</td>
</tr>
</tbody>
</table>

Redesign:

Based on these recommendations the part is modified as follows. Hole locations are made symmetric and sizes are kept constant with standard drill sizes to avoid multiple setups and drill bit changes (rule 3, 4, 5). The part has been redesigned so that all machined surfaces are on one plane (rule 9). Holes are redesigned to accommodate drill bushing (Rule 8). The modified part is shown in figure 21.

Figure 21 : Revised Prismatic part Sample
Chapter 6: Conclusion and Future Work

6.1 Conclusion

A novel DFM based GT coding system based on the part geometric features was developed leveraging the knowledge of DFM guidelines at an early design stage. The availability of DFM knowledge during the early design ensures possible cost reduction and smooth manufacturability of the product downstream. The proposed concept was explained using cylindrical and prismatic sample parts with the help of SE macro. The redesign based on violated DFM guidelines demonstrated the importance of appropriate DFM based design changes at an early design stage, thus reducing overall product development cost and time.

6.2 Future Work

For future extension of this research, other manufacturing processes such as casting, forging, and metal and sheet forming can be included. There is also scope to automate the GT assignment process using existing feature recognition techniques that can be incorporated within the SE macro. The set of guidelines can be improved to include DFA, DFx, and take into account newer processes such as additive manufacturing.
Chapter 7: References


Appendix 1

The appendix is a collection of GT coding and classification developed in this thesis, DFM Rules considered and the relevant mapping between them. Section 1.1 describes the GT classification and coding system developed for both cylindrical parts and prismatic parts with a detailed description of the code and each having a unique CODE ID. Section 1.2 is a list of all the DFM Rules used for the mapping process. Each rule has its own unique RULE ID. The CODE ID and RULE ID are used as references on the Mapping Tables. Section 1.3 is the mapping that shows the association between the CODE ID and Rule ID. To identify the rules associated with a GT Code, the CODE IDs are located with the corresponding RULE IDs.

1.1 GT code classification

1.1.1 Rotational Components Classification

<table>
<thead>
<tr>
<th>Shape Category</th>
<th>CODE ID</th>
<th>DIGIT</th>
<th>GT Code</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>Digit 1</td>
<td>1</td>
<td>L/D Ratio &lt; 0.5 (Thin Disks)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Digit 1</td>
<td>2</td>
<td>0.5&lt; L/D Ratio &lt; 3 (Medium length)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Digit 1</td>
<td>3</td>
<td>L/D Ratio &gt; 3 (long components, Shafts )</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Digit 1</td>
<td>4</td>
<td>Components with Axis Deviation</td>
</tr>
<tr>
<td>External Shape</td>
<td>5</td>
<td>Digit 2</td>
<td>0</td>
<td>Smooth , no External Features</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Digit 2</td>
<td>1</td>
<td>Stepped on one side. – straight sidewalls/faces</td>
</tr>
<tr>
<td>CODE ID</td>
<td>DIGIT</td>
<td>GT Code</td>
<td>Designation</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td>---------</td>
<td>-------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>Stepped on one side. – Angled sidewalls/faces</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>Stepped on one side, straight sidewalls/faces -With Screw threads.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>4</td>
<td>Stepped on one side, Angled sidewalls/ faces -With Screw threads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>Stepped on both sides straight sidewalls/ faces</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>6</td>
<td>Stepped on both sides Angled sidewalls/ faces</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>7</td>
<td>Stepped on both sides’ straight sidewalls/ faces -With Screw threads.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>8</td>
<td>Stepped on both sides Angled sidewalls/ faces -With Screw threads</td>
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<td></td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>No External Features</td>
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<tr>
<td>15</td>
<td>1</td>
<td>Sharp Corners, Essential Features.</td>
<td></td>
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<tr>
<td>16</td>
<td>2</td>
<td>Chamfered Corners.</td>
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<tr>
<td>CODE ID</td>
<td>DIGIT</td>
<td>GT Code</td>
<td>Designation</td>
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<td>---------</td>
<td>------------------------------</td>
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<tr>
<td>17</td>
<td>3</td>
<td>Undercuts</td>
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<td>18</td>
<td>4</td>
<td>Angular undercuts</td>
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<tr>
<td>19</td>
<td>0</td>
<td>No Groove or Keyway.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>Groove Square edges.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>2</td>
<td>Keyway Square edges.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>3</td>
<td>Groove Angular edges.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>4</td>
<td>Keyway Rounded ends.</td>
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<td></td>
</tr>
<tr>
<td>24</td>
<td>5</td>
<td>Groove -Square; Keyway Square</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>6</td>
<td>Groove -Angled; Keyway Square</td>
<td></td>
<td></td>
</tr>
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<td>CODE ID</td>
<td>DIGIT</td>
<td>GT Code</td>
<td>Designation</td>
<td>Surface Finish</td>
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<tr>
<td>26</td>
<td>7</td>
<td>Groove -Square ; Keyway round</td>
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<td></td>
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<td>27</td>
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<td>Groove -Angled; Keyway round</td>
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<td></td>
</tr>
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<td></td>
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<td>2</td>
<td>25 Ra</td>
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<td>3</td>
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<td>Smooth Internal hole</td>
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<td>Stepped on one side.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>3</td>
<td>Stepped on one side -With Screw threads.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CODE ID</td>
<td>DIGIT</td>
<td>GT Code</td>
<td>Designation</td>
<td>Description</td>
</tr>
<tr>
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<td>-------</td>
<td>---------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>46</td>
<td>4</td>
<td>Stepped on both sides.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>47</td>
<td>5</td>
<td>Stepped on both sides -With Screw threads.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>6</td>
<td>Blind hole</td>
<td></td>
<td></td>
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<td>49</td>
<td>7</td>
<td>Blind hole screw thread Overall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>8</td>
<td>Blind hole Stepped on one side.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>9</td>
<td>Blind hole Stepped on one side -With Screw threads.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>0</td>
<td>No Internal Features</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digit 7</td>
<td></td>
<td></td>
<td></td>
<td>Sharp Corners, Essential Features.</td>
</tr>
<tr>
<td>CODE ID</td>
<td>DIGIT</td>
<td>GT Code</td>
<td>Designation</td>
<td></td>
</tr>
<tr>
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<td>Groove/Slot</td>
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<td>179</td>
<td>8</td>
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<td>Groove/Slot with machined surface</td>
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<td>180</td>
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<td>185</td>
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<tr>
<td>202</td>
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<td>Cast Part Stock</td>
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<tr>
<td>203</td>
<td>2</td>
<td>Forged part</td>
<td></td>
<td></td>
</tr>
<tr>
<td>204</td>
<td>3</td>
<td>Standard Stock</td>
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</table>
1.2 DFM Rules

<table>
<thead>
<tr>
<th>RULE ID</th>
<th>Rule description</th>
<th>Source</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Components with large L/D ratios have a tendency to deflect under cutting tool loads and should be modified or avoided.</td>
<td>[1]</td>
</tr>
<tr>
<td>2</td>
<td>Ensure parts are short and stubby, yet not very long or thin.</td>
<td>[1,6]</td>
</tr>
<tr>
<td>3</td>
<td>Due to the difficulty of work holding, extremely thin components should be avoided.</td>
<td>[27]</td>
</tr>
<tr>
<td>4</td>
<td>If a flat piece requires surface machining, allow sufficient stock for roughing and finishing operations.</td>
<td>[6]</td>
</tr>
<tr>
<td>5</td>
<td>In case of square or hexagonal stock, the turned diameter should be equal to or less than the distance between the opposite ends of the stock.</td>
<td>[6]</td>
</tr>
<tr>
<td>6</td>
<td>Sidewalls and faces should have a draft to prevent tool markings while the tool is withdrawn.</td>
<td>[6]</td>
</tr>
<tr>
<td>7</td>
<td>Angular undercut (internal or external) should be avoided during screw machining operations.</td>
<td>[6]</td>
</tr>
<tr>
<td>8</td>
<td>Provide a slight draft (1/2° or more) to the sidewalls of the grooves.</td>
<td>[28]</td>
</tr>
<tr>
<td>9</td>
<td>Design screw machine parts so that they can be cut off directly from the stock with the least operations.</td>
<td>[28]</td>
</tr>
<tr>
<td>10</td>
<td>Design screw machine parts so that they can be machined without any additional operations.</td>
<td>[6]</td>
</tr>
<tr>
<td>11</td>
<td>Avoid undercuts, because they may require additional machining operations that may increase part cost.</td>
<td>[25]</td>
</tr>
<tr>
<td>12</td>
<td>Avoid designs requiring sharp corners while generously providing rounded corners that may reduce stress concentration.</td>
<td>[6]</td>
</tr>
<tr>
<td>13</td>
<td>Design parts to be made in the least number of steps.</td>
<td>[25]</td>
</tr>
<tr>
<td>14</td>
<td>Unless generous bottom radius is provided, avoid groove depth 1.5 times the width.</td>
<td>[6]</td>
</tr>
<tr>
<td>15</td>
<td>Cast/forged parts with large shoulders should have surfaces that are 2° to 3° from the plane normal to the axis.</td>
<td>[6]</td>
</tr>
<tr>
<td>16</td>
<td>Undercuts and grooves with parallel or steep sidewalls should be avoided.</td>
<td>[6]</td>
</tr>
<tr>
<td>17</td>
<td>Prefer annular groove on external surface to an internal surface.</td>
<td>[6]</td>
</tr>
<tr>
<td>18</td>
<td>External grooves on screw machine parts are cheaper than internal recesses.</td>
<td>[28, 6]</td>
</tr>
<tr>
<td>19</td>
<td>Rather than have square bottom, hole bottom should be designed with standard drill point angles</td>
<td>[27]</td>
</tr>
<tr>
<td>20</td>
<td>Sharp corners should be avoided to prevent tool breakage.</td>
<td>[25]</td>
</tr>
<tr>
<td>21</td>
<td>Although sharp corner should be avoided, if necessary, use undercuts to make an inside corner sharp.</td>
<td>[6, 28]</td>
</tr>
</tbody>
</table>

56
<table>
<thead>
<tr>
<th>RULE ID</th>
<th>Rule description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>If sharp corners are required, it should be produced within specified limits.</td>
<td>[6]</td>
</tr>
<tr>
<td>23</td>
<td>When corner space is needed, use undercuts instead of sharp corners, although these should be avoided.</td>
<td>[6]</td>
</tr>
<tr>
<td>24</td>
<td>Internal corners should have a radius of a standard rounded tool.</td>
<td>[1]</td>
</tr>
<tr>
<td>25</td>
<td>Avoid small holes with a L/D ratio &gt; 3 to account for chip clearance &amp; maintain straightness deviation.</td>
<td>[32, 6]</td>
</tr>
<tr>
<td>26</td>
<td>To circumvent the problem of chip clearance and deviation from straightness, avoid holes with depth longer than 3 times the diameter.</td>
<td>[28, 6]</td>
</tr>
<tr>
<td>27</td>
<td>Avoid very small auxiliary holes. A diameter of 3 mm is a minimum.</td>
<td>[6]</td>
</tr>
<tr>
<td>28</td>
<td>For large holes, cast holes are preferable prior to the drilling operation to reduce material wastage.</td>
<td>[6]</td>
</tr>
<tr>
<td>29</td>
<td>Very deep holes may result in tool deflection or breakage.</td>
<td>[6]</td>
</tr>
<tr>
<td>30</td>
<td>In order for chips to flow through, blind holes should be bored 1/4th diameter deeper.</td>
<td>[6]</td>
</tr>
<tr>
<td>31</td>
<td>For a hole, unless higher dimensional accuracy or surface finish is required, do not ream or bore if drilling is sufficient.</td>
<td>[6]</td>
</tr>
<tr>
<td>32</td>
<td>To avoid drill bit entry problems, entry surfaces of auxiliary holes should be parallel or perpendicular to the workpiece axis.</td>
<td>[1]</td>
</tr>
<tr>
<td>33</td>
<td>To avoid drill bit exit problems, entry surfaces of auxiliary holes should be parallel or perpendicular to the workpiece axis.</td>
<td>[1]</td>
</tr>
<tr>
<td>34</td>
<td>Avoid bent holes and interrupted cuts if hole straightness is a critical requirement</td>
<td>[1,6]</td>
</tr>
<tr>
<td>35</td>
<td>“Ensure that ends of the blind holes are conical.”</td>
<td>[1]</td>
</tr>
<tr>
<td>36</td>
<td>Provide extra drill depth for blind holes that requires follow up reaming.</td>
<td>[6]</td>
</tr>
<tr>
<td>37</td>
<td>Due to reduced accuracy as a result of boring bar deflection, hole depth to diameter ratio should be kept under 4.</td>
<td>[6]</td>
</tr>
<tr>
<td>38</td>
<td>Bores and holes should be cylindrical and L/D ratio should match standard drill / boring tools.</td>
<td>[6]</td>
</tr>
<tr>
<td>39</td>
<td>If possible, hole spacing and separation should be such that it can be performed on one operation.</td>
<td>[28, 6]</td>
</tr>
<tr>
<td>40</td>
<td>Designs that requires interrupted cutting actions should be avoided as much as possible.</td>
<td>[6]</td>
</tr>
<tr>
<td>41</td>
<td>To facilitate fixturing, dimension all holes from a common datum if multiple drilling holes are required.</td>
<td>[25, 6]</td>
</tr>
<tr>
<td>42</td>
<td>Holes should be located using rectangular instead of angular coordinates while using a common datum.</td>
<td>[25, 6]</td>
</tr>
<tr>
<td>43</td>
<td>To simplify tooling, holes should be designed such that they can be drilled from the least number of sides.</td>
<td>[28, 6]</td>
</tr>
<tr>
<td>44</td>
<td>Provide space for drill bushing near the surface of the hole.</td>
<td>[6]</td>
</tr>
<tr>
<td>45</td>
<td>In order to minimize drill changes, use standard size holes, fasteners and threads.</td>
<td>[6]</td>
</tr>
<tr>
<td>RULE ID</td>
<td>Rule description</td>
<td>Source</td>
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<tr>
<td>---------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
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</tr>
<tr>
<td>46</td>
<td>For large production quantities requiring multiple drill arrangements, drill holes should be spaced to ease simultaneous drilling.</td>
<td>[6]</td>
</tr>
<tr>
<td>47</td>
<td>The center point of the drill should remain in the work throughout the drilling operation for holes which have intersecting openings.</td>
<td>[6]</td>
</tr>
<tr>
<td>48</td>
<td>The Drill bit should be perpendicular to the entry and exit surface.</td>
<td>[6]</td>
</tr>
<tr>
<td>49</td>
<td>Locate all holes from one surface.</td>
<td>[6]</td>
</tr>
<tr>
<td>50</td>
<td>Use rectangular coordinates instead of angular coordinates to locate all holes.</td>
<td>[6]</td>
</tr>
<tr>
<td>51</td>
<td>There should be sufficient room for drill bushing which are close to the surface.</td>
<td>[6]</td>
</tr>
<tr>
<td>52</td>
<td>The intersection of drilled as well as reamed holes should be avoided.</td>
<td>[6]</td>
</tr>
<tr>
<td>53</td>
<td>If it is critical to have finished hole straightness, avoid interrupted cuts. If unavoidable, use guide bushing at each reentry surface.</td>
<td>[28]</td>
</tr>
<tr>
<td>54</td>
<td>Allow sufficient thread relief at the end of the thread.</td>
<td>[28]</td>
</tr>
<tr>
<td>55</td>
<td>Leave some unthreaded length at the bottom of a bling hole for chip clearance. An alternative to this is a through hole.</td>
<td>[28]</td>
</tr>
<tr>
<td>56</td>
<td>Tapped blind holes should not continue to the bottom of the holes and should leave some unthreaded length.</td>
<td>[1]</td>
</tr>
<tr>
<td>57</td>
<td>For machining internal threads sufficient chip clearance should be allowed.</td>
<td>[6]</td>
</tr>
<tr>
<td>58</td>
<td>Use chamfers and countersinks at the ends of threads. Use a standard angle of 45° when using a chamfer.</td>
<td>[25]</td>
</tr>
<tr>
<td>59</td>
<td>Screw thread starting surface should be flat and square with the axis of the thread.</td>
<td>[28]</td>
</tr>
<tr>
<td>60</td>
<td>Ensure slots, cross holes, and flats do not intersect a screw thread.</td>
<td>[28]</td>
</tr>
<tr>
<td>61</td>
<td>Use standard thread form and size based on off-the-shelf threading tools.</td>
<td>[28]</td>
</tr>
<tr>
<td>62</td>
<td>For tubular parts that are to be machined or formed, walls should be designed thick enough to withstand pressure of the cutting or forming.</td>
<td>[28]</td>
</tr>
<tr>
<td>63</td>
<td>“Castings and forging of odd shapes should not have thin sections at a portion of the thread's circumference. Otherwise, out-of-roundness will occur.”</td>
<td>[6]</td>
</tr>
<tr>
<td>64</td>
<td>Use the widest possible tolerance and surface finish commensurate with the performance of the surface.</td>
<td>[32]</td>
</tr>
<tr>
<td>65</td>
<td>Threads to be ground should not have sharp corners at its roots.</td>
<td>[6]</td>
</tr>
<tr>
<td>67</td>
<td>If threads are rolled, they should have similar requirements of roundness, straightness, and should not have tapers and burrs.</td>
<td>[6]</td>
</tr>
<tr>
<td>68</td>
<td>Design parts to be gripped tightly and firmly to withstand machining forces in planning and shaping processes.</td>
<td>[1,25]</td>
</tr>
<tr>
<td>69</td>
<td>Put machine surfaces on one plane to minimize number of setups and operations.</td>
<td>[6]</td>
</tr>
<tr>
<td>RULE ID</td>
<td>Rule description</td>
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<tr>
<td>70</td>
<td>“If possible, restrict plane surface machining (slots, grooves etc.) to one surface of the component” [1].</td>
<td>[1]</td>
</tr>
<tr>
<td>72</td>
<td>Allow a relief of at least 6 mm from an obstruction for shapers and slotters.</td>
<td>[6]</td>
</tr>
<tr>
<td>73</td>
<td>Allow stock for stress relief between roughing and finishing operations for surface machining of thin, flat pieces.</td>
<td>[6]</td>
</tr>
<tr>
<td>74</td>
<td>Use standard Keyway or slot size. They should be sized at a minimum of 1 inch.</td>
<td>[6]</td>
</tr>
<tr>
<td>75</td>
<td>It is not feasible to machine a slot longer than 4 times the diameter of the shaft because of the lack of rigidity of long cutting tool extensions.</td>
<td>[6]</td>
</tr>
<tr>
<td>76</td>
<td>Provide for large square clamping surface if the finish of the machined surface is of paramount importance.</td>
<td>[29]</td>
</tr>
<tr>
<td>77</td>
<td>Part to be broached should be designed to be easily held by clamping surface.</td>
<td>[6]</td>
</tr>
<tr>
<td>78</td>
<td>For external broaching provide the holding fixture that can sustain the cutting stroke.</td>
<td>[6]</td>
</tr>
<tr>
<td>79</td>
<td>The final shape of the forged parts should be close as possible to the final product to minimize machining and processing.</td>
<td>[32]</td>
</tr>
<tr>
<td>80</td>
<td>Allow appropriate allowances for cast parts for post machining and finishing.</td>
<td>[1]</td>
</tr>
<tr>
<td>81</td>
<td>Avoid thin walls on components as they have a tendency to distort during machining.</td>
<td>[32]</td>
</tr>
<tr>
<td>82</td>
<td>Design parts so that a group of parts that require a similar broaching operation can use the same broaching tool.</td>
<td>[6]</td>
</tr>
<tr>
<td>83</td>
<td>For parts with internal ground components, the designer should standardize on one part design whenever possible.</td>
<td>[6]</td>
</tr>
<tr>
<td>84</td>
<td>Provide generous surface for gripping and location for parts to be chucked.</td>
<td>[6]</td>
</tr>
<tr>
<td>85</td>
<td>Thin-walled parts can deform while grinding on the outer surface.</td>
<td>[31]</td>
</tr>
<tr>
<td>86</td>
<td>Allow sufficient surface on the end face to allow parts to be held on a magnetic chuck.</td>
<td>[6]</td>
</tr>
<tr>
<td>87</td>
<td>Avoid holes longer than length to diameter ratio of 6 for grinding operation. Grinding deep, small holes results in waviness and chatter.</td>
<td>[6]</td>
</tr>
<tr>
<td>88</td>
<td>Grinding holes with depth 6 times the diameter are difficult to achieve unless the area is wide enough to provide support to the wheel spindle.</td>
<td>[6]</td>
</tr>
<tr>
<td>89</td>
<td>Grinding a blind hole takes longer because the flow of coolant in the contact region may be insufficient.</td>
<td>[6]</td>
</tr>
<tr>
<td>90</td>
<td>Avoid circumferential interruptions on the ground surface. The grinding wheel has a tendency to remove more material near the keyway or spline.</td>
<td>[25]</td>
</tr>
<tr>
<td>RULE ID</td>
<td>Rule description</td>
<td>Source</td>
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<td>---------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
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</tr>
<tr>
<td>91</td>
<td>A reciprocating wheel will remove more stock near an interruption like a circumferential valve groove or a relief. This should be taken into consideration.</td>
<td>[6]</td>
</tr>
<tr>
<td>93</td>
<td>Appropriate relief in the center of an internal face will allow the coolant to flow in to the contact zone.</td>
<td>[6]</td>
</tr>
<tr>
<td>94</td>
<td>The size of the entrance must be such that a wheel of reasonable size can pass through without interference.</td>
<td>[6]</td>
</tr>
<tr>
<td>95</td>
<td>Consider access to coolant while designing internally ground holes.</td>
<td>[6]</td>
</tr>
<tr>
<td>96</td>
<td>Keep parts as symmetrical as possible for ease of assembly.</td>
<td>[25]</td>
</tr>
<tr>
<td>97</td>
<td>To avoid deflection, grinding long shafts should be avoided.</td>
<td>[6]</td>
</tr>
<tr>
<td>99</td>
<td>Interrupted surfaces cause vibrations and thus affecting final surface finish. They should be avoided as much as possible.</td>
<td>[25]</td>
</tr>
<tr>
<td>100</td>
<td>Avoid undercuts on parts unless absolutely necessary. They are harder to machine even with a specially ground tool.</td>
<td>[25]</td>
</tr>
<tr>
<td>101</td>
<td>Make fillets as large as possible. For grinding, machine a relief in the work piece where two ground surfaces meet.</td>
<td>[6]</td>
</tr>
<tr>
<td>103</td>
<td>Hollow, thin walled tubular parts can deform while being held be a three jaw chuck. Design the tubular part to have thick walls or have it magnetically chucked.</td>
<td>[6]</td>
</tr>
<tr>
<td>104</td>
<td>Remove minimum stock by grinding.</td>
<td>[6]</td>
</tr>
<tr>
<td>105</td>
<td>Keep the ground surface to be the largest (least in case of internal) to allow through feed grinding.</td>
<td>[6]</td>
</tr>
<tr>
<td>106</td>
<td>Keep ground surfaces one diameter in length to avoid unspecified taper while grinding.</td>
<td>[6]</td>
</tr>
<tr>
<td>107</td>
<td>“Try to ensure that cylindrical surfaces are concentric, and plane surface are normal to component axis.”</td>
<td>[1]</td>
</tr>
<tr>
<td>108</td>
<td>“Try to ensure that the diameter of external features increase from the exposed face of the workpiece.”</td>
<td>[1]</td>
</tr>
<tr>
<td>109</td>
<td>“Try to ensure that the diameter of internal features increase from the exposed face of the workpiece.”</td>
<td>[1]</td>
</tr>
<tr>
<td>111</td>
<td>To achieve accuracy, avoid keyways, flats and holes on a surface to be ground.</td>
<td>[1]</td>
</tr>
<tr>
<td>112</td>
<td>If a flat surface is necessary, it should be normal to the axis of the shaft and if tolerances are tight, the flat should be put at the opposite side.</td>
<td>[6]</td>
</tr>
<tr>
<td>113</td>
<td>The Recommended values of W = 2 and H = 2</td>
<td>[34]</td>
</tr>
<tr>
<td>114</td>
<td>The Recommended values of W = 3 and H = 3</td>
<td>[34]</td>
</tr>
<tr>
<td>115</td>
<td>The Recommended values of W = 4 and H = 4</td>
<td>[34]</td>
</tr>
<tr>
<td>116</td>
<td>The Recommended values of W = 5 and H = 5</td>
<td>[34]</td>
</tr>
<tr>
<td>117</td>
<td>The Recommended values of W = 6 and H = 6</td>
<td>[34]</td>
</tr>
<tr>
<td>118</td>
<td>The Recommended values of W = 8 and H = 7</td>
<td>[34]</td>
</tr>
<tr>
<td>119</td>
<td>The Recommended values of W = 10 and H = 8</td>
<td>[34]</td>
</tr>
<tr>
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<td>The Recommended values of W = 12 and H = 8</td>
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124 | The Recommended values of $W = 20$ and $H = 12$ | [34]
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137 | The Recommended values of $W = 90$ and $H = 45$ | [34]
138 | The Recommended values of $W = 100$ and $H = 50$ | [34]

### 1.3 Mapping

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