Product and Process Innovation for Modeling of Sustainable Machining Processes

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Abstract

Sustainability is recognized as the driver for innovation. However, there is a critical need for improved sustainability evaluation methods, as well as for improved predictive models and optimization methods, to aid decision-making and selection of novel product and process designs for sustainable manufacturing. In the case of machining, increased awareness of the need for sustainability in manufacturing operations has led to significant research in advancing with new and more sustainable processes such as dry, near-dry and cryogenic machining. This paper presents an overview of product and process sustainability evaluation methods and modeling techniques, including analytical, empirical and computational methods, as well as optimization procedures, developed for predicting the performance of sustainable machining processes and major sustainability elements in machined products. The paper also highlights the technological challenges involved, and the future work needed, in developing comprehensive predictive models and optimization techniques for sustainable machining.

Keywords:
Sustainable manufacturing, Machining, Modeling, Products, Processes

1 INTRODUCTION

The critical need to achieve general sustainable development and, in particular, sustainability in manufacturing operations is now well recognized. Sustainable manufacturing is defined as "*the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound*" [1]. Further, sustainable manufacturing includes the manufacturing of *sustainable products* as well as the sustainable manufacturing of *all* products [2]. Thus, the overall need for sustainability drives product and process innovation to yield benefits for all elements of the triple bottom line: environment, economy, and society. Due to the multiple and complex trade-offs involved in product and process design for sustainability, optimization, and hence modeling, becomes critical. Figure 1 presents a schematic view of the blueprint for model-based sustainable manufacturing, enabled by product and process innovation – i.e., model-based product and process design for sustainability, as shown in Figure 2, are essential to achieving overall model-based sustainable manufacturing. In the case of machining processes and machined products, which are the subject of this paper, increased awareness of the need for sustainability has led to significant research in advancing dry, near-dry and cryogenic machining as alternatives to conventional flood cooling. However, there is a lack of comprehensive models for dry, near-dry and cryogenic machining, as well as for sustainability elements of machined products.

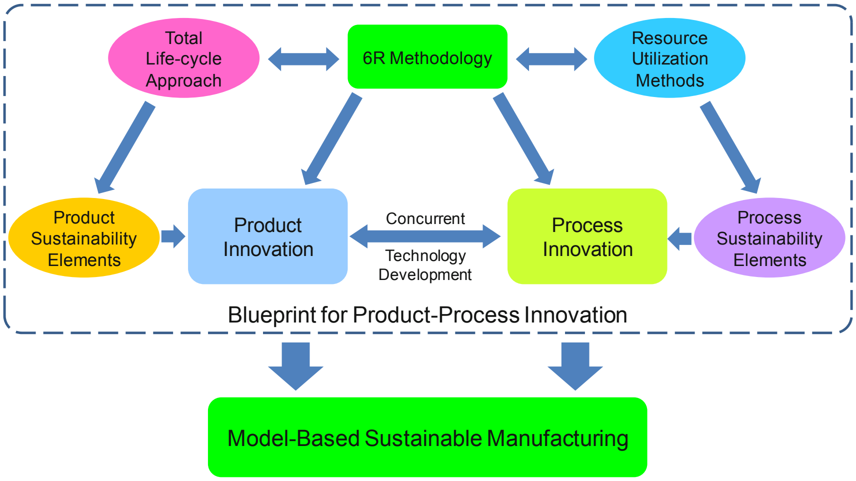

Figure 1: Blueprint for product and process innovation towards achieving model-based sustainable manufacturing.

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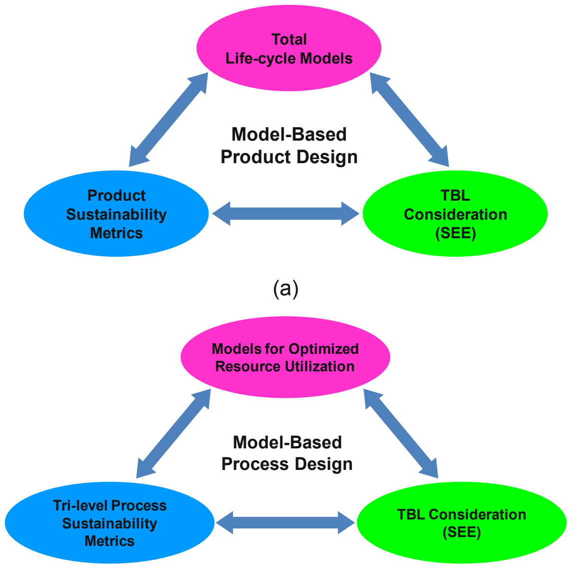

(a)

(b)

Figure 2: Integral elements of (a) model-based product design for sustainability, and (b) model-based process design for sustainability.

This paper presents an overview of product and process sustainability evaluation methods and modeling techniques, including analytical, empirical and computational methods, as well as optimization procedures, developed for predicting the performance of sustainable machining processes and major sustainability elements in machined products. The paper also underlines the challenges involved, and the future work needed, in developing comprehensive predictive models and optimization techniques for sustainable machining.

2 PRODUCT SUSTAINABILITY EVALUATION

Evaluation of product and process innovations aimed at improving sustainability must consider the effect on the total product life cycle due to the multiple energy and material flows involved in a product's life, and the effects of manufacturing processes on product performance and life. Graedel [3] has presented an extensive analysis of streamlined life-cycle analysis (SLCA) methods, including matrix approaches using target plots for five major product life-cycle stages: pre-manufacture; manufacture; product delivery; use; and recycling. In more recent work, a simplified total life-cycle of a manufactured product was assumed to consist of four key stages: pre-manufacturing, manufacturing, use and post-use [4]. Further, the "6R" approach [5] - *Reduce*, *Reuse*, *Recycle*, *Recover*, *Redesign* and *Remanufacture* – was introduced as a significant departure from current manufacturing methodologies (traditional and lean), and from the conventional 3R-based green concept (*Reduce*, *Reuse* and *Recycle*), as it enables the innovation-based transformation from an open-loop, single life-cycle paradigm to a closed-loop, multiple life-cycle paradigm. Developing upon the above-mentioned concepts, de Silva et al. [6] presented a simplified sustainability assessment of design alternatives for a commercial laser printer. The six major sustainability elements identified – environmental impact, functionality, manufacturability, recyclability and remanufacturability, resource utilization/economy, and societal impact (Figure 3) – were classified into 24 sub-elements, which were further divided into 46 influencing factors for the product (Figure 4). The overall product sustainability score was derived based on inputs from design engineers and a survey of manufacturers and consumers, which helped to not only quantify the individual impacts of different influencing factors, but also to determine their relative importance or weighting factors. This work was extended to develop a comprehensive rating system, or generic Product Sustainability Index (PSI), which is versatile enough to be applied to a wide range of products [4]. A (3x4) dimensional matrix, with three rows representing the components of sustainability, and four columns representing the four product life-cycle stages, is developed. A set of influencing factors are then identified and weighted based on their relative importance and company priorities and simple mathematical formulas are used to integrate the PSI across the rows and columns and the overall PSI is evaluated.

3 PROCESS SUSTAINABILITY EVALUATION

The critical challenge in sustainability assessment of machining processes is that only three of the six major sustainability elements of manufacturing processes [9] (Figure 5) can be modeled using analytical and numerical techniques because of their relatively deterministic nature. Modeling of the other three elements requires non-deterministic means, such as fuzzy logic. By extending the previously developed sustainability assessment methodology for machining processes [10], a hybrid model has recently been developed for comprehensive sustainability evaluation of machining processes [9]. Also, this model is extended to include an optimization module to provide the optimum sustainability level of the given machining process in the form of a sustainability index. Thus, as a first approximation, the overall sustainability score for a machining process is constructed as a combined function of the deterministic and non-deterministic sustainability elements:

$$S = (S_{SHE}, S_m) \qquad (1)$$

where S_{SHE} is the sustainability component for safety, health and environmental issues assessed using fuzzy logic and S_m represents the deterministic component dealing with process-related elements such as machining cost, power consumption and waste management, which can be modeled analytically.

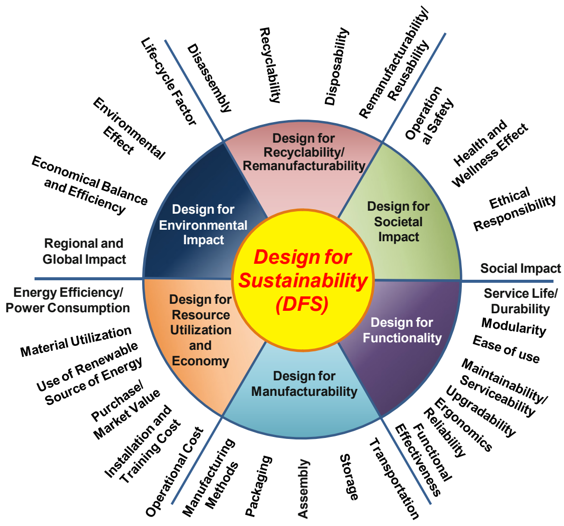

Figure 3: Product sustainability wheel [7].

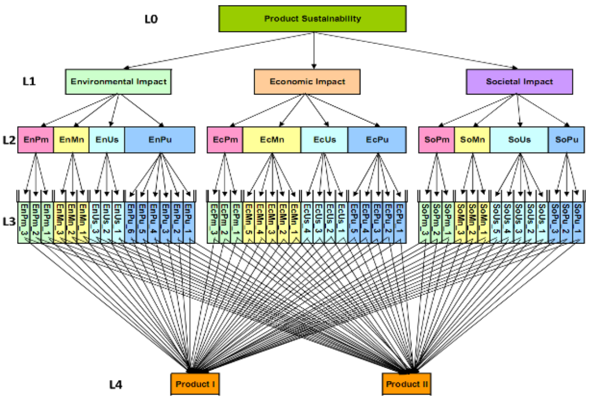

Figure 4: Product sustainability hierarchy [8].

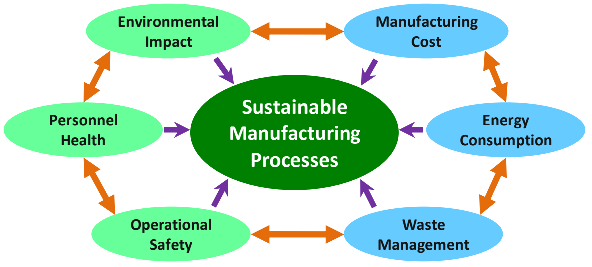

Figure 5: Six elements of sustainable manufacturing processes [9].

For assessing S_{SHE} several primary, secondary and tertiary level sub-elements are identified and classified according to linguistic variables, and then related through fuzzy rules. Finally, the area center method is employed to defuzzify the fuzzy set into a numerical value:

$$Z^* = \frac{\sum_{j=1}^{q} z_j \mu_c(z_j)}{\sum_{j=1}^{q} \mu_c(z_j)} \qquad (2)$$

where z_j is the value of the jth element of the fuzzy set for the output variable and $\mu_c(z_j)$ is its membership grade. The deterministic component of the sustainability rating of the machining process, S_m, is evaluated by considering the machining operation cost, the power consumption and the waste generation. All these elements can be analytically modeled as a function of the cutting conditions. In this study, the generation of waste has been related to chip breakability since achieving good chips during the machining process is directly related to the reduction of waste generation as it increases their reusability and recyclability. MC, PC and CB denote the machining cost, power consumption and chip breakability, respectively. Corresponding constraints on these are assumed as MC_{min}, MC_{max}, PC_{min}, PC_{max}, CB_{min} and CB_{max}. The partial sustainability rating for this component of the machining model is constructed as:

$$S_m = C_{MC}\left(\frac{MC_{\max} - MC}{MC_{\max} - MC_{\min}}\right) + C_{PC}\left(\frac{PC_{\max} - PC}{PC_{\max} - PC_{\min}}\right) + C_{CB}\left(\frac{CB - CB_{\min}}{CB_{\max} - CB_{\min}}\right) \qquad (3)$$

where each term is normalized by the user-provided information concerning machining operational sustainability requirements. The parameter S_m is expressed as a value between 0 and 1 and C_i (i = MC, PC, CB) are the weighting factors considered as the contribution coefficients of ith machining sustainability parameter to the value of the operation. Using the above procedure for calculating S_{SHE} and S_m, and by initially assuming that there is no significant interaction between the two, separate optimization techniques are applied to determine a global optimum for achieving maximum process sustainability.

4 DRY MACHINING

Research efforts in sustainable machining have mainly focused on: (a) dry machining, or machining without any coolants/lubricants [11]; (b) near-dry or minimum quantity of lubrication (MQL) machining, in which minute quantities of lubricants/coolants are employed in spray form [12]; and (c) cryogenic machining, which utilizes ultra-low temperature coolants (usually N_2 or CO_2) that are non-hazardous and easily evaporate leaving no residue [13]. This section presents brief summaries of recent modeling and optimization efforts, and the challenges involved, in dry machining.

4.1 Analytical modeling of turning operations

The difficulty in extending fundamental 2D models to practical 3D operations is the major challenge for analytical and computational modeling of dry machining. Our initial work to overcome this limitation includes the development of a comprehensive model for prediction of elemental primary forces (main cutting and thrust forces) and secondary (machine tool-oriented) forces, with the total forces evaluated as the sum of the 'edge' forces at the cutting edge and the 'area of cut' forces at the rake face [14]. Further, the equivalent toolface (ET) method [15] was developed for predicting cutting conditions and chip curl in turning with grooved tools by determining the equivalent flat-faced tool geometry that generates the same machining forces. Ghosh et al. [16] also developed a model for 3D chip curl by approximating the chip as a twisted 3D elastic beam and proposed a new failure criterion for chip breaking based on the calculated octahedral shear stress. In the case of fundamental 2D modeling, major research efforts have been undertaken at the University of Kentucky to develop new slip-line models for machining of ductile materials with rounded cutting edge restricted contact grooved tools [17]. Oxley's machining theory [18] was integrated with the new slip-line model to give predictions of cutting forces, chip thickness, chip curl radius, strain, strain-rates and temperatures in the shear zone and at the tool-chip interface [17].

4.2 Numerical modeling of turning operations

Recent work at the University of Kentucky involves the development of improved finite element models to study residual stresses in 2D dry machining [19] by: (a) employing a modified Johnson–Cook model to describe the material behavior as a non-Newtonian fluid; (b) using a remeshing scheme to simulate material flow around the cutting tool edge without the use of a separation criterion; (c) properly accounting for the unloading path; and (d) considering the thermomechanical coupling effect on deformation. Subsequently, the FE model was expanded to also include coolant effects for simulating near-dry and flood-cooled machining [20] (Figure 6).

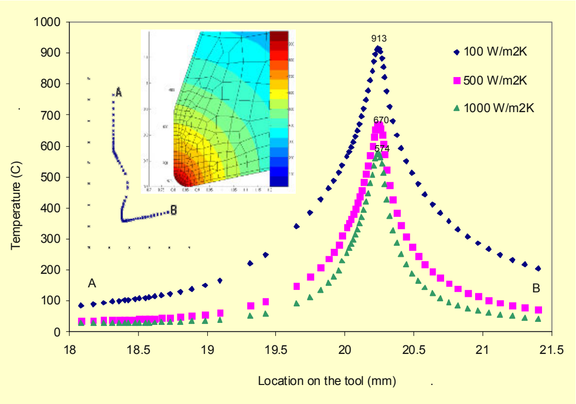

Figure 6: FE modeling of the temperature profile on the tool surface under different cooling conditions [20].

More recently, a hybrid empirical-FE model has been developed to investigate surface integrity phenomena – formation of white and dark layers in the surface and subsurface of hard machined parts – by including empirical equations for phase transformation, in combination with a hardness-based flow rule, in a FE model for orthogonal machining of hardened AISI 52100 steel [21].

4.3 Hybrid predictive modeling and optimization

Our recent research highlights the use of advanced computer-aided, fuzzy logic and genetic algorithms (GA) applications for single and multi-pass machining optimization in turning, milling and drilling using hybrid experimental and predictive models. For example, Wang and Jawahir [22] have employed GA methods for optimization of cutting conditions and tool selection in multi-pass turning with tool-wear by using predictive models for some machining performance measures, such as cutting forces, experimental databases for certain other measures, such as surface roughness, and a fuzzy logic-based assessment method for chip-form/chip breakability [23]. Predictable chip breaking is an essential requirement for automated machining and early work on the analysis of 3D cyclic chip formation and chip breaking cycles provides the foundation for subsequent analysis of chip breaking in machining with grooved tools [24]. Using the chip charts produced for different combinations of tools, work materials and cutting conditions, a new method for quantifying chip breakability was derived based on the fundamentals of fuzzy reasoning [23].

4.4 Tool-wear/tool-life prediction

Tool-wear/tool-life is one of the most important machining performance measures for process planning. The conventional methods of tool-wear measurement for flat-faced tools are inadequate for characterizing the multiple, concurrent and complex wear mechanisms in grooved tools. Jawahir et al. [25] presented a new methodology for the complex tool-wear in grooved tools, and developed a new method [26] to predict tool-life in turning with coated grooved tools, which includes the chip-groove effects (W_g) and the coating effects (W_C) as follows:

$$T = T_R W_g \left(\frac{V_R}{V}\right)^{W_C \frac{1}{n}} \tag{4}$$

where, T = tool-life, T_R = reference tool-life (1 minute), W_g = chip-groove effect factor, V_R = reference cutting speed (for 1 minute tool-life), V = cutting speed, W_C = coating effect factor and n = Taylor's tool-life exponent.

5 NEAR-DRY MACHINING (NDM)

5.1 Significance

NDM (or minimum quantity lubrication – MQL) provides a sustainable alternative to dry machining as it helps to reduce the use of cutting fluids significantly while the tool-life and performance requirements are maintained uncompromised. Our early work on spray cooling in machining of stainless steels showed significant improvement in surface roughness, cutting forces, chip forms and tool-life [27]. Attempts to quantify the performance improvements in NDM show a great potential for reducing the tool-chip friction coefficient and improving machining performance [20, 28-29].

5.2 Case studies in modeling of NDM

Near-dry turning of AISI 4140 steel

Experimental observations of NDM in turning lead to several conclusions [20]: (i) Flood-cooling produces approximately 10-18% higher cutting forces than oil-based NDM in finish-turning; (ii) Cutting forces and surface roughness are lower over time with NDM, while an increasing trend is observed in flood-cooling; (iii) Chip-form/chip breakability improves with proper application of NDM methods; (iv) In fine finish-turning with oil-based NDM the surface roughness is significantly lower than with flood cooling and water-based NDM; (v) Metallographic analysis shows reduced tool-chip interface friction in NDM compared to flood cooling; (vi) NDM is more effective in light machining operations as compared to heavy machining. The original tool-life equation by Jawahir et al. [25] was modified to include the fluid type, flow rate and nozzle(s) position with respect to the cutting tool and workpiece [28]:

$$T = T_R \frac{km}{f^{n_1} d^{n_2}} \left(\frac{V_R}{V}\right)^{\frac{1}{n} W_C \frac{1}{N_{NDM}}} \tag{5}$$

where N_{NDM} is the NDM effect factor, given by:

$$N_{NDM} = n_{mist} / n_c \tag{6}$$

where n_c is the coating effect factor and n_{mist} is the modified coating factor for NDM mist spray, defined as:

$$n_{mist} = \frac{\log V_1 - \log V_2}{\log(G_{F,W,N,M_{ZX},M_{ZY}}) - \log T_1} \tag{7}$$

where $G_{F,W,N,M_{ZX},M_{ZY}}$ is the new modified tool-wear using the NDM application, empirically derived while varying fluid type, flow rate and nozzle(s) position. The new tool-life equation provides significantly greater accuracy than the original equation proposed for dry machining.

Near-dry face milling of automotive alloy A380

The face milling of automotive aluminum alloy A380 was studied under four different lubrication/cooling conditions: dry, flood cooling, MQL (Oil), and MQL (Water). Empirical models of surface roughness and cutting forces were developed in terms of cutting speed, feed and depth of cut. A previously developed comprehensive optimization procedure for multi-pass turning [22] was extended to two-pass face milling to optimize the performance under different lubrication/cooling conditions based on a criterion integrating the effects of all major machining performance measures: surface roughness, cutting forces, tool-life and material removal rate [29]. Three combinations of lubrication/cooling conditions were studied for the two-pass face milling operation: Dry-Flood, Dry-MQL (Oil) and Dry-MQL (Water). Comparison between the finish passes of flood cooling, MQL (Oil) and MQL (Water) shows that the optimum point for finish pass with MQL (Oil) condition gives comparable results to that of the optimum point in finish pass with flood cooling. The surface roughness in case of flood-cooling is marginally lower than with MQL (Oil) but the cutting forces are nearly double of the MQL (Oil) condition.

6 CRYOGENIC MACHINING

6.1 Research activities in cryogenic machining

Research in cryogenic machining encompasses several areas, including: cryogenic properties of cutting tools [30]; cryogenically machined work surface properties [31]; and cryogenic machining performance in hardened materials and heat-resistant alloys [13]. Cryogenic machining has been shown to impart several improvements, including: (i) Environmentally-friendly and safe coolant: Nitrogen is an inert gas that constitutes 79% of atmospheric air; (ii) Increased productivity: Both hardness and toughness of cutting tools have been shown to increase under cryogenic cooling, allowing increased material removal rates; (iii) Improved part surface quality: Cryogenically machined parts were found to have improved surface integrity and fatigue resistance [31]; (iv) Process step reduction: Cryogenic cooling results in more economical machining in the hardened condition for many materials, allowing intermediate heat-treating steps to be eliminated [31].

6.2 Modeling and optimization of Inconel 718 machining

Inconel 718, a nickel-based aerospace alloy, is difficult to machine since it does not undergo significant thermal softening during cutting and its low thermal conductivity causes the heat generated to be concentrated near the cutting edge, leading to excessive tool-wear. Thus, the optimized selection of cooling/lubricating agents and cutting conditions is crucial for high-performance machining of Inconel 718. Pusavec [13] studied the effects of different cooling/lubrication methods (dry, near-dry, cryogenic, and combined cryogenic-MQL) on machining forces, surface roughness, tool-wear and chip breakability during turning of Inconel 718 under various conditions. The models developed through response surface methodology were employed to optimize the process using genetic algorithms. As shown in Figure 7, the combined application of cryogenic fluid from the flank and MQL application from the rake side yielded the best overall results.

7 CONTROL OF MACHINING FOR IMPROVED SURFACE INTEGRITY AND PRODUCT LIFE

An important aspect of product sustainability is the effect of manufacturing processes on the product's service life, which is often limited by failure through fatigue, corrosion, wear, etc., through their effect on the product's surface integrity. The product life is an important sustainability parameter since it determines the rate at which products end up in the landfill, or undergo remanufacture or recycling. Our recent work in this area includes experimental investigation and numerical modeling of the effects of cutting tool edge radius on microstructural changes and residual stresses in the surface and subsurface of machined parts [33] (Figure 8).

8 SUMMARY

This paper presents an overview of product and process innovation for sustainability and modeling techniques, including analytical, empirical and computational methods, as well as optimization procedures, developed for predicting the performance of sustainable machining processes and major sustainability elements in machined products, such as the surface integrity measures with critical influence on product performance and life. The paper also highlights the technological challenges involved, and the future work needed, in developing comprehensive predictive models and optimization techniques for sustainable machining.

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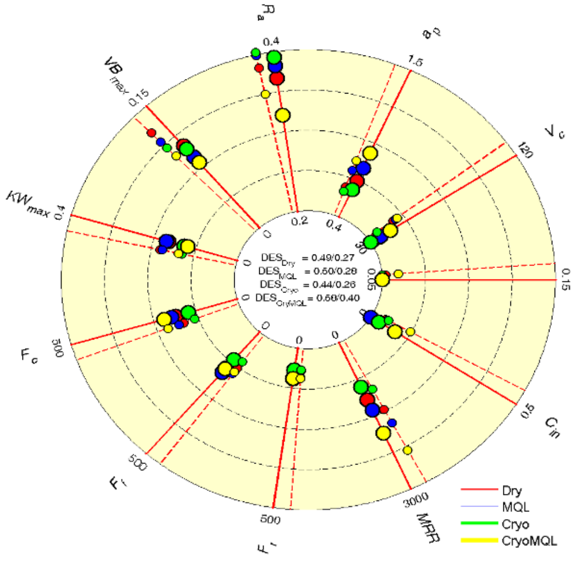
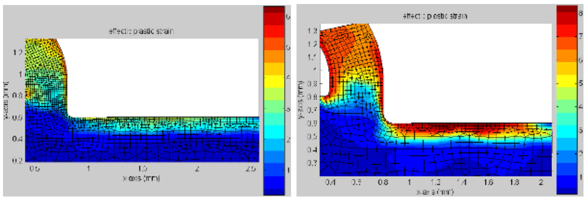


Figure 7: Optimum cutting conditions and corresponding desirability index (DES) with (solid lines) and without (dashed lines) inclusion of fuzzy-rule evaluation of chip breakability in the optimization procedure [13].



(a) (b)

Figure 8: FE simulation of plastic deformation produced in AISI 1045 steel by: (a) 50 µm and (b) 80 µm cutting edge radius tools (*V* = 175 m/min, *f* = 0.20 mm/rev) [33].

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