Title:

CAD/CAM Framework for Parametric Design and Fabrication of V-Groove-Based Functional Surfaces

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Introduction:

Functional surfaces are patterned/structured surfaces tailored to a specific surface engineering application, such as control of wettability, friction, aero- and hydro-dynamics, etc. Different applications require different micro-/nano-scale geometric structures and features that are responsible for a specific functionality. Microgrooves or otherwise known as microriblets, are one of the most versatile structures that can enable functionality for different applications. Many examples of this particular type of surfaces can be found in nature and they commonly serve as functional prototypes and designs for bio-inspired drag reduction surfaces [1, 2]. Other common applications of functional surfaces relying on V-grooves include open-channel microfluidics [10], friction control [8], micro-Fresnel lenses [9], light guiding solar [4] and automotive [3] optical designs. In case of open-channel microfluidics, capillary forces cause flow through micro-channels, thus allowing for low cost and low volume diagnostic devices to be manufactured [10]. V-grooves can also provide friction control by allowing lubricant to flow freely along the micro-channels located on a stochastic surface, thus allowing for full lubrication and improvement of the tribological conditions associated with sheet forming processes [8]. Low-cost V-groove-based sun light trapping structures placed on top of solar panels improve photo-voltaic energy conversion of >10% [4] whereas novel sine-shape V-grooves can be efficiently used in automotive light guides reaching an illumination efficiency of 97.7% [3].

However, the high-quality cost-efficient microfabrication of ultraprecise micro-/nano-scale V-grooves is not a trivial task, particularly in case of ferrous alloys. Because of this, single point diamond cutting (SPDC) is typically employed in fabrication of micro V-grooves [5]. This technology usually involves up to six-axis motion control for ultraprecise micro-cutting [7]. In this fabrication approach, V-groove is generated as an 'inverted replica' of the single-point cutting tool geometry. SPDC can be used in several different strategy implementations [9] in order to avoid bending and breakage of high aspect ratio riblets and pyramids that are typically used for super hydrophobic surfaces [1]. Cutting strategies that are significantly different from the previously reported ones (regardless if in their constant chip thickness or constant cutting variants) are required for the fabrication of high-aspect ratio V-grooves characterized by small included angles [6]. Moreover, alternate V-groove generation techniques rely on the redistribution of the superficial layers of workpiece material that was melted as a result of laser irradiation. This newer technology can be regarded as a derivative of laser polishing [3].

The primary rationale of the present study resides in the fact that there are no CAD/CAM solutions available for the automated generation of the tool path trajectories that are specifically developed for micro-cutting of a single and/or a set of V-grooves. To address this, the current study will be mainly focused on the development of a CAD/CAM framework to be used for parametric design and fabrication of linear V-groove-based functional surfaces. The proposed framework includes several functional blocks focused on the automated geometric modelling of a flat surface enclosing a set of periodic V-grooves as well as their generation by means of numerically controlled SPDC operations.

Generalized CAD/CAM Framework for Design and Fabrication

The effective development of functional surfaces requires several interconnected steps starting with the modeling of the surface followed by its fabrication. Once the first surface prototypes are fabricated, they can be subjected to physical tests for evaluation of their functional performance.

According to this intention, the proposed framework illustrated in Fig. 1 consists of several functional blocks related to the parameterization of the workpiece, geometry of the single V-groove, functional surface topography, cutting tool geometry/process strategy/plan. Each function block (FB) represents a specific operation or a set of the geometric parameters required to define a particular design component. In addition, the links between FBs depict the informational flow required to obtain one of the two intended outputs of the framework: a CAD solid body of the functional surface or an NC program to be used to fabricate the desired structured surface.

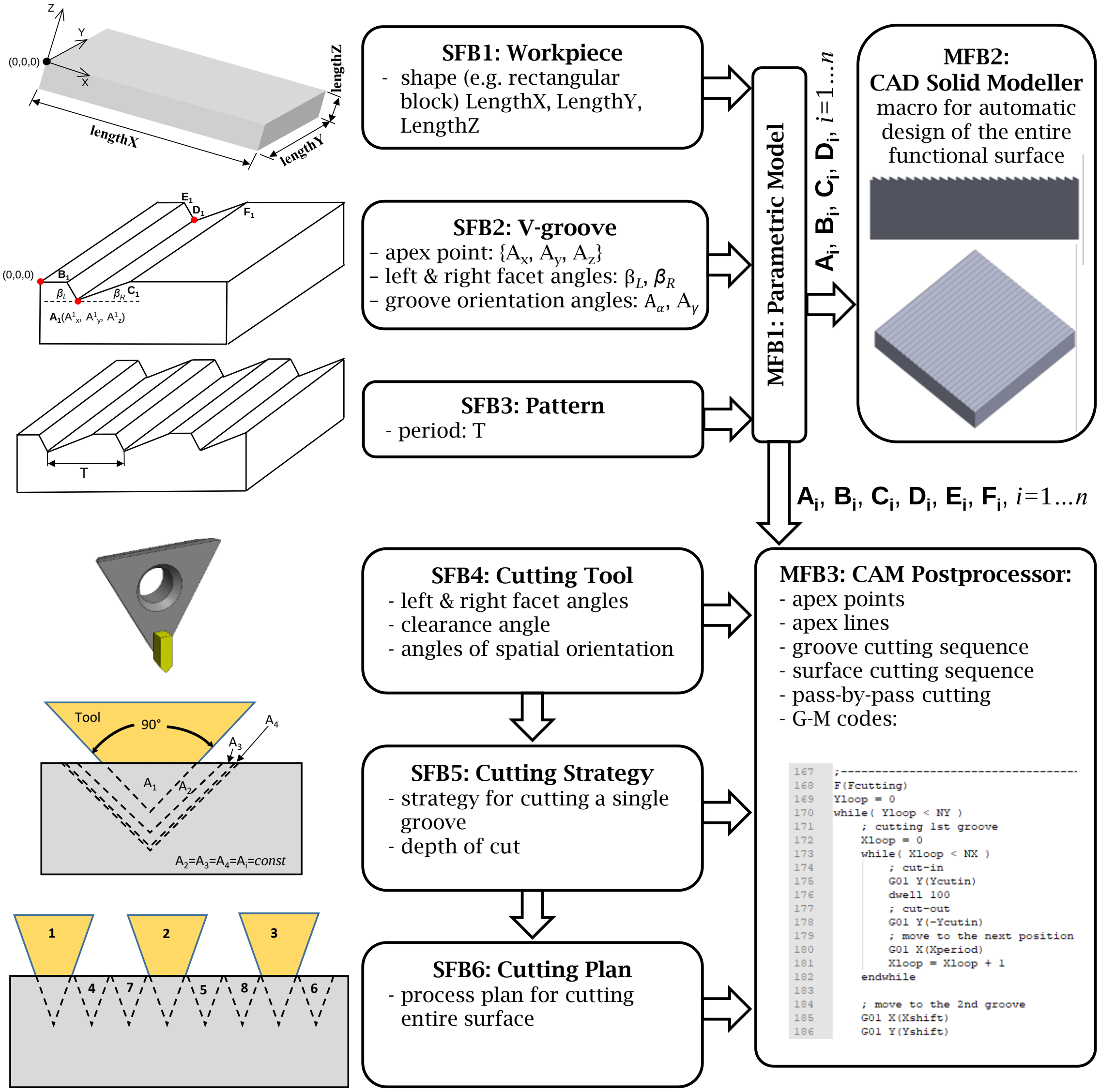
The CAD/CAM framework consists of three main function blocks (MFB) defining core operations and six secondary function blocks (SFB) responsible for defining required design and process parameters. The three MFBs are “Parametric Model” (MFB1), “CAD Solid Modeler” (MFB2), “CAM Postprocessor” (MFB3). The main function of the MFB1 is to define the parametric model of the desired functional surface. For this purpose, this block relies on a set of trigonometric equations to describe the geometry of the functional surface. MFB2 transforms these equations into a corresponding solid model that can be used for visualization, numerical simulations and many other purposes. Finally, MFB3 is used to generate the NC program used in multi-axis SPDC operations. This last FB is the most complex one since it requires comprehensive information with all prior design and fabricated phases.

Parametric Model of the Functional Surface (MFB1)

From a general point of view, the design of any V-groove-based functional surface is comprised of three main geometric components: stock surface geometry, single groove geometry, and distribution pattern of the V-grooves. For this reason, the parametric model of the functional surface design can be conceived as a set of interconnected trigonometric equations involving the aforementioned geometric components.

The development of the parametric model takes place in SFB1-3. In this regard, SFB1 defines the overall shape of the workpiece, location of the origin as well as its main geometric parameters. SFB2 details the geometric model of the “base” V-groove with a triangular cross-section and an apex line as shown in Fig. 2. The V-groove model requires at least seven geometric parameters to be fully defined: coordinates of the first apex point $\mathbf{A}_1 = A_X^1, A_Y^1, A_Z^1$, left and right facet angles β_L and β_R, and two orientation angles of the apex line A_α and A_γ around X and Z axes, respectively. The analytical expression of a 3D line segment enables the determination of $\mathbf{D}_1 = D_X^1, D_Y^1, D_Z^1$ to be become an input for MFB2 and MFB3. While it is possible that the range of definition for the four angular parameters play an important role on the manufacturability of the V-grooves, their actual effect remains unknown at this time and it will constitute the subject of future studies.

The next step is represented by the characterization of the functional surface as a geometrical set of V-grooves that are defined according to the periodic pattern indicated in SFB3. To exemplify this concept, the simplest case of periodic pattern is defined by the period T essentially conceived as the distance between two consecutive apices located along the X-axis. According to this approach, the functional surface will consist of n evenly spaced V-grooves that are located along *lengthX*. SFB1-3 are integrated in MFB1 that outputs two sets of data: i) A_i, B_i, C_i, D_i, $i = 1\ldots n$ as an input to MFB2 (responsible for the generation of a geometric model of the functional surface), and ii) A_i, B_i, C_i, D_i, E_i, F_i, $i = 1\ldots n$ as an input to MFB3 (responsible for generation of the NC program to be used during fabrication of the functional surface).



```
;----------------------------------------
F(Fcutting)
Yloop = 0
while( Yloop < NY )
    ; cutting 1st groove
    Xloop = 0
    while( Xloop < NX )
        ; cut-in
        G01 Y(Ycutin)
        dwell 100
        ; cut-out
        G01 Y(-Ycutin)
        ; move to the next position
        G01 X(Xperiod)
        Xloop = Xloop + 1
    endwhile

    ; move to the 2nd groove
    G01 X(Xshift)
    G01 Y(Yshift)
```

Fig. 1: Proposed CAD/CAM framework.

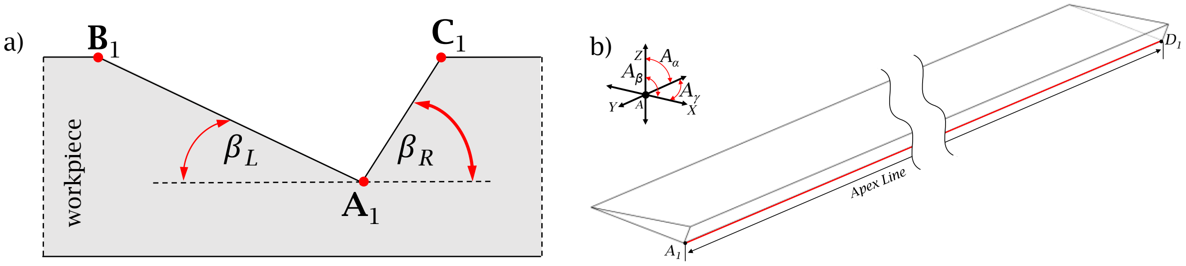


Fig. 2: Geometry of the single V-groove: a) cross-section and b) apex line.

Automated Generation of the Geometric Model (MFB2)

The developed CAD macro constitutes the core of MFB2. This module takes the input parameters represented by points A_i, B_i, C_i, D_i, $i = 1\ldots n$ and converts them into the geometry of the i-th V-groove to be subsequently subtracted from that of the stock. An overview of the CAD macro is presented in Fig. 3. Of note, the geometric modeling approach chosen matches the one subsequently used to fabricate the prototypical V-groove-based surface.

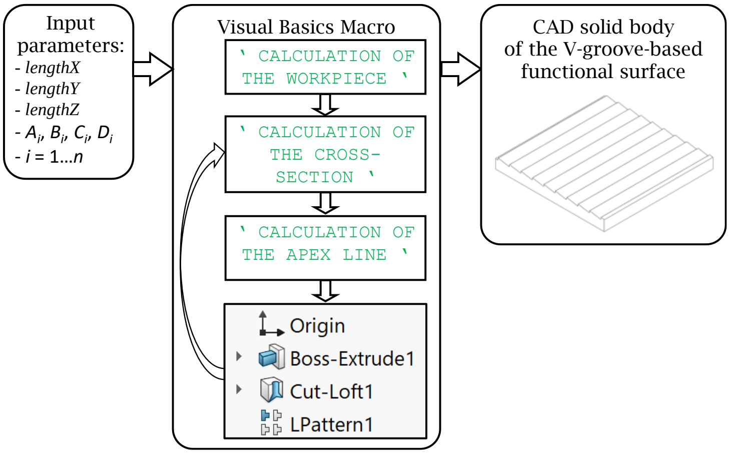


Fig. 3: Overview of the developed CAD macro.

NC Postprocessor (MFB3)

The geometric model of the V-groove-based functional surface represents the key input to the fabrication module aiming to produce its physical replica. Because of this, the NC postprocessor represents one of the key components of the developed framework since in addition to the geometric information it also requires details on tool geometry (SFB4), cutting strategy (SFB5), as well as the overall machining plan for the entire surface (SFB6).

Summary and Conclusions

This study introduces a CAD/CAM framework to be used for parametric design and fabrication of V-groove-based functional surfaces. The framework relies on the geometric parameters of a single V-groove as well as their spatial distribution to generate a solid model of the functional surface. This model constitutes the key input to the fabrication module to employ ultraprecise SPDC in order to produce the surface prototype.

The developed framework makes use of a holistic approach to V-groove design and fabrication and this in turn enables generation of structured surfaces characterized by an elevated level of geometric complexity. The complete version of the current work will present several possible applications of the framework whose results will include both geometric and physical embodiments of V-groove-based functional surfaces. Along these lines, the immediate application of the proposed framework will be represented by the generation of performant drag reduction surfaces. The longer term goal of this research is constituted by the development of a flexible CAD/CAM solution that can design and propose fabrication strategies for complex micro-/nano-scale structures to be placed on a broad variety of non-flat surfaces.

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