Axiomatic design applied to a practical example of the integrity of shaft surfaces for rotating lip seals

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Abstract

The objective of this work is to explore axiomatic design as an approach to designing for surface integrity, particularly in regard to topography for rotating lip seals. Functional requirements can be fulfilled by some combination of surface integrity elements. Difficulties can arise because texture characterization parameters do not independently address functional requirements for the surface and cannot be independently controlled by abrasive processes. Some of the difficulties can be addressed by the topographic characterization parameters.

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1. Introduction

This work studies the relation between manufacturing processes, the analysis of the topographic component of surface integrity, and functional performance of components, and introduces rotating lip seals as practical examples. The objective of this work is to explore the application of axiomatic design to products, processes, and quality assurance that involve surface integrity, particularly in relation to surface topography for rotating lip seals.

This work is important because it advances the practice of design of surface topographies. Design procedures for surface integrity facilitate better products and processes. Important functional
requirements potentially can be fulfilled by surface integrity elements. This potential may be 
underutilized. The approaches to design discussed here can advance this utilization.

Designing the topographic component of surface integrity is a special kind of geometric problem 
because at some sufficiently fine scale topographies are generally chaotic in nature. Characterization of 
these topographies by conventional height parameters can be critically incomplete. The qualities of the 
topographic features that control topographically dependent functions are combinations of height and 
spacing and are scale dependent [1,2].

The literature on surface integrity is largely related to manufacturing processes and their influence. 
Much of it addresses fatigue life through residual stresses and suppressing microcracks, rather than using 
topography [3-7]. The author is not aware of any literature that addresses design methods for products 
and processes of the topographic component of surface integrity for seals.

This work applies axiomatic design [8] to the problem of simultaneous, or concurrent, design process 
of surface topographies for rotating lip seals. Characterization of the topographies to facilitate the 
integration of product and process design is discussed for designing and manufacturing the topographic 
components of surface integrity.

2. Axiomatic Design Applied to Surface Integrity - Generalities

Axiomatic design is distinguished by the use of two axioms, maximize independence and minimize 
information, in order to select the best design solutions. The application of the independence axiom 
assures that the solution selected will be the one that is the most adjustable and controllable. The 
application of the information axiom, which occurs after the application of the independence axiom, 
assures that the solution selected will be the most robust [8]. The hypothesis is that application of the 
axioms will select the best design solution for a given set of functional requirements and constraints.

In order to apply the axioms the design is decomposed into domains, including principally: functional, 
physical and process. The domains are decomposed hierarchically from abstract to specific. To develop 
a detailed design solution, a top down design process that zigzags between the domains is used.

The performance, or functional, requirements (FRs), such as, to control friction and wear, or to 
provide seals, are specified in the functional domain. These requirements are developed in response to 
customer needs. In the case of a seal, the customer needs are to keep fluid, such as oil, from leaking out 
of some containment, like an engine block, around a rotating shaft, and do this for an extended period of 
time.

Design parameters (DPs) are the elements of the physical domain and define the physical solution. To 
comply with the independence axiom, each FR must be fulfilled by an individual DP. The positive 
elements of surface integrity, those which would enhance performance, are DPs. These are principally: 
residual compressive stresses, favorable microstructures, and advantageous aspects of the topography.

Upper level DPs constrain lower level decompositions. If, for example, power is to be transferred by 
a rotating shaft, then all the elements in the lower level decomposition are based on this kind of 
mechanical power transmission, rather than some other kind of power transmission, like electromagnetic.

Process variables (PVs) are the manufacturing methods for producing the DPs. To comply with the 
independence axiom there should be some PV that can be applied to produce some DP, and adjusted to 
bring the DP into tolerance.

The negative elements of surface integrity are those which would erode performance. These are 
principally: cracks, residual tensile stresses, unfavorable microstructures, and disadvantageous 
topographies. In the design process these negative aspects could be avoided by listing them as constraints 
applied to manufacturing processes. The literature on the processes that produce these negative elements 
is valuable in identifying processing procedures to be avoided [3-7].

The hierarchical decomposition in the domains starts at one level, in one branch, with the FRs then 
goes to the DPs and PVs at the same level in the same branch, before it continues to the FRs at next level
down. This zigzag process continues through all the branches descending from abstract to specific until the solution is obvious and nothing more specific is required to produce the product.

At each level, and in each branch, the design solution should be checked for violation of constraints and for compliance with the two axioms. Changes would be made as appropriate for compliance.

In order to test the independence of the design solution, the influences of the DPs on the FRs are mapped in the design matrix, and the influences of the PVs on the DPs are mapped in the process matrix.

The test for compliance with the information axiom starts with the calculation of the probability of success, e.g., the likelihood of achieving a physical tolerance. The information components content for candidate design options can be calculated as \( \ln(1/p) \) where \( p \) is the probability of success in fulfilling the FR with a DP and in manufacturing the DP with the PV. The total information content can be the sum of the components [8].

3. Application to Rotating Seals

Consider the practical example of a hydraulic pump. Somewhere in the upper levels of the decomposition of the design of a device, appear the DPs of a rotating shaft and a flexible polymer seal counter-face. The DP for the shaft is a hard, metallic cylinder responding to the FR to transmit power into the pump housing. One of the FRs for the shaft is to provide one side of the seal, a surface for a softer, counter-face material to slide on. This surface is discussed below.

The DPs selected to fulfill the FRs for the surface of the shaft include texture specifications. The ISO and the RMA (Rubber Manufacturers Association) both have developed standard specifications for the topography of the shaft side of the interface [9, 10]. The common aspects of these specifications are maximum and minimum (double-sided) tolerances for the average (Ra) and peak-to-valley (Rz) roughness.

Manufacturing this kind of specification with current abrasive finishing technology can be problematic. One problem is that Ra and Rz can be difficult to adjust independently. In 1985 Nowicki [11] showed that for certain processes roughness characterization parameters are covariant. This means that changes in the PVs used to finish the shaft surface that influence Ra are likely to influence Rz as well. This is a practical example of undesirable coupling which violates the independence axiom.

The RMA specification was developed experimentally. A large number of surfaces with different topographies were manufactured, measured and then tested for leakage during use [12]. Three, double-sided tolerances for topographic characterization parameters (peak height, Rp, in addition to Ra and Rz mentioned above) are in the surface roughness specifications. In addition, there are constraints on the lead angle of the lay of the texture. All of these criteria were required to discriminate the good seals from the bad.

The development of processes to create these seals is known to be problematic. Multiple, double-sided tolerances of covariant characterization parameters appear to be undesirable by both the independence and the information axiom. The decomposition presented below attempts to address this from the perspective of design method.

3.1 Practical example of a FR-DP-PV Decomposition: shaft for a rotating lip seal

The customer need of a seal with significant life could result in two FRs: FR1 could be to provide a shaft surface to resist flow and FR2 could be to promote counter face life. Then DP1 could be a topography which has features that block fluid flow past the seal, i.e., a sealing topography. This DP could provide either a sufficiently smooth, or a sufficiently intricate, topography that can provide enough of a barrier to flow across the seal to meet the customer needs. This topography should exist in the contact zone completely along a band around the circumference of the shaft. This solution would work, provided that form and concentricity requirements for sealing are already met. Assuming that the life
limiting process is wear, DP2 could be a topography that limits wear of the counter-face, or a protective topography. The PV for producing the sealing topography could be fine honing.

The FR, promote counter-face life, could be decomposed at the next lower level of the hierarchy into: FR2.1 resist abrasive wear and FR2.2 provide lubrication. DP2.1 could then be topographic features that promote sliding and that resist wear of the counter-face, e.g., fine-scale, appropriately rounded contact zones features, and DP2.2 could be topographic features that retain a certain amount of the fluid in the interface below the contact zone, e.g., lubricant pockets. Contact zone refers to the portion of the topography, in a vertical orientation, most likely to be in contact with the counter face, i.e., the upper part, or greatest elevations.

Arguably there could be another FR, getting the lubricant into the pockets. Such an FR might not be necessary because however the shaft is finished there will be a labyrinth of features which will provide sufficient flow into the interface to provide adequate lubrication. The necessity could be determined by some kind of modeling or by prototyping.

Experience suggests that plateau honing [e.g., 13] could produce DP2, a protective topography. The decomposition of PV2 would be PV2.1 to produce DP2.1 by fine honing, and PV2.2, to produce DP2.2 by rough grinding.

The complete decomposition surface of a rotating shaft for interfacing with a lip seal is shown in Table 1.

### Table 1. Decomposition of the surface of a rotating shaft for interfacing with a lip seal

| Domains→ | Functional (FRs) | Physical (DPs) | Process (PVs) |
|----------|------------------|----------------|---------------|
| 1        | Resist flow      | Sealing topography | Fine honing   |
| 2        | Promote counter-face life | Protective topography | Plateau honing |
| 2.1      | Resist abrasive wear | Contact zone features | Fine honing |
| 2.2      | Provide lubrication | Lubricant pockets | Rough grinding |

3.2 Applying the Independence Axiom

If the surface topography is viewed as only one DP, then using it to fulfill both FR1 and FR2 would violate the independence axiom. This means that the flow resistance could not be adjusted independently of the seal life. Physical changes to the topography that could improve sealing, like making it smoother, could reduce life by not allowing sufficient liquid in to lubricate the surface.

In these situations, where the topography needs to fulfill two different requirements, the challenge is to find different aspects of the topography that can constitute two independent DPs. This problem is similar to that addressed by Johnsen [14] for pavement topographies that provides adequate friction and resist wearing tires. He showed that wear and friction are separable. Mortar surfaces with a variety of wear/friction ratios were produced in his work [14]. In these situations a working hypothesis can be that the two mechanisms might be decoupled by using some different aspects of the topographic features (shape, size, distribution) to fulfill the FRs independently.

Adjusting the process variables is also problematic. The decomposition in Table 1 violates the independence axiom. Fine honing is part of the plateau honing and appears in its decomposition. Fine honing now is used to produce the sealing topography and to produce contact zone features to resist abrasive wear. The physical aspects of these two topographies cannot be produced independently by one process. This will be discussed further below.

The order of the processing in the promote counter-face life is dictated by the influence that PV2.1 has on DP2.1 as shown in the process matrix below (Table 2).
Table 2. Process matrix for plateau honing in the promote counter-face life branch

| DPs↓                  | PV2.1 fine honing | PV2.2 rough grinding |
|-----------------------|-------------------|----------------------|
| DP 2.1 contact zone features | X                 | X                    |
| DP2.2 lubricant pockets        | O                 | X                    |

In Table 2 Xs indicate that the PV on top of the column will influence the DP in the row; an O indicates that it does not. If the design is fully independent, or uncoupled, then the matrix would be diagonal. If the matrix is triangular, as this one is, then there is a specific order of processing that needs to be followed. PV2.2, rough grinding, negatively influences DP2.1 by leaving sharp peaks. This negative influence could be corrected by the fine honing. The fine honing could remove the peaks and produce fine-scale, rounded contact zone features, for DP2.1, while leaving the lubricant pockets below the contact zone.

3.3 A Practical Example of Quantification and Application of the Information Axiom

Rigorous applications of the axioms to select the best design options, and development of complete design solutions, can both be facilitated by developing quantitative relations between the elements in the domains. Development of equations relating the FRs to DPs and the DPs to the PVs can be a lengthy process requiring experimentation and theoretical insights. Nevertheless axiomatic design can be used advantageously qualitatively and the attempt to develop the quantitative relations can be valuable.

At the upper level FRs 1 and 2 are resist flow and promote counter face life. To quantify these FRs the leak rate across the seal and the life of the seal can be measured and compared to functional tolerances, which would be established from the customer needs. Logically, the leak rate would have an upper bound tolerance and the life would have a lower bound tolerance.

The DPs have physical tolerances. Verifying compliance with the physical tolerances requires quantifying the topographic component of the surface integrity. DP1 is a topography which has features that block fluid flow past the seal, and DP2 is a topography that has features that resist wearing the counter-face. A parameter that could characterize the topography, to verify that DP1 was satisfied, would need to quantify the connectivity of the gaps across the seal. These gaps could be caused by peaks, ridges, and scratches. An inspection sufficient to assure that DP1 is satisfied would require measurement of the entire sealing region all the way around the shaft. An algorithm that could calculate this kind of parameter is imaginable, and this kind of measurement is certainly technically feasible. To the knowledge of the author these technologies have yet to be used together in this application.

The quantification of the topography at this level is inconsistent with the information axiom. None of the texture characterization parameters that are currently available in the ISO standards have been shown to characterize the extent of the connectivity of the gaps across the seal, to the knowledge of the author. Some of the new, feature-based parameters that describe hills and dales could be capable of doing this with appropriate Wolf pruning. Currently some combinations of parameters are adequate, according to the RMA and ISO standards. These are adequate because there are a large number of functioning seals currently in use. Part of the ability to function is because only specific finishing processes are used. The same values of the same characterization parameters might not work if the process were changed.

Currently several criteria need to be satisfied to verify that the topography will provide an adequate seal. Generally, when a greater number of criteria have to be met in order to create a successful design solution, the probability that all of them will be met will be smaller. The smaller probability increases the information content, indicating that the design solution less desirable.

At the next level, FR2.1, resist abrasive wear, could be quantified by mass loss, and an upper bound tolerance established. FR2.2, provide lubrication, could be quantified by the friction coefficient, with an upper bound tolerance. DP2.1, contact zone features for low wear, could be indicated by low slopes and
correspondingly large radii in the contact zone. Berglund showed that these features could be characterized by conventional parameters like developed area or average slope [1]. These are calculated at the scale of sampling interval used in the measurement of the surface. Relative area can be calculated over the range of scales available in the measurement, from the sampling interval to the size of the region measured. Relative areas tend to correlate with friction over certain scale ranges.

DP 2.2 Lubricant pockets, classically could be characterized by the bearing area curve [15], however the bearing area curve does not indicate the size or distribution of the pockets. A scale based filling algorithm [16] has the potential to provide a more complete description of the lubricant pockets.

Table 1 only describes the general kind of abrasive process and makes no attempt to further describe all the variables involved in abrasive processes, principally: abrasive and bond type, feed, speed and depth of cut. Determination of the values of the PVs currently is based on experience and experiment. It is imaginable that more specific descriptions of the desired geometry and of the abrasive could be used to design the process in more detail. This might require new topographic characterization parameters.

3. Discussion

Axiomatic design appears to give some insights into the difficulties of manufacturing the topographic components of surface integrity of seals. One of the current limitations is the kinds of characterization parameters that are used. They are largely statistically based and are not scale sensitive beyond the filtering to separate waviness and roughness.

Many surfaces have strong chaotic components in their topographies at scales that are important for the interactions that control the phenomena required to provide the desired functions. This is because the finishing process uses abrasive media which have significant chaotic components to their topographies at these same scales.

4. Conclusions

• Axiomatic design can provide insights in designing topographic components of surface integrity.
• The surface topography can be decomposed into separate DPs to address separate FRs
• A decomposition has been demonstrated by the practical example of shaft surfaces for rotating lip seals.
• Design of surface topographies is limited by the surface texture characterization parameters.

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