Journal of Manufacturing Processes 32 (2018) 455–468

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

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

Ultrasonically generated pulsed water jet peening of austenitic stainless-steel surfaces

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ARTICLE INFO

Article history:
Received 1 October 2017
Received in revised form 21 February 2018
Accepted 13 March 2018

Keywords:
pulsating water jet
peening
residual stress
acoustic emission

ABSTRACT

In this study, the effects of pulsating water jets were investigated as a surface treatment process using circular and flat nozzles by considering the integrity of a stainless steel (AISI 304) surface. The local energy distribution was controlled by changing the traverse speed and the pulsating water jet (PWJ) effects were assessed in terms of the residual stress and strengthening effect. The strengthening effect of the process was evaluated by measuring the micro-hardness of the treated surface and by studying the impact of the treatment on the surface based on micro-structural analyses using scanning electron microscope (SEM). The residual stress of the subjected area was evaluated using X-ray diffraction technique. Based on the results from the studied samples, it was found that the initial tensile residual stress was relieved and converted to a compressive residual stress. An increase in the hardness of the treated samples was also observed as compared to the untreated samples up to certain depth along the cross-section of the treated region. The micro-structural examination of the samples revealed the plastic deformation that occurred during the treatment process. Additionally, the acoustic emission (AE) generated during the impact was used as an online monitoring tool for observing the behaviour of the elicited signals under different parametric conditions, and as a control mechanism for obtaining better results. The experimental results show that the pulsating water jet constitutes a new potential technology for surface treatment processes.

1. Introduction

It is well known that the presence of surface defects or tensile residual stress causes the failure of engineering structures. These are known as fatigue failures and frequently occur in regions of increased stress concentration. Therefore, fatigue failures are a major concern in engineering design [1]. In order to improve the life and economic viability of these components, surface treatment becomes essential. Over the years, different surface treatment methods have been used to improve the lifetime of the components. There are numerous methods available that can be used to increase the lifetime of materials by inducing compressive residual stresses on the surface and sub-surface layers, and by increasing the material hardness and surface finish. However, newly emerging methods have been shown to overcome the shortcomings reported for conventional methods. Compared to conventional methods, such as shot peening, and laser shot peening, water jet peening (WJP) does not cause any surface defects owing to the embedment of particles on the treated surface, thereby increasing the surface roughness in a manner similar to abrasive WJP. Additionally, the material does not melt, as may occur in cases of laser shock peening, especially with materials that have low melting points [2].

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https://doi.org/10.1016/j.jmapro.2018.03.016

Nomenclature

Symbols

d	orifice nozzle diameter [mm]
f	frequency [kHz]
A	amplitude of sonotrode [mm]
p	pump pressure [MPa]
P	ultrasound power [W]
E	young's modulus [GPa]
Ψ	tilt angle [°]
μ	poisson's ratio
σ_t	ultimate tensile strength [GPa]
σ_K	yield strength [GPa]
Rm	tensile strength [MPa]
R_p	yield strength [MPa]
k	liquid constant
v	traverse speed [mms−1]
z	stand-off distance [mm]
ρ_o	density of the liquid [l s^{-1}]
C_o	speed of sound in liquid [m s^{-1}]
V	impact velocity [m s^{-1}]

The application of high pressure water jets has been a topic of interest for many researchers over the years. This technology is being extensively used in industrial applications, such as cleaning [3], surface removal [4], cutting [5], drilling [6], turning [7–9], milling [10], and surface treatment or peening [11]. Compared to other applications, WJP is a relatively new application. The process was first reported in 1984 [12]. It is a surface strengthening process which causes local plastic deformation on the surface owing to the frequent impact of water droplets. This induces compressive residual stress on the surface and sub-surface layers, and thus increases the fatigue life of the component. The introduction of compressive residual stress on the surface has benefits since it hinders the initiation of cracks.

The WJP process has been effectively used by researchers to enhance the fatigue life of the component. Chillman et al. [13] conducted an experimental study of WJP on Titanium (Ti-6AL-4V) at 600 MPa. It was observed that plastic deformation occurred in sub-layers at greater depths than laser shock peening. Additionally, strong dependencies of the plastic deformation and the state of surface were observed on peening conditions and surface roughness. Ramulu et al. [14] reported that this method had induced plastic deformation on the surface layer equivalent to shot peening when performed on Aluminium alloys (Al 7075-T6), and the degree of plastic deformation was strongly influenced by the peening conditions. The evaluation of residual stress using x-ray diffraction distinguished the influence of material properties on the surface integrity. Arola et al. [15] compared the fatigue strength of stainless steel (AISI 304) and titanium alloy (Ti-6Al-4V) samples when they were subjected to an abrasive WJP process. A strong dependence of peening conditions on the improvement of fatigue life of the component was observed. The increase in the pressure and peening time resulted into an increase in the surface hardness, but at the same time, the fatigue limit declined rapidly owing to the increase in surface erosion, as this encouraged crack initiation. Azhari et al. [16] studied the effects of the number of passes on the surface integrity of austenitic stainless steel 304. It was observed that when the number of passes and the pressure increased, increased roughness values were achieved, and extensive erosion occurred on the treated surface. The hardness value of the treated surface revealed that a higher number of passes and a higher pressure resulted in a greater increase in the hardness of the surface at deeper hardening layers. In conjunction with the exploration of the effects of the process parameters on the Aluminium specimen, Azhari et al. [17] also observed that the higher number of passes resulted in treated surfaces with higher hardness values.

As reported in the aforementioned studies, until now, the surface treatment process has been performed using plain water jet and abrasive water jet (AWJ), but owing to certain technological and economical limitations of high-pressure water jets, such as the cost of high-pressure pumps, maintenance cost, wear of the parts, etc. the industries have adopted a method to obtain surface erosions at lower pressures [18]. This can be achieved by using pulsating water jet (PWJ) where the efficiency of the jet is increased by the generation of pulses [18]. The water jet can be pulse-modulated using different methods, such as mechanical modulators, which are responsible for the forced periodical modulation of the jet, use of self-resonating nozzles where discrete annular whirls are generated when the frequency of the impacting pressure corresponds to the natural frequency of the flow, and use of ultrasonic converters, which allow changes in the frequency and amplitude of an actuator used to generate vibrations. Initially when the jet exits the nozzle, it is continuous. After a certain distance it starts to form individual clusters [19]. In recent years, PWJ was applied to different areas of applications. Foldyna et al. [20] used the technology for studying the erosion effects on stainless steel (CSN EN 17 347) where the effect of repeated impacts of water pulses and impact velocity on the erosion of metal surface was investigated. A three-stage erosion process was observed in this study comprising an (i) initial plastic deformation, (ii) creation of erosion pits, and the (iii) emergence of pits to form erosion craters. The surface characteristics were found to be dependent on the number of impacts determining the stage of erosion on the surface. Foldyna et al. [21] also examined the effect of PWJ on aluminium surfaces. The impact effect of pulsating water jets on the Aluminium surface was characterised and related to the parametric conditions of the process using optical microscopy and image analyses. The results obtained through this study were helpful in selecting the appropriate parameters for the required surface characteristics. Lehocka et al. [18] studied the effect of PWJ on surface morphology during the disintegration of copper alloys. Surface topography, morphology, and anisotropy of copper alloys, were investigated, and the average surface roughness values were compared with the mechanical properties of each groove, subjected to different parametric conditions, for assessing the required microgeometry and purity of surfaces. The PWJ technology has also been applied in the medical field. Hloch et al. [22] disintegrated bone cement using PWJ and evaluated the depth of penetration using an optical profilometer. It was concluded that this technology can be used effectively for re-implantation of cemented endo-prosthesis without causing thermal and mechanical damage to the surrounding tissue [20]. Disintegration of rock is another field of application where this technology has been tested. Sitek et al. [23] compared the effect of continuous water jet and PWJ in repairing the concrete structures using optical microscopy and image analyses. The results obtained showed that PWJ achieved higher efficiency with less energy consumption as compared to continuous water jets when operated under the same conditions. De-scaling of carbon steel and steel sheets was also performed using PWJ by Hnizdil et al. [24]. The results revealed that thinner layers of scales on cold sheets were obtained using PWJ compared to continuous water jet. The technology of PWJ was also found efficient in disintegrating rock samples [25]. The present work focuses on the use of PWJ technology as a surface treatment process.

The phenomenon of jet impact on the solid surface involves the local plastic deformation of the treated surface, and is an important source of information of the ongoing process. Today, many sensors exist for monitoring ongoing processes, but acoustic emission (AE) sensors constitute one of the unique sensor types available for efficient monitoring of the deformation process in real time [26]. AE