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Software prototype for solving multi-objective machining optimization problems: Application in non-conventional machining processes

Marko Kovačević [a,*], Miloš Madić [b], Miroslav Radovanović [b], Dejan Rančić [a]

[a] Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, Niš, Serbia
[b] Faculty of Mechanical Engineering, University of Niš, Aleksandra Medvedeva 14, Niš, Serbia

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ABSTRACT

For an effective and efficient application of machining processes it is often necessary to consider more than one machining performance characteristics for the selection of optimal machining parameters. This implies the need to formulate and solve multi-objective optimization problems. In recent years, there has been an increasing trend of using meta-heuristic algorithms for solving multi-objective machining optimization problems. Although having the ability to efficiently handle highly non-linear, multi-dimensional and multi-modal optimization problems, meta-heuristic algorithms are plagued by numerous limitations as a consequence of their stochastic nature. To overcome some of these limitations in the machining optimization domain, a software prototype for solving multi-objective machining optimization problems was developed. The core of the developed software prototype is an algorithm based on exhaustive iterative search which guarantees the optimality of a determined solution in a given discrete search space. This approach is justified by a continual increase in computing power and memory size in recent years. To analyze the developed software prototype applicability and performance, four case studies dealing with multi-objective optimization problems of non-conventional machining processes were considered. Case studies are selected to cover different formulations of multi-objective optimization problems: optimization of one objective function while all the other are converted into constraints, optimization of a utility function which combines all objective functions and determination of a set of Pareto optimal solutions. In each case study optimization solutions that had been determined by past researchers using meta-heuristic algorithms were improved by using the developed software prototype.

1. Introduction

In recent years there has been an increase in development and application of difficult-to-machine materials such as titanium, stainless steel, high-strength temperature-resistant alloys, ceramics, composites, super alloys, etc. (Samanta & Chakraborty, 2011). These materials have a wide use in modern industry due to their improved technological properties such as high mechanical strength and hardness, high temperature, wear and corrosion resistance and strength-to-weight ratio. Machining of these materials by conventional machining processes gives rise to problems such as high cutting forces and temperatures, rapid tool wear and generation of residual stresses in the workpiece. As a result, the tool life and machining quality are reduced, while the machining time and costs are increased (Rao & Kalyankar, 2011; Samanta & Chakraborty, 2011). In recent years customer demand for machining new, hard and difficult-to-machine materials of complex geometries with tight tolerances and high demands regarding quality as well as manufacturers' striving for reducing costs and improving customer service level, in order to increase competitiveness on the market, have resulted in the fact that the application field of non-conventional machining processes has been further expanded and become more and more important in the industry.

A large number of non-conventional machining processes are available in the manufacturing industries such as ultrasonic machining, laser beam machining, abrasive water jet machining, electrical discharge machining, wire cut electric discharge machining, chemical machining, electro-chemical machining, plasma arc machining, etc., and each process possesses its own advantages and limitations (Rao & Kalyankar, 2011). In general, the application of non-conventional machining processes involves the use of energy in direct form, e.g. mechanical energy by abrasive water jet machining, heat energy by laser and plasma machining, thermoelectric energy by electric discharge machining, etc. A unique characteristic of these processes is that there is no direct

* Corresponding author. Tel.: +381 642705028.
E-mail address: marko.kovacevic@elfak.ni.ac.rs (M. Kovačević).

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contact between the tool and the workpiece, as well as the ability to concentrate large amounts of energy per unit area.

From the technological point of view, each non-conventional machining process is a very complex, multi-input multi-output process governed by a large number of machining parameters (input variables). In most of the non-conventional machining processes, more than one machining performance characteristic (output, response) has to be considered for the selection of machining parameters, making it necessary to formulate and solve multi-objective optimization problems (Somashekhar, Mathew, & Ramachandran, 2012). For an effective application of these machining processes the selection of optimal machining parametersfor achieving high quality and productivity at minimum cost is of prime importance (Samanta & Chakraborty, 2011). Furthermore, as noted by Rao and Pawar (2009), the optimal selection of machining parameters is essential as non-conventional machining processes incur high initial investment, tooling cost, operating cost and maintenance cost.

In many manufacturing industries it is common practice that machine tool operators select the machining parameters based on acquired knowledge, previous experience and machining handbooks. This approach is in essence subjective and selected values do not guarantee an optimum machining conditions. Furthermore, an inadequate selection of machining parameters may lead to product quality deterioration, increase in operation cost and machining time and reduced production (Rao & Kalyankar, 2011). Finally, the procedure of machining parameters selection may be time consuming.

To gain a competitive advantage on the fierce market, get the most from a machine tool and enhance machining efficiency in terms of satisfying multiple performance characteristics, it is necessary to select machining parameters more intelligently. The development of relationships between the machining performance characteristics and its machining parameters by modeling the process using mathematical methods and optimization by applying suitable optimization algorithms and techniques has been well recognized as an effective way for selection of optimal machining parameters (Rao & Pawar, 2009; Somashekhar et al., 2012). An expert system for selection of optimal machining parameters has been developed by Torres-Treviño, Escamilla-Salazar, González-Ortíz, and Praga-Alejo (2013). The developed expert system incorporates both mathematical modeling and optimization using symbolic regression alpha–beta and evolutionary algorithm Evonorm. Although, as noted by authors, proved to be very useful in selection of optimal parameters in various machining processes, its applicability for solving multi-objective optimization problems has not been considered.

An analysis of literature related to the optimization of different conventional and non-conventional machining processes (Kondayya & Gopala Krishna, 2013; Mukherjee & Chakraborty, 2013; Pandey & Dubey, 2012; Rao & Kalyankar, 2011; Rao & Pawar, 2009; Sadeghi, Razavi, Esmaeilzadeh, & Kolahan, 2011; Samanta & Chakraborty, 2011; Somashekhar et al., 2012; Yildiz, 2009; Yusup, Zain, & Hashim, 2012; Zain, Haron, & Sharif, 2011) reveals that, because of the complexity and nonlinearity between machining parameters and performance characteristics, authors prefer direct search methods over traditional mathematical methods such as linear and nonlinear programming methods. As noted by Rao and Pawar (2009), these traditional mathematical methods do not fare well over a broad spectrum of problem domains, may not be robust and they tend to obtain a local optimal solution. Furthermore, they are very complex in nature and cannot handle multi-objective problems effectively (Rao & Kalyankar, 2011).

Among different direct search methods, meta-heuristic algorithms have attracted considerable attention from researchers for solving machining optimization problems. These algorithms offer a derivative-free approach for near-optimal solution(s) search direction, and may be applied to discrete or continuous objective function. By using the objective function information (fitness) instead of the functional derivatives they tend to be more robust and effective than the traditional methods (Rao & Pawar, 2009), and do not have the limitations of gradient methods i.e. concavity, continuity, and derivability of the objective function (Pandey & Dubey, 2012). Meta-heuristic algorithms are also suitable for solving multi-objective optimization problems. Particularly, population based meta-heuristic algorithms are suitable for finding Pareto optimal solutions of multi-objective problems. As noted by Yildiz (2009) and Mukherjee and Chakraborty (2013), they are characterized by high computational and convergence speed.

Although it has been shown that meta-heuristic algorithms offer better performance over traditional methods for solving complex optimization problems, they are plagued by various limitations such as: (i) premature convergence to a local optimum and poor exploitation abilities (Wan-li & Mei-qing, 2013; Yildiz, 2009), (ii) difficulty of determining optimum algorithm-specific controlling parameters so that meta-heuristic algorithms may not provide an optimal solution for a complex optimization problem having a large number of input variables and constraints (Rao & Kalyankar, 2011), (iii) even expert knowledge in meta-heuristic algorithms, systematical selection of the algorithm-specific controlling parameters, as well as understanding of the optimization problem being solved, do not guarantee the optimality of the optimization solution (Kovačević, Madić, & Radovanović, 2013), and (iv) stochastic nature of meta-heuristic algorithms implies that, even for the same algorithm-specific controlling parameter settings, each run of the meta-heuristic algorithm may produce different optimization solutions.

Recently, new meta-heuristic algorithms and hybridization of existing meta-heuristic algorithms for solving optimization problems have emerged (Cuevas & Cienfuegos, 2014; Maashi, Özcan, & Kendall, 2014; Nguyen, Li, Zhang, & Truong, 2014). Although proved to be competitive over existing meta-heuristic algorithms, their application for solving multi-objective machining optimization problems are not yet well analyzed in literature.

The potential for solving the aforementioned machining optimization problems also have other optimization methods that are conceptually simpler, and, arguably, easier for practitioners. The continual increase in computing power and memory size has revived interest in brute force techniques for a good reason (Nievergelt, 2000). These techniques are especially suitable for the use in the machining optimization domain, where technical–technological limitations of machine tools impose that some or all input variables take values from the order set of discrete values. Our previous work presented a software prototype, based on an exhaustive iterative search, for solving single-objective machining optimization problems and a narrow subset of multi-objective optimization problems that can be transformed to single-objective optimization problems (Kovačević et al., 2013).

The motivation of this paper was to develop software prototype for solving multi-objective machining optimization problems using conceptually simple algorithm based on an exhaustive iterative search, and explore its efficiency and effectiveness by comparing it to the state of the art algorithms for multi-objective optimization of non-conventional machining processes. Developed software prototype represents an improved and extended version of the software prototype presented by Kovačević et al. (2013). Use of an algorithm based on an exhaustive iterative search is justified by two main reasons: (i) it determines solutions which optimality is guaranteed in the given discrete space of input variable values, and (ii) there are no algorithm-specific controlling parameters. The first reason is of prime importance for machining processes where techno-technological limitations of machine tools impose that some or all input variables take values from the order set of