Journal of Cleaner Production 85 (2014) 293–305

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Concurrent multi-response optimization of austenitic stainless steel surface roughness driven by embedded lean and green indicators

George J. Besseris [a, b, *], Alexandros T. Kremmydas [a, b]

[a] Advanced Industrial & Manufacturing Systems Program, Mechanical Engineering Department, Technological Education Institute of Piraeus, Greece
[b] Kingston University, London, UK

ARTICLE INFO

Article history:
Received 28 May 2013
Received in revised form
11 May 2014
Accepted 23 May 2014
Available online 8 June 2014

Keywords:
Drilling
Surface roughness
Order statistics
Design of experiments
Manufacturing sustainability
Lean and green production

ABSTRACT

International ecodesign initiatives encourage drilling process improvements that are also attentive to energy and peripheral materials consumption. A stainless-steel heat-exchanger component is optimized for surface quality during drilling while taking into account lean-and-green improvements. A non-linear four-factor fractional factorial scheme has been utilized to investigate the surface roughness performance due to: 1) the feed rate, 2) the spindle speed, 3) the twist drill type and 4) the coolant concentration. We address simultaneously the cumulative effect of multiple consecutive drillings on the surface quality of the last machined hole of a tube-sheet test plate. The concurrent optimization effort regulated the weighted surface quality performance of the drilling process by suppressing consumptions for: 1) energy – monitored at the final drilling and 2) coolant fluid. The weighted distribution-free optimization scheme was repeated to compound information from a key lean process indicator, the drilling processing time. It was found that the feed rate (at 70 mm/min) and the spindle speed (at 350 rpm) commonly influence non-linearly the surface roughness response (predicted at 1.05 μm) in both multi-response scenarios. The drill type (Guhring No. 8520) was also a statistically important effect when excluding optimality with respect to improved lean and green process performance. In such a case, the spindle speed needed to be decreased to 300 rpm for a predicted surface roughness of 0.86 μm (confirmed within 3%).

1. Introduction

High-throughput manufacturing processes need to undergo intensive environmental and sustainability enhancement in order for products to remain competitive in global markets (Hallstedt et al., 2013; Laszlo and Zhexembayeva, 2011). For modern product developers, it is not sufficient anymore to screen and optimize a product/process based solely on its terminal technical functionality. When building or improving successful products/processes, the technical prowess of a process or a product is anticipated to be balanced with specific lean and green quotas to ensure sustainable growth in the future (Dhingra et al., 2012; Dues et al., 2013; Zokaei et al., 2013). The lean concept addresses the progressive minimization of waste and maximization of productivity in a holistic way across an enterprise (Byrne and Womack, 2012). The green concept espouses resource and energy consumption minimization often in synergy with promoting leanness in an operation (Baumann et al., 2002; Deif, 2011; Friend et al., 2009). Production designed for enduring competitive global positioning then fosters development on an unbreakable triple axis that dictates three concerns: quality, sustainability and productivity. While quality and productivity may be boosted through company-wide standard business initiatives such as the Lean Six Sigma, the same quality-related concepts may well be suited for accelerating the greening of host operations (Silva et al., 2013a,b; Voehl et al., 2013). In optimizing and stabilizing processes for breakthrough performance, Lean Six Sigma endorses Design of Experiments (DOE) as core strategy to plan and screen the data-driven improvement cycle (De Mast and Lokkerbol, 2012; Pyzdek and Keller, 2009). DOE has been shown to be a promising tool to be deployed for 'designing for the environment' by materializing robust solutions for green production (Ben-Gal et al., 2008; Besseris, 2010a, 2012a). Dealing synchronously with lean and green responses has been demonstrated to be convincingly handled with multi-response multi-factorial DOE routines, even in complex operations such as those encountered in the maritime field (Besseris, 2011). Cleaner production propounds the incessant searching for

* Corresponding author. Advanced Industrial & Manufacturing Systems Program, Mechanical Engineering Department, Technological Education Institute of Piraeus, Greece.

E-mail address: besseris@teipir.gr (G.J. Besseris).

http://dx.doi.org/10.1016/j.jclepro.2014.05.074
0959-6526/

discovering and deploying tactics and methods to facilitate the delivery of sustainable product/process improvements by enmeshing environmental innovation (Aguado et al., 2013). We present in this work a concurrent optimization case study that engulfs all three aspects of leading edge manufacturing by attempting to comprehensively improve traits of quality, sustainability and productivity in a single effort. The showcased paradigm is drawn from the popular field of machining processes. It aims to aid in exemplifying the 'leaning' and 'greening' of surface roughness performance in mainstream mass customization steel products.

1.1. Towards lean and green machining operations: improving surface roughness

In the manufacturing industry, one of the most important cutting processes is drilling, since about 75% of the total material removal processes in metal-cutting are attributed to drilling operations (Manikandan and Rajeswari, 2013). Drilling, if not controlled properly, could affect the machining properties of the workpiece, create burr on the exit of the holes and leave the inside of the holes with high surface roughness and helical feed marks. High profile products directly affected by cutting processes are mainly identified with the aerospace, automotive, and energy industries. Besides investigating the pure phenomenological aspects of machining technology, modern production tactics for processing turned parts propound the sustainability of host operations (Pusavec et al., 2010). It becomes imperative that operational efficiency be counterbalanced in terms of energy efficiency and quality performance as in the instructive case of face-milling C45 steel blanks (Yan and Li, 2013). In an optimization effort for a machining process, the environmental performance should be accounted along with the relevant process characteristics in a synchronous manner and not independently (Mijanovic and Kopac, 2005; Zhou et al., 2012). Thus, fundamental work in optimizing energy consumption has been conducted for CNC-turned-parts quality studies through in-depth applications assisted by implementing multi-response DOE tools (Aggarwal et al. 2008; Rajemi et al., 2010). Similarly, Taguchi methods supported with multi-factorial ANOVA treatment have been demonstrated to be decisive for minimizing energy requirements while turning a valuable AISI 6061 (T6) aluminum-alloy product (Camposeco-Negrete, 2013). Research on the interplay between minimizing energy and optimizing surface roughness and tool wear for an AISI 304 steel workpiece material exemplifies the current trend for deciphering viable adjustments with DOE techniques in green end-milling (Kuram et al., 2013). Moreover, favorable results have been achieved through multi-response DOE methods when suppressing power consumption and tool deterioration in CNC-turning parameter optimization of an aluminum metal-matrix (SiC-particle) composite (Bhushan, 2013). Meanwhile, great interest receives the issue of reducing resource consumption such as the amount of cutting fluids (Fratila and Caizar, 2011). The cutting fluid performance has become an indispensable issue for managing green operations, therefore, its evaluation has been shown to be a key theme in machining quality (Cetin et al., 2011). The subject of effecting minimum quantity lubrication has already been critically assessed regarding a wide range of machining operations (Lawal et al., 2013). The drivers for minimum quantity lubrication are eventually economic and environmental while they aid in reinforcing a manufacturer's image as socially more accountable by preventing waste generation (Silva et al., 2013a,b). The determinants for limiting lubricant/coolant usage are specific among others to the workpiece material and geometry, tool material and type, machining parameters and the lubricant formulation itself thus making it difficult to generalize accurately for all possible cases. Hence, it is recommended that in clean production studies there should be a provision for parallel lubricant monitoring until the optimal quantity has been identified for the particular examined conditions. Finally, managing to minimize simultaneously the process duration (lead time) may be a high priority goal in making operations more competitive while sustainable and in accord with the premises of lean manufacturing.

1.2. Statement of the problem

The surface roughness of machining a heat-exchanger tube sheet (AISI 304L stainless steel) receives a concurrent profiling by including characteristics of quality, sustainability and productivity. The selected controlling factors for the cutting process are: feed rate, spindle speed, cutting tool type and cutting (coolant) fluid. Attaining optimal surface roughness on a set of sequentially completed holes on a tube sheet is critical since tube expansion is dependent on the actual hole dimensioning. A satisfactory expansion of a tube in the tube-sheet structure will give a trouble-free operation for the heat exchanger while assuring that the two heat-exchanger working fluids will not come in direct contact. However, drilling a complete set of holes in a tube sheet is a time-consuming process. For a given experimental layout, we complete 25 drillings at a time before pausing for drill maintenance, since that count of drillings mirrors in-house real-life production demands while ensuring the aversion of a drill breakdown. Henceforth, the emphasis is placed on measuring certain quality, sustainability and productivity traits for drilling solely on the 25th hole for each set of sequentially executed trials. In this manner, we quantify the level of machining reliability at the completion of a scheduled job, i.e. at a point where the machine tooling amasses the most wear. Monitoring the surface roughness performance as compounded on the last drilling of a material removal job has not been explored before with simultaneous profiling for ameliorating specific traits related to sustainability and productivity. Thus, the optimization approach will be carried out on three stages. First, a simple profiling will be effected on a replicated dataset of surface roughness such as to establish optimally the proper settings for the mechanistic aspect of the drilling process alone. By providing energy and cutting fluid consumption indicators for the drilling process, the surface roughness profiling is conducted in a second round by embedding concurrently selected lean-and-green indicators which are also important for any process sustainability check. Lastly, surface roughness profiling is executed by including the energy and environmental responses from the second round while additionally encompassing the processing time to conduct a single (last) drilling as planned for each particular experimental recipe separately. Hence, the third round of the optimization effort factors in productivity concerns along with the selected quality and sustainability characteristics for the terminal drilling. Taguchi-type orthogonal arrays for non-linear sampling are utilized to accomplish the structured data collection endeavor for surface roughness, energy and coolant consumption as well as the process timing for the last drilling. Multi-response multi-factorial concurrent optimization is achieved by adopting a distribution-free model.

2. Methods and materials

2.1. Shell-and-Tube heat-exchanger test-plate materials

A 'shell-and-tube' heat exchanger (S&T HE) is a system that is built to effectively transfer heat from one medium with higher temperature to another medium with lower temperature (Kakaç and Liu, 2002). The surface finish quality of tube sheets