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Surface integrity of SA508 Gr 3 subjected to abusive milling conditions

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Abstract

SA508 Gr 3, a bainitic forging steel employed in the fabrication of nuclear pressure vessels has been characterised after dry-milling to investigate extent of machining abuse on the surface. A detailed study of the evolution of residual stresses, microstructure, micro-hardness and roughness in relation to different milling parameters is presented. A central composite orthogonal (CCO) design of experiments (DoE) was used to generate a statistic model of the milling process. Deformation of the sub-surface layer was assessed via SEM BSE imaging. The developed statistical model is discussed aiming to illustrate availability of different cost-effective manufacturing techniques meeting the high standards required by the industry.

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Keywords: Surface integrity; face milling; machinability; design of experiments.

1. Introduction

The systematic increase in world-wide demand for carbon-free energy has greatly augmented the pressure to the nuclear industry to consider ways to meet energy needs while maintaining environmental sustainability. Steels alone represent the majority of structural materials employed in light water reactors and low alloy steels such as SA508 Gr 3 are commonly used in the fabrication of pressure vessels. In this application they are used for extended times at maximum operating temperatures of 280 to 315 °C, and pressures between 7 and 15 MPa (respectively in BWR and PWR) [1]. Machinability of this steel is relatively good and significant experience has been developed over the years to solve machining problems caused by its high ductility, tensile strength and work-hardening ratio. New trends in the nuclear industry, however, are pushing the operational life of reactors to 60 years and beyond [2]. For such extended operation, surface defects resulting from the manufacturing process can influence fatigue, corrosion resistance and resistance to brittle fracture. Thus, surface integrity requirements can become even more stringent limits [3].

Nomenclature

a_p	depth-of-cut
f_z	feed per tooth
V_c	cutting speed
XRD	X-Ray Diffraction
SEM	Scanning Electron Microscope
BSE	Backscatter Electron
R_a	Arithmetic mean surface roughness
R_z	Mean roughness depth
DoE	Design of Experiments
RS	Residual stress

When the work-piece is subject to non-uniform deformations such as in the case of machining, locked-in stresses develop [4]. The material undergoes compressive deformation in front of the cutting edge and tensile deformation immediately after [5]. The deformation energy and friction release large amount of heat which adds to the undesired tensile stress field after cooling [6]. Bainitic steels, however, exhibit higher thermal conductivity coefficients when compared with austenitic stainless steels thus reducing the effect of the heat generated during cutting. The goal of the modern nuclear industry is to manufacture low-cost, high quality products in short time to drive down the associated costs. When compared

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with other methods, hard milling produces excellent surface integrity while being cost effective. In the case of dry milling, additional good cleanliness and smoothness of the machined surface are expected.

Modeling the dry hard milling process can be used to implement a more efficient process. In this work, a statistical model, which considers the complex interrelation between machining parameters, is presented and material's response to challenging cutting conditions is investigated.

2. Experimental

The alloy studied in this work was a SA508 Grade 3 steel with chemistry presented in Table 1. Machining coupons were produced out of water-jet cut plates. Each coupon dimensions were 100x200x25 mm; the 100 mm sides were both machined and four responses were recorded: R_a, R_z, maximum residual stress and surface hardness. The dry machining process was performed in one pass, ensuring that a tool engagement of 80% was achieved. After each machining test, cutting inserts were inspected and replaced when any wear or damage was apparent since tool wear is known to significantly influence magnitude of surface deformation and thus the residual stresses [6].

Surface roughness was assessed with a Mitutoyo Surftest SJ-410 stylus on finished work-pieces. Residual stress measurements were performed by X-Ray Diffraction using a Proto iXRD combo residual stress analyser fitted with a Mn-K_α tube and operating at 20 kV and 4 mA.

The specimens were subsequently evaluated using a Zeiss Sigma VO field emission gun (FEG) – scanning electron microscope (SEM) operated at 20kV and equipped with an Oxford Instruments X-max 150 Silicon Drift Detector (SDD) energy dispersive x-ray spectrometer, with the Aztec analysis system. To quantify the extent of the deformed layer, BSE imaging analysis of the work-piece was performed on a metallographic cross-section specimen. Samples for BSE analysis were prepared via a standard metallographic procedure with a final stage of polishing with 0.02 µm colloidal silica.

Machining tests were performed on a 3-axis Mazak Vertical Venter Smart 430A using a Sandvik Coromill R300 tool head with 53 mm diameter, extra close pitch and five insert spaces. The indexable button insert selected for the experiments was a tungsten carbide, Ti(Al)N coated, Coromill R300-1240-1040 with a diameter of 12 mm.

Surface hardness measurements were obtained using a Vickers micro-indenter with 0.1 N load and a dwell time of 15 s.

Table 1: Chemical composition of the SA508 Gr 3 steel

Element	Fe	C	Si	Cr	Ni	Mn	Mo
Weight%	balance	0.23	0.31	0.3	0.85	0.75	0.6

A Box-Wilson (CCO) Design of Experiment was used to identify which cutting parameters had statistically significant influence on the responses and the interaction between them. The DoE incorporated three key process parameters: depth of cut a_p, feed per tooth f_z and cutting speed V_c. The relatively complex CCO design (Table 2) with three center points and no replicates allowed to accurately describe the system's response keeping into account the non-linearity and estimating the variability and repeatability of its response. Tests were randomized to minimize external influences into the measured responses and analysis of the results was carried out on Umetrics' Modde 11 software by using the Partial Least Square method.

Table 2: Experimental cutting parameters

Run order	V_c [m/min]	a_p [mm]	f_z [mm/th]
1	120	2.5	0.275
2	363	3.24	0.18
3	363	1.76	0.37
4	260	1.5	0.275
5	260	2.5	0.4
6	400	2.5	0.275
7	260	2.5	0.275
8	363	1.76	0.18
9	157	1.76	0.37
10	157	3.24	0.18
11	157	1.76	0.18
12	260	3.5	0.275
13	157	3.24	0.37
14	260	2.5	0.275
15	363	3.24	0.37
16	260	2.5	0.15
17	260	2.5	0.275
18	260	1.5	0.275

3. Results

Five different areas were selected on each machined surface and their surface roughness results averaged to reduce the influence of accidental damage or local inhomogeneity. The standard deviation of the results was used to evaluate the quality of the measure. Surface roughness remained good in the full experimental range even at cutting parameters that were significantly higher than the recommended values. Both the R_a and R_z appeared to change in a non-linear way when varying the key cutting parameters, sign of an interaction between the parameters.

All hardness test results showed limited scatter, averaging at 235±9 HV0.1-15, with good replicate match.

Surface XRD residual stress measurements were performed for seven areas, which were selected on the cut face of the sample. These results were then averaged to increase confidence in the measure and reduce the effects of surface quality or transient inhomogeneity in the cutting process. The measured stress appeared to decrease with a lower depth of cut a_p and increase with increasing V_c. It was interesting to note that the majority of data points fell in the region of ~450-550 MPa with only two measures reporting stresses slightly above it (586 and 625 MPa). The chance that those higher values were due to local inhomogeneity in the microstructure or in the surface of the samples was ruled out by performing several additional measurements on the surface and obtaining similar