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An Integrated Approach towards Achieving Agility in Design and Development of a Broken Free-form Object

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ABSTRACT

This paper attempts to introduce a unified approach for design and development of a broken free-form object in order to achieve agility in the process. A combination of reverse engineering (RE), re-engineering (ReE) and rapid product development (RpD) approach has been tailored to address the design and development issues of the broken free-form object. A broken clutch shoe from a centrifugal clutch assembly is selected for demonstrating the efficacy of the proposed integrated methodology. To achieve agility in the process, RE is employed for quick recovery of technical data and re-construction of the entire part model. Subsequently, re-engineering is sustained through geometric dimensioning and tolerancing (GD&T) which is used as a validation tool for inspection/comparison of the reference and digitized parametric computer aided design (CAD) models. Furthermore integration of finite element analysis (FEA) is performed iteratively for optimization of influential factors of the part such as feature characteristics and material properties. Finally, computer aided manufacturing (CAM) system is introduced for rapid prototyping of the selected part. This process can manifest itself into similar industrial situations to achieve agility in the product design and development process so that the developed part can be distributed quickly to the customer. Design for better performance of the product in a short turnaround time is the main outcome of this research.

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Introduction

Contemporary manufacturing organizations require adaptability and rapid response to the forceful changes influenced by customer and market needs so that a competitive advantage is maintained. Reduced manufacturing times together with high quality products and services are issues to be addressed [1]. Research has been conducted to glimpse these issues from which agile manufacturing (AM) has emerged as the capability of an organization to respond quickly in accordance with the customers' dynamic demands without compromising quality and profitability [2].

Traditional manufacturing relied on forecasting and planning techniques in the 1950s and 1960s. In the 70s and 80s, through productivity and quality, the way to lean was paved, and the 90s brought with it the adaptability and responsiveness which was the agile era [2]. AM was the solution proposed to deal with new radical customer's needs and not just a product in an ever changing environment [3]. AM was first initiated in 1991 at the Iacocca Institute [4] to illustrate a significant structure for a wide range of applications for achieving agility in manufacturing. Researchers later identified the drivers of agility [1, 5, and 6] such as reverse engineering (RE) and rapid product development (RpD).

This paper presents an integrated product design approach that combines RE, re-engineering (ReE) and RpD in order to achieve agility in manufacturing. The proposed framework is validated through a case study of a broken clutch shoe. In fact there is a need to recover the broken clutch shoe design information due to the non-availability of a spare part in the market.

Literature Review

Reverse Engineering

RE refers to the process in which designers acquire a design concept of a product from digitization of a physical model, and create the CAD model to realize approximation to the physical model: the model created can be reused, modified and optimized [7]. Its non-conventional nature imparts solutions to multi-disciplinary issues thus encompassing diverse applications. RE has been widely recognized as being a substantial step in the product development cycle [8]. It has been defined as systematic evaluation of a product with the purpose of replication which involves either direct copies (when no design/manufacturing documentation exists) or adding improvements to the existing design [9 and

10]. Other applications of RE include recovery of a damaged or broken part, design of a new component and inspection of a numerical model [11]. Research in RE has matured from development of algorithms for optimization of the RE process to development of integrated RE approaches for the enhancement of product development cycle. For quality control of quick response products, an integrated RE approach combined with rapid prototyping principles has been presented in the literature [12]. Prototypes were made from the reference CAD model and then digitized. Physical measurements of certain features were taken off the prototypes and similar measurements taken off the digitized model. These were then compared to the actual size of the features with smaller deviations observed from the digitized model. [1] have reverse engineered two components. Both laser scanner and coordinate measuring machine (CMM) were used for digitization after which rapid prototyping of the 3D solid models were performed to illustrate the concept of agile design and manufacturing through reduced product developmental time and cost.

Re-engineering

It is often necessary to modify the design or to optimize existing design in terms of performance, material or total cost. Research has been conducted through an integrated test-bed for RE of aging systems and components [13]. Integrated topology and shape optimization capabilities have been developed and incorporated for boundary smoothing and geometry reconstruction operations as well as to ensure that the components contain minimum material and yet meet all the performance requirements. [14] have examined a 'Fixed Grid Finite Element' method together with evolutionary algorithms for shape optimization to minimize stress and weight of as-built parts. The experiments developed indicate that a good correlation of the optimization parameters and control points selected will lead to a good solution. [15] have focused on technological-oriented AM research with CAD and CAE as enablers of AM. The existing design of an automobile sprocket was developed using CAD technology followed by engineering analysis and design optimization in a CAE system. The optimized parameters generated were utilized to obtain new models of the sprocket which were then validated using a questionnaire to determine practical feasibility within its manufacturing organization. The results indicated 90 per cent feasibility and claims that this kind of technology integration would enable the manufacturing organization to improve their agility level.

Rapid Product Development

Rapid product development refers to product development in the decreased development lead times and the resulting methods that have been developed to meet these reduced lead times [16]. [13] have introduced fast prototyping

as part of the integrated test-bed developed to produce physical samples and functional replacement parts of small quantity in a short turnaround time. Three prototyping capabilities included in the test-bed were rapid prototyping, CNC machining and metal forming simulation. Moreover, a RE approach was proposed to recover the design information for broken parts [8]. However, the part digitization was achieved through a CMM. An iso-phote method was then used for surface continuity analysis of the developed CAD models which were subsequently transferred into a CAM module for manufacture by means of CNC milling machine. [17] have explored the feasibility of introducing agile characteristics in manufacturing organizations through development of new CAD models from a reference model within a CAD system. A 3D printer is then used to build the prototypes of the newly generated CAD models. Statistical validation through hypothesis testing was implemented to depict the acknowledgment and practicality of using 3D printer to achieve agility.

Research Methodology

The integrated process flow implemented for the recovery of the broken clutch shoe is shown in Figure 1. The RE process constituted data acquisition of the broken clutch shoe and subsequent development of the point cloud to polygon and surface models. Construction of the digitized parametric CAD model through utilization of the initial graphics exchange specification (IGES) format of the surface model is then performed to allow for ReE tasks. These tasks include GD&T analysis to gain feedback of form and fit of the digitized data which is critical to functionality of the component. Furthermore, modeling in FEA system and a re-iterative procedure which involves agile testing of newly evolved CAD models generated through design table feature for a better design of the part is then performed. RpD of the newly evolved CAD model selected is embraced through 3D- printing and finally manufactured by means of CNC machining. Each process is further explained in the following sections.

Case Description

This paper discusses an approach integrating RE, ReE and RpD to achieve manufacturing agility in the recovery of a broken clutch shoe design data. As an extension to the significant contributions mentioned in section 2, this paper focuses on an approach in which a flexible design is supported through agile testing and RpD processes. A clutch shoe from the centrifugal clutch assembly of a customer's miniaturized motorcycle was broken during operation hence leaving it non-functional. There are no local manufacturers and no spare parts are available. This leaves the customer unsatisfied and burdened with heavy investment in terms of purchasing the part from a foreign market. This forms
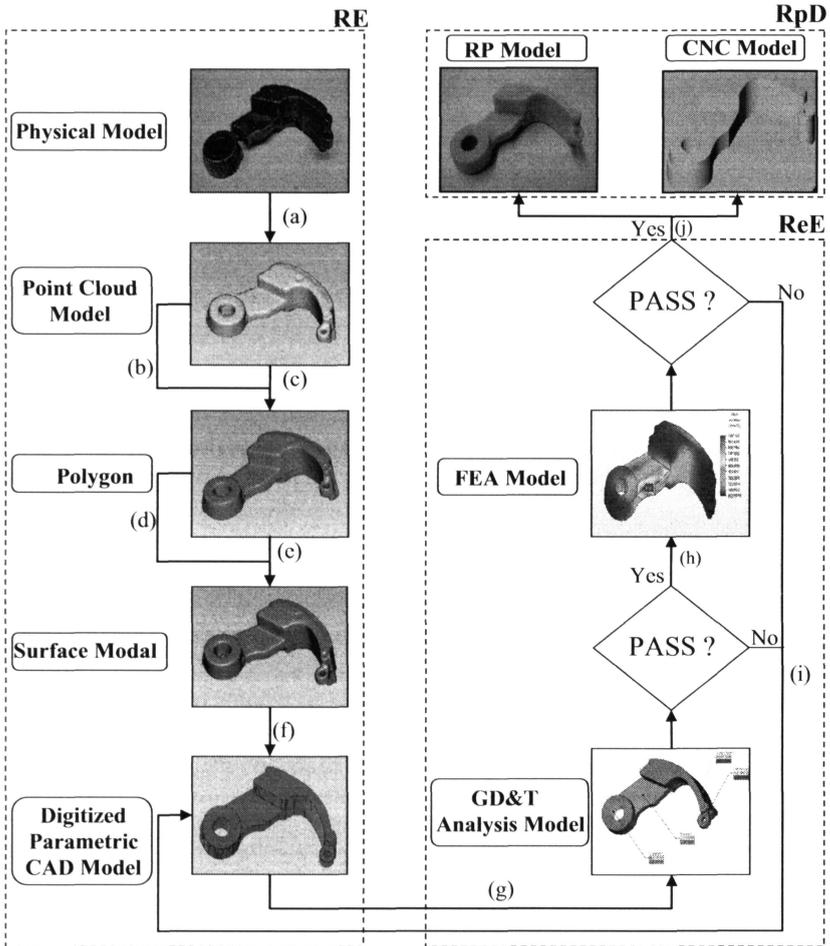
(a) Data Acquisition
(b) Wrap Point Cloud
(c) Merge Point Cloud
(d) Manual Patch Construction
(e) Automatic Patch Construction
(f) Export of IGES File

(g) Reference and Digitized Parametric CAD Model Alignment
(h) Meshing of the Digitized Parametric CAD Model
(i) Modified Digitized Parametric CAD Model
(j) Export of STL File

Figure 1: Integrated Process Flow for Rapid Product
Design and Development

the motivation for this research project. The broken clutch shoe selected for the study can be seen in Figure 2.
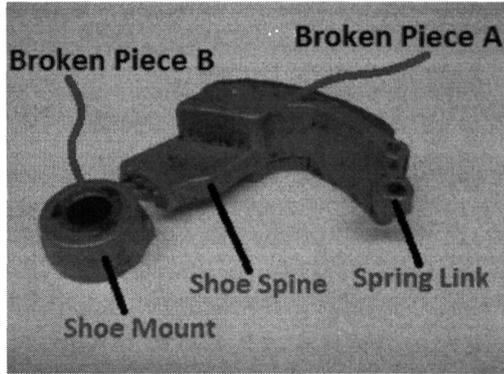
Figure 2: An Overview of Broken Centrifugal Clutch Shoe

Reverse Engineering

The RE work flow consists of the sequential development of discrete models at the data acquisition, data capture, data editing and data fitting phases [18]. These models include: (a) physical model, (b) point cloud model, (c) polygon model, (d) surface model, and (e) digitized parametric CAD model.

Physical Model

The physical model is that part/component which:

- Needs to be reproduced and there are no existing design/manufacturing documentation
- Broken/damaged data must be recovered
- Modification to its design is made
- Requires inspection and comparison to its original CAD model.

The RE process is initiated with data acquisition of the physical model. Retrieval of part data for the broken clutch shoe was accelerated through a recommended non-contact digitization method known as laser triangulation [19]. This technique acquires data at very fast rates and can digitize highly detailed objects such as free-form objects [20]. These characteristics justify its selection as a suitable candidate for this study. The hardware utilized is the ShapeGrabber® AI310 3D laser scanner. Each broken piece was digitized independently. Accordingly, preliminary investigations were conducted and the optimal data acquisition settings assigned include a trajectory length of 17mm and 48mm for 'Broken Piece A (Pc-A)' and 9mm and 19mm for 'Broken Piece B (Pc-B)' at horizontal and vertical digitizing positions respectively. The other

optimal data acquisitions settings assigned were kept constant for digitization of both Pc-A and Pc-B. These settings are summarized below:

- Temperature: 26.5°C
- Y-axis Resolution: 0.05 mm
- Laser Power: 4 (Medium)
- Number of scans: 8
- Increment between scans: 45°.

Point Cloud Model

The digitized point cloud data obtained from the horizontal and vertical positions of each broken piece were imported into a RE system. The retrieved data is processed in preparation for the development of a digitized parametric CAD model. This requires the unordered point cloud to be edited for removal of noise and data registration in order to combine the data acquired from different views and positions into a complete set of points in a single view. Noisy data may result due to stray reflections and these points were separated from the main body of the point cloud [20]. Two data registration approaches manual and automatic alignment, were performed. In manual alignment, landmark points were manually assigned for fixed and floating point clouds, and they were used as references for alignment of Pc-A with Pc-B. Floating point clouds from Pc-B were translated and rotated to align with the fixed cloud from Pc-A based on these references. The manual registration gives a good approximation of the alignment but there still needs to be fine-tuning to obtain an optimal cloud. This was done in the automatic alignment operation, in which the tolerance between the fixed and floating point clouds is used as the constraint for the alignment process [20].

Polygon Model

The prepared point cloud model is then developed into a polygon model either by merging or wrapping to allow for further pre-processing (refer to Figure 1). Both processes were attempted but the polygon model developed from merging was selected as it contained fewer errors and furthermore it was found easier to manipulate due to smaller file size and was generated quicker than the wrapping operation. Errors in the merged polygon model were then repaired. These include holes as well as intersections in the triangular mesh generated. This mesh represents a rough surface of the outer skin defining the shape of the object [18]. While scanning complex shapes, some part information may be missed due to occlusions and as such the missing data result in holes within the polygon mesh generated. Also approximations made by the triangulation algorithm to join point data for creation of the polygon mesh may lead to intersections. These

errors are repaired through editing tools available in the RE system such as "fill holes" and "repair intersections". It is crucial that these deficiencies be resolved before they can be developed because the polygon model is used as a reference to produce the non-uniform rational B-splines (NURBS) surface model, hence, it should be sound and of a particular quality [21].

Surface Model

The repaired polygon model was developed into a surface model. Segmentation was done to divide the polygon mesh into surface patches [18]. The patch structure consists of quadrangular shapes for NURBS surface construction. These patches (or loops) can be drawn on the polygon model manually or automatically based on a target patch count and curvature of the model. Curvature detection identifies components of the model based on surface curvature. The boundary curves that define the clutch shoe were automatically detected to produce a NURBS surface model with the necessary topological detail.

Digitized Parametric CAD Model

In order to support the ReE stage, geometric features embedded in the NURBS surface model were recognized and properly parameterized [13]. This phase aimed at reconstructing the digitized parametric CAD model within a CAD system. This was accomplished by importing the IGES format of the NURBS surface model into the CAD system and implementation of the direct solid modeling approach [13]. Tangential planes to various surface features were created to accommodate the construction of completely new fully parametric sketches as shown in Figure 3. Boss and cut extrusion operations were then performed to produce the digitized parametric CAD model.

Re-engineering

What needs to be done before any optimization process takes place is to capture the original design [14]. GD&T serves as a validation/ check point to establish if the digitized parametric CAD model is well within tolerance when compared to the reference CAD model. Following this, the development of a FEA model assists in the identification of highly stressed areas in support of re-design.

GD&T Model

GD&T is of particular importance not only in industrial production but also in product development, equipment upgrading and maintenance. Suitable applications include tolerancing of a RE component in terms of its actual functionality in the prototype assembly or as a spare part for machines that
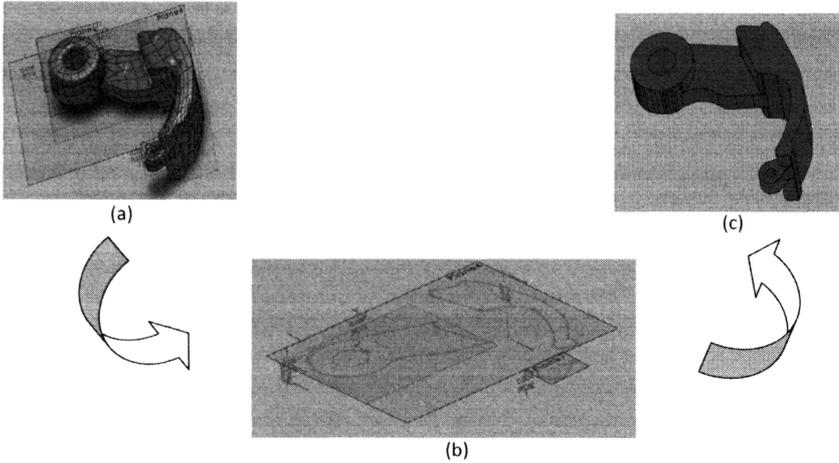
Figure 3: Workflow for Achieving Digitized Parametric CAD Model
(a) NURBS Surface Model, (b) Parametric Sketches, and
(c) Digitized Parametric CAD Model

are out of production and no drawings are available as well as for damage repair [22]. Therefore, prior to RpD, it is beneficial to conduct inspection and comparison of the digitized parametric CAD model, with a reference CAD model. This provides visual feedback on the form and fit of the digitized data [21] to facilitate informed decisions or design modifications before implementing any manufacturing process.

Initially, alignment of the reference CAD model and digitized parametric CAD model was required due to the nature of each CAD model having its own coordinate system. This was achieved with the use of datums followed by an automatic best fit resulting in the digitized parametric CAD model superimposed onto the reference CAD model to permit GD&T function.

Generation of feature control frames or 'callouts' off the reference CAD model is then performed. This allows for certain geometric characteristics of features of interest to be defined for inspection. Cylindricity of the shoe mount (Cylindricity 1) and spring link (Cylindricity 2) as well as flatness of the shoe spine (Flatness 3) and two surface profiles (Surface Profile 4 and Surface Profile 5) were designated as shown in Fig. 4. Furthermore a specified tolerance of 0.5mm was defined for all characteristics since it is critical for the functional requirement of the centrifugal clutch shoe and useful for manufacturing operations. The generated feature control frames were then evaluated within set tolerance.

From Table 1, it can be seen that Surface Profile 5 failed since it exceeded the specified tolerance. The surface profile callouts represent areas of greater

freeform shape. Alterations of the polygon mesh may have affected this region when attempting to reconstruct gaps of data in a flat manner as opposed to a more complex curvature based filling method. These results were to the satisfaction of the customer and as such FEA of the digitized parametric CAD model was initiated.
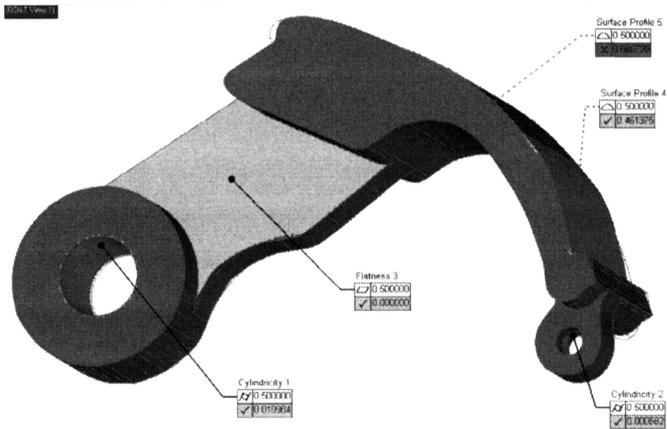
Figure 4: GD&T Callouts

Table 1: GD&T Evaluation

Callout	Tolerance	Measured	Result
Cylindricity 1	0.5	0.011	Passed
Cylindricity 2	0.5	0.001	Passed
Flatness 3	0.5	0.000	Passed
Surface Profile 4	0.5	0.461	Passed
Surface Profile 5	0.5	0.681	Failed

FEA Model

The digitized parametric CAD model was exported as IGES format into the ALGOR software package, with the aim of performing an analysis to determine the stress variations on the clutch shoe. In order to retrieve realistic results, a FEA model of the clutch shoe was generated with constraints and parameters derived from analytical calculations and laboratory based tests emulating its real life operational environment. Initially solid meshing of the clutch shoe within its assembly was performed. Aluminum 201 T6 Cast Alloy, Iron, Gray Cast ASTM A-48 Grade 20 and AISI 1005 Steel materials were then assigned to the clutch shoe, centre plate and clutch bolt components respectively. Furthermore

pinned restraints were set between the clutch bolt and clutch shoe and the centre plate was constrained to rotation only in the z-axis. Subsequently, a centrifugal load of 10000 rpm (anti-clockwise) about the z-axis, surface/contact pressure of -10N/mm² and spring forces of 19.8 N were applied to the clutch shoe within its assembly (refer to Figure 5) after which a static stress with linear material models analysis was conducted.
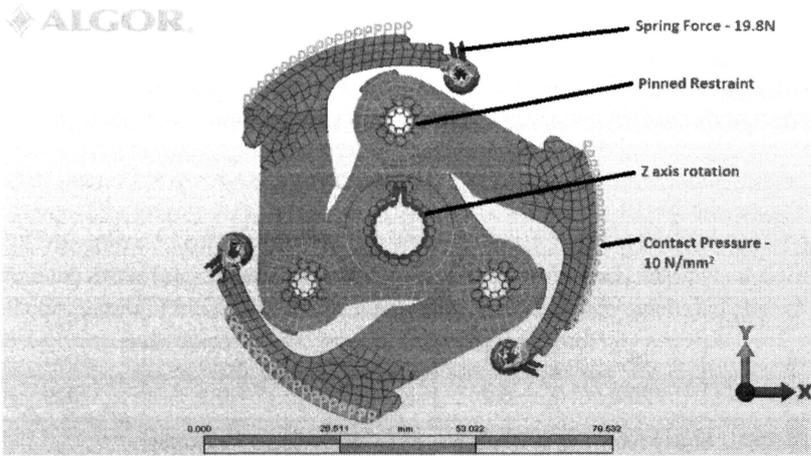
Figure 5: FEA Model of the Centrifugal Clutch Assembly with Constraints and Parameters

The results obtained for stresses on the clutch shoe was noted and verified through manual calculations. On examination of both manual and simulated results, it was found that the simulation results are valid. The high stressed area of the clutch shoe as displayed from the analysis is coincident with the region where the physical clutch shoe actually fractured (refer to Figure 6). This is indicative that under similar conditions, high stresses may have caused the clutch shoe to fail. Now having been able to detect the zone in which the clutch shoe is vulnerable to greater stress, allows for quick modification of the original design through evolution of new models in the CAD system. The purpose is to produce a design that would alleviate the stresses on the clutch shoe especially in the high stress zone detected. Generation of these new CAD models was accelerated through the design table feature available in the SolidWorks package. This parametric tool allows for features on the clutch shoe to be specified and various values assigned to feature dimensions in tandem. Therefore, each new CAD model results in its individual set of feature dimensions.

Figure 2 highlights the features of the clutch shoe. Two new parametric CAD models, M_1 and M_2, were created and individually tested in the FEA system under the same conditions. Accordingly manual calculations were

performed for each new model. Table 2 shows the feature dimensions of the digitized parametric CAD model and assigned values for M_1 and M_2 as well as the maximum calculated and simulated stress values obtained. A comparison of the distribution of stresses in each model is shown in Figure 6. Here we can see that the features, shoe mount outer diameter (SMOD) and shoe spine thickness (SST) have an influential role in stress reduction of the clutch shoe. From the original model to M_2, deviation of the stresses can be seen with the aid of the color spectrum. The red zone indicating the greatest stresses has been diffused from the original model to M_2 due to a wider distribution of smaller stresses indicated by the green and yellow regions of Figure 6. M_1 and M_2 illustrate improvement in design through reduction of the maximum stress on the clutch shoe. As such M_2 was selected for RpD, being the design with least maximum stress.

Table 2: Feature Dimensions and Stress Results of Parametric CAD Models

Model	SMOD (mm)	SST (mm)	SLID (mm)	CMS (N/mm²)	SMS (N/mm²)
Digitized	18.0	4.5	4.0	1932	1643
M_1	19.0	5.5	4.4	1558	1067
M_2	20.0	6.0	4.6	1401	1029

SMOD – Shoe Mount Outer Diameter; SST – Shoe Spine Thickness;
SLID – Spring Link Inner Diameter; CMS – Calculated Maximum Stress;
SMS – Simulated Maximum Stress
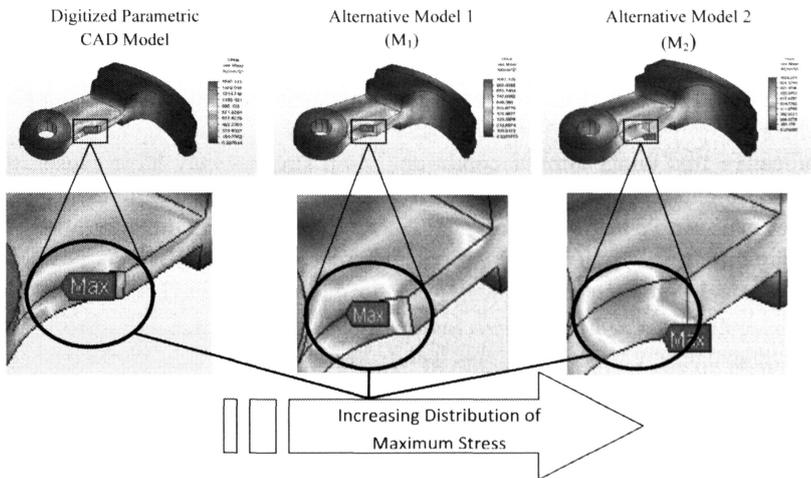
Figure 6: Comparison of Digitized and Alternative Parametric CAD Models'
FEA Results

Rapid Product Development

This is the final stage in which RP and CNC technology were employed for effective design communication to achieve synchronization of the manufacturing process as well as for fast prototyping. RP allows for reduced lead times to produce prototyped components, and improved ability to visualize the part geometry due to its physical existence [23]. The prototype built is then inspected and authorized by the customer for manufacture through CNC machining.

RP Model

The RP model for the broken clutch shoe was built utilizing the Z-Corp 310 3D-Printer. This involved converting the parametric solid CAD model, M_2 into a stereo-lithography (STL) format. Algorithms within the RP system slice the STL file into two-dimensional (2D) cross-sectional layers which is then saved and sent to the 3D printer for building. The RP model is built one layer at a time till completion. Finally, the model was post-processed which included cleaning, post-curing and removing the support materials utilized.

CNC Model

With the RP model meeting the customer's satisfaction, the digitized parametric CAD model selected for prototyping was transferred to a CAM system via STL file. A combination of pocketing and contouring operations was prepared for the generation of the cutter location data. Simulation of the milling sequences for verification of the toolpaths was then performed after which post-processing was initiated to retrieve the NC codes necessary for the CNC machining process. Subsequently the NC codes were imported to the Boxford 300VMCi vertical machining centre for manufacture of the clutch shoe.

Discussion

Although RE and RpD technologies as enablers of agility in product design and development is recognized, little emphasis is placed on the significant contribution of ReE. Validation and testing of CAD models help to detect if the design is within specified tolerance and facilitate identification of areas for improvement. This was demonstrated by an approximate 25 per cent stress reduction with the new parametric CAD model selected, M_2. Also, this iterative process rapidly revises and advances the design which can avoid the overfull prototyping repeats thereby reducing material costs of prototyping and development time of the product [24]. The outcome of this research project supports that agility in design and development stages can be advanced through

integration of RE and RpD technologies together with FEA and GD&T function. The digitized parametric solid CAD model is retrieved from the broken clutch shoe within 24 hours. The optimized design for better performance is made available in only 1 day and once the data sets are processed, the prototype and manufactured part can be delivered within another 48 h. When compared with the expected total downtime of at least one week as well as shipping and part costs, the process presented as part of this research proves to be viable.

Conclusion

In essence, this research has presented a novel framework to integrate design, testing and development processes for better performance of a product in short turnaround time. To achieve agility, computer aided systems were utilized and demonstrated through a case study of a broken free-form centrifugal clutch shoe. RE and CAD systems were instrumental in the rapid development of a digitized parametric CAD model which was first inspected using GD&T and then carried iteratively to engage testing in a FEA system and modification. Design table feature supported instant generation of new CAD models for further testing. The CAD model (M_2) with best results was selected for RpD using a 3D-printer for effective design communication to the customer. CNC machining of the selected CAD model (M_2) was performed after the customer's authorization is granted. Future research is currently being pursued in the area of ReE for optimization of the clutch shoe in terms of material and weight. As such the clutch shoe was manufactured from nylon material for initial investigations.

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