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Effect of multiple passes treatment in waterjet peening on fatigue performance

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ABSTRACT

The influence of waterjet peening on the residual stresses and fatigue performance of AISI 304 is investigated. The specimen surfaces were treated with multiple jet passes. The fatigue strength was evaluated using an alternating bending fatigue tester. The results of XRD measurements showed that a higher amount of compressive residual stresses is induced in the treated specimens. This strengthening layer is limited within the first 100 μm below the surface, which had been confirmed by micro hardness measurements. Even though the treated specimens showed compressive residual stresses the fatigue limit is lower than that of the untreated specimens. The roughness of the surface and the resulting notch effect seems to be stronger than the positive effect of the hardened layer.

1. Introduction

In today's practice, mechanical surface treatments have been widely applied particularly in the spring-manufacturing, automotive and aerospace industries. It was realized that the failure due to fatigue depends on many factors, and very often it develops from particular surface areas of engineering parts. So an, it seems possible to improvement of the fatigue strength of metallic components could be realized by the application of suitable mechanical surface strengthening processes [1]. The technology and applications of high pressure waterjet have been studied since many decades (as early as 1960s) [2]. Waterjet surface treatment or better known as waterjet peening (WJP) is a relatively new application of the waterjet technology. It is a mechanical surface strengthening process where high-frequent impact of water drops on the surface of metallic components, which causes local plastic deformation [3]. As a result, high compressive residual stresses are induced in the surface near layer of the workpiece, which leads to enhanced surface hardness and fatigue life [4].

A fatigue failure under cyclic loads is most commonly originated at the near-surface area where it has the highest stress concentrations and tensile stresses resulting from production processes. A major method of increasing fatigue performance is by imposing compressive residual stresses within a thin outer surface layer. As a result, the possibility of crack initiation leading to fatigue failure is reduced. The method may offer some positive effects by enhancing the fatigue strength of the components than the usage of highly alloyed and more expensive materials [3].

A few studies have reported that the WJP process is employed to modify material surfaces by introducing compressive residual stresses which consequently may increase the fatigue life of the materials. Arola et al. [5] reported the improvement of fatigue strength in abrasive waterjet peening of stainless steel 304 and titanium alloy Ti6Al4V. They compared the fatigue strength of both specimens treated with two parametric conditions that gave a high and low induced compressive residual stresses respectively. However, a rather limited increase in the fatigue strength for both materials (<10%) was found. Kunaporn et al. [6] reported a maximum increase in the fatigue strength by 20–30% in waterjet peening of aluminium alloy 7075-T6. They noticed that the degree of fatigue improvement was strongly dependent on the peening conditions. They observed that increasing the pressure and the peening time might yield an increase in surface hardness, but the fatigue limit would rapidly decline due to an increase in surface erosion as well. It is well known that surface irregularities may encourage fatigue crack initiation at the specimen surface [7]. Han et al. [8] reported an

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Table 1
Chemical composition (weight-%) of stainless steel 304.

C	Mn	Si	P	S	Cr	Ni	Others	Fe
0.07	2.00	1.00	0.045	0.015	17.00–19.50	8.00–10.50	N 0.11	Balance

increase of fatigue life of about 15–20% in water cavitation peening of carbon steel 1045. They noticed that the improvement of fatigue life was obviously apparent at higher cycles.

Considerable works have been done in investigating the effect of various WJP parameters on the fatigue strength of metals. However, all the works were carried out in a single-pass treatment. There is a possibility that the residual stress can be introduced in a higher amount and/or deeper below the surface if the metallic surfaces are treated repeatedly with multiple passes. Hence, its fatigue life can be further improved. As shown in studies on traditional machining processes particularly grinding, it is clear that there is a variation in magnitude of residual stress with respect to the depth of the residual stress distribution in multiple passes grinding technique [9]. It was also revealed that as the number of grinding passes increases, the normal grinding force increases as well, which resulted in a higher amount of compressive residual stresses being induced [10]. Furthermore, a study on multipass abrasive waterjet cutting has shown its superiority over a single-pass cutting where it produces better surface quality and penetration depth [11]. A study on shot peening using a double-peening technique has shown an improvement on fatigue life of leaf springs when using smaller second-peening media [12].

Based on the previous works, it is obvious that WJP can be employed to increase the fatigue life of metallic surfaces. It will be interesting to investigate further the effect of WJP process on fatigue strength by utilizing a method of multiple passes treatment. This method has been successfully employed to increase the surface hardness of the treated specimens in WJP as reported by the same authors [13]. Therefore, it is hoped that a higher increase in the hardness may result in the increase of the specimen's fatigue life. The present study discusses the effect of the multiple passes treatment in waterjet peening on the residual stresses and fatigue performance of stainless steel 304.

2. Materials and methods

Austenitic stainless steel AISI 304 (X5CrNi1810 and material no. 1.4301) was selected as the test material. The typical chemical composition and mechanical properties of austenitic stainless steel 304 are given in Tables 1 and 2 respectively [14]. The surfaces of the received specimens were already smoothed and film coated from the production process through the rolling method. It had an average surface roughness, R_a of 0.15 μm. Therefore, no necessary smoothing of surfaces was needed prior to the experiments.

Table 2
Mechanical properties of stainless steel 304.

Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
230	540–750	45

The waterjet surface treatment was carried out using the UHDE waterjet machine. The machine is capable of generating pressure up to 600 MPa. It has a nozzle made of stainless steel, brass seal and sapphire stone. The nozzle has a diameter of 0.3 mm. The incidence angle was set at 90° (i.e. the nozzle was perpendicular to the specimen surface). The process was done without the use of abrasives so that surfaces free of embedded abrasive particles could be expected. The fatigue test specimens were prepared according to the dimensions as shown in Fig. 1(a). The plate has a thickness of 3 mm. Three different conditions were used in the waterjet treatment of the fatigue specimens. The conditions were selected based on three different numbers of jet passes (i.e. 2, 4 and 6) as reported in the previous work [13]. The rest of the parameters were kept constant i.e. water pressure = 200 MPa, feedrate = 2000 mm/min, nozzle diameter = 0.3 mm and standoff distance = 30 mm. The waterjet surface treatment was conducted on both sides of the specimens in the region where it may experience the highest stress concentration (i.e. in the middle of the specimen) up to a length of 15 mm as shown in Fig. 1(b). A rate of overlapping was about 20–30% providing sufficient uniformity of the WJP treatment. A minimum of 14 specimens for each treatment condition was used for the fatigue test with an alternating bending machine. The specimens were tested at different stress levels with an interval of about 25 MPa. The original specimens were also tested so that the fatigue strength could be compared between the treated and non-treated specimens.

A sample of treated specimen at each waterjet peening condition was also used to measure the amount of induced compressive residual stresses. X-ray stress analysis was carried out for the surface as well as sub-surface regions. The residual stresses were measured up to a surface depth of about 100 μm using a method of successive removal of layers by electropolishing. The fatigue tests were conducted at room temperature on an alternating bending fatigue test machine type PWO (manufactured by Schenck GmbH). It is an alternating bending fatigue machine which is able to perform dynamic fatigue test in accordance with the German standard DIN 50142 [15]. The machine displacement is controlled through a crank-linkage mechanism as illustrated in Fig. 2. This produces a sinusoidal waveform with a frequency of 23 Hz. The test was

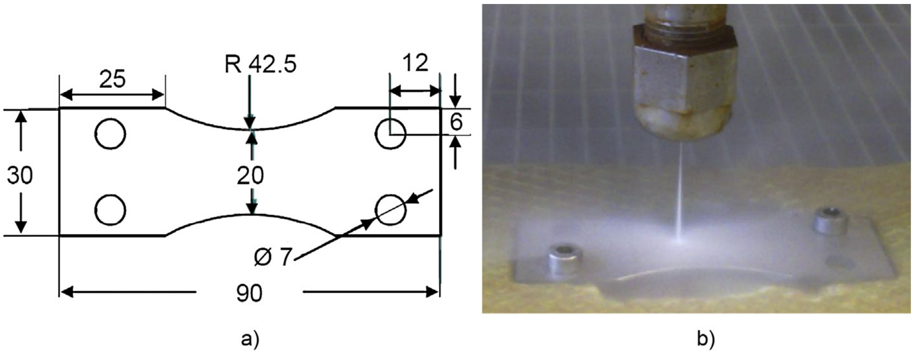

Fig. 1. (a) Schematic drawing of the fatigue test specimen (all dimensions are in millimetres), (b) waterjet peening of fatigue specimen.