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Influence of surface topography and needle size on surface quality of steel plates treated by ultrasonic peening

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ABSTRACT

Five groups of D36 steel plates with different surface topographies were prepared to evaluate the influence of topography and needle size on the surface quality after ultrasonic peening treatment. Factors such as the stress distribution, micro-hardness, and fold defects were studied to quantify the surface quality. In addition, ABAQUS/Explicit finite element modeling was employed to simulate the peening process. The numerical results revealed that fold overlapping was dependent on the initial surface topography and the size of the peening needle could influence the morphology of the fold defects. The results further indicated that fold defects were closely related to the initial surface topography, with the aspect ratio being a key determining factor for the dimensions of fold defects.

1. Introduction

Developments in modern industry have created service conditions for components that have become more and more demanding. Common surface treatments, such as carburizing [1,2], nitriding [3,4], rolling [5,6], and shot peening [7–9], are already widely used to improve the fatigue resistance of structural materials [10]. The traditional shot peening technique has been modernized (upgraded) into the ultrasonic peening treatment (UPT) method. This is a cold-work surface treatment that has been used to improve the mechanical properties of metallic materials in aerospace, marine, automotive, railway, and bridge structure applications, i.e., situations requiring very high strength, corrosion and wear resistance, and a long fatigue life [11]. Compared to the other peening methods such as laser shock peening [12], shot peening, and high energy shot peening [13], UPT offers a number of benefits. The equipment is lightweight (easy to carry), has high productivity, low cost, and can be adapted to manage complex shapes and local treatment.

A study by Zhao [14] on U75V rail steel showed that the surface nanocrystal layer induced by UPT can prevent crack initiation, improve fatigue, wear and corrosion property. This is made possible by preventing dislocations and the recombination of grains on the surface, which facilitates nano-crystallization that enhances the welded joint. Mordyuk [15] fabricated a composite layer on the surface of Al–6Mg alloy specimens by ultrasonic impact peening (UIP), and proposed that compressive residual stresses trap the reinforcing particles. This reduces the rate at which small cracks propagate to the extent that they stop or close, thereby shifting the source of fatigue cracks from surface to beneath the hardened/stressed layer.

Past research has focused on the compressive residual stresses and surface nano-crystallization formed during UPT; however, the sources of fatigue failure in components are always defects induced by manufacturing. During UPT, a thin layer of plastic deformation occurs near a component's surface that induces not only residual compressive stresses, but also fold defects. These fold defects occur not only in welding joints [16], but also in the sub-surface of the base metal [17]. In previous studies, we found that the main influencing factors for fold defects were the initial surface topography and UPT. However, the interaction between these two factors is not clear and has not yet been systematically investigated.

As peening is a dynamic process, experiment methods have limited ability to elucidate the mechanisms. Hence recent studies tend to use numerical simulations of the peening process. There are several studies using residual stress analyses that confirm simulation

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Table 1
Metallurgical composition of D36 steel (wt%).

C	Si	Mn	P	S	Cr	Ni	Al	B	Cu
0.13	0.32	1.5	0.015	0.001	0.03	0.02	0.028	0.0002	0.05

is a reliable tool for evaluating the peening process [8,18]. However, there are few studies regarding the effect of surface defects.

In order to investigate the interaction between the initial surface topography and UPT parameters and how these affect the surface quality, five groups of samples with different surface topographies (aspect ratios) were treated using the same UPT parameters. Then we used an ABAQUS/Explicit finite element model to simulate the UPT process to discuss the relationship between the surface topography and peening needle size and their effect on the surface quality. The surface quality of UPT treated samples was experimentally quantified by the stress distribution, micro-hardness, and fold defects. In addition, the fatigue properties were evaluated by three-point bend fatigue testing.

2. Experimental

2.1. Materials and ultrasonic peening parameters

The material used in this study was D36 steel; the metallurgical composition is listed in Table 1. Plates of this alloy were machined

Table 2
Surface topography of D36 steel.

Group	Aspect ratio	D (μm)	W (μm)
A	0.25	100	400
B	0.5	100	200
C		200	400
D		400	800
E	1	400	400

to obtain five groups of grooves with different surface topographies (i.e., aspect ratios, as shown in Table 2). The 2D morphology of the grooves is shown in Fig. 1(c).

The ultrasonic peening treatment was carried out using an automatic UPT machine (Fig. 1(a)), which consisted of an ultrasonic generator, piezoelectric transducer, pneumatic pump, 3 mm-diameter peening needle, and ABB robot. Fig. 1(b) shows the path of the peening needle. The traverse direction of the peening needle was perpendicular to the undulating gap. Fig. 1(c) shows the different surface morphologies of the five sample groups. The UPT processing parameters are listed in Table 3.

2.2. UPT model

Due to the low computational complexity, 2D modeling has been a popular method for simulating the peening process,

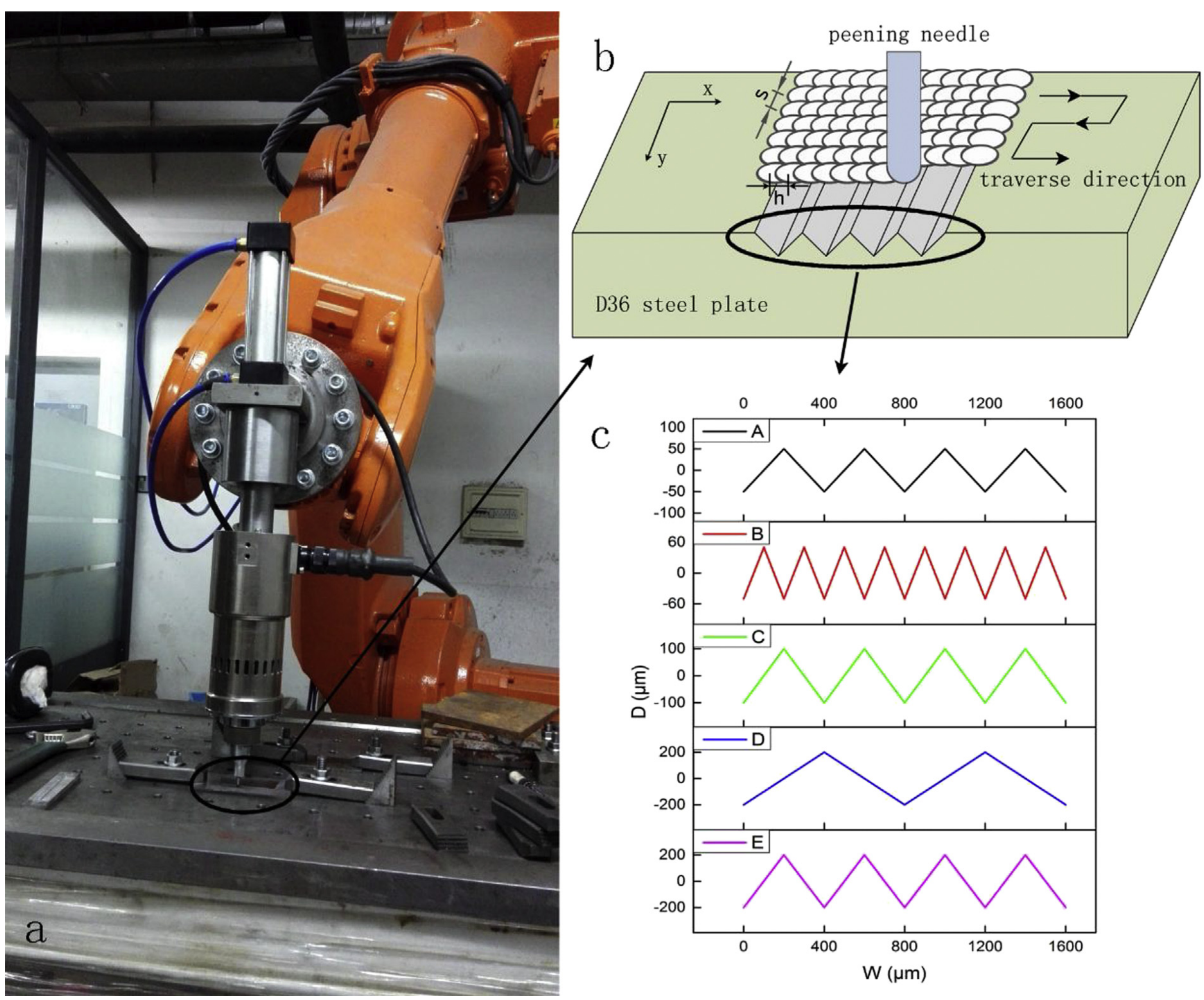

Fig. 1. (a) Photograph of the UPT equipment. (b) Detailed schematic of the UPT process. (c) 2D morphology of the five groups with different aspect ratios.