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INFLUENCE OF MECHANICAL SURFACE TREATMENTS ON THE ROUGHNESS, HARDNESS AND RESIDUAL STRESS OF AISI 304 STAINLESS STEEL

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Abstract. *Effects of laser shock peening, water jet cavitation peening, water jet shot peening, and ultrasonic impact treatment on surface roughness, hardness, and residual stress of AISI 304 stainless steel were studied. Owing to new surface relief formation, the Ra roughness parameters became lower after ultrasonic and shot peening than those after laser and cavitation peening. The ultrasonic processing led to the highest surface hardness among the studied peening treatments. The optimum regimes were determined by accounting for the minimum magnitudes of surface roughness and maximum magnitudes of the surface hardness and residual stresses. In comparison with the initial state, these regimes result in the HRC surface hardness increase (LSP2 ~30.7%, WjCP2 ~38.4%, WjSP2 ~69.6%, UIT4 ~73.2%) and in the Ra roughness parameter reduction (LSP2 ~5.5%, WjCP2 ~7.8%, WjSP2 ~38.2%, UIT4 ~91.1%) inducing the compressive residual stress (LSP2 –470 MPa, WjCP2 –377 MPa, WjSP2 –519 MPa, UIT4 –693 MPa).*
Keywords. *Strain hardening, roughness, hardness, residual stress, laser shock peening, water jet cavitation peening, water jet shot peening, ultrasonic impact treatment*

Advanced surface modification technologies, such as laser shock peening (LSP), air cavitation peening (CP) or water jet cavitation peening (WjCP), air shot peening (SP) or water jet shot peening (WjSP), light plasticity burnishing (LPB), surface mechanical attrition treatment (SMAT), ultrasonic shot peening (USP), and ultrasonic impact treatment (UIT) or ultrasonic nanocrystal surface modification (UNSM), etc., are recently developed methods that were shown to improve mechanical properties and performance significantly [1–3].

In particular, the UIT and UNSM can be regarded as the most effective processes to improve both the surface roughness and hardness of the surface layer [3, 4]. The influences of the UNSM and the mono-pin UIT processes on the material properties were recently reviewed in comparison with the other peening techniques [5, 6]. Conversely, the comparative studies of the UIT process applying the multi-pin impact head, which is known to be more effective and applicable in industrial scale, and LSP, WjCP and WjSP processes are virtually absent.

The aim of this paper is to study the effects of the LSP, WjCP, WjSP and multi-pin UIT on the surface roughness, hardness and residual stress of the austenitic stainless steel AISI 304.

The LSP process (Fig. 1a) was carried out at the pulse width of 6 ns, the spot diameter of 0.8 mm, the overlap of 50%, the pulse number density of 4 (LSP1), 8 (LSP2), 12 (LSP3) and 16 (LSP4) pulses/mm^2 [2]. The LSP regimes are given in Table 1.

Table 1 Determinative processing parameters of the used mechanical surface treatments.

Regime number	Mechanical surface treatment methods							
	WjCP		LSP		WjSP		UIT	
	Treatment duration		Pulse number density		Treatment duration		Treatment duration	
	(s/mm)	Per unit area (s/mm^2)	(pulses/mm^2)	Per unit length	(s/mm)	Ten passes per unit area (s/mm^2)	(s/mm)	Per unit area (s/mm^2)
1	4	0.8	4	0.12	0.44	0.098	15	0.05
2	8	0.178	8	0.24	0.88	0.196	30	0.1
3	12	0.24	12	0.36	1.32	0.294	45	0.15
4	16	0.36	16	0.48	1.76	0.392	60	0.2

The WjCP process (Fig. 1b) was implemented at the injection pressure of the jet of 30 MPa, the ambient pressure of the jet of 0.1 MPa, the nozzle diameter of 2 mm, the WjCP duration was in a range of 4–16 s/mm (Table 1) [2].

The WjSP process (Fig. 1c) was performed the shot diameter of 3.2 mm, the number of a shot of 500, the pressure of water jet of 12 MPa, the standoff distance between the nozzle and the surface specimen of 50 mm [2]. The WjSP duration was in a range of 0.44–1.76 s/mm (Table 1).

The UIT process (Fig. 1d) was conducted at the amplitudes of ultrasonic horn of 15 μm, the frequency of ultrasonic horn of ~ 21 kHz, the static force of 50 N, the rotational speed of the impact head of 76 rpm, and UIT duration of 15 s (UIT1), 30 s (UIT2), 45 s (UIT3) and 60 s (UIT4) [5]. The UIT regimes of the studied steel are listed in Table 1.

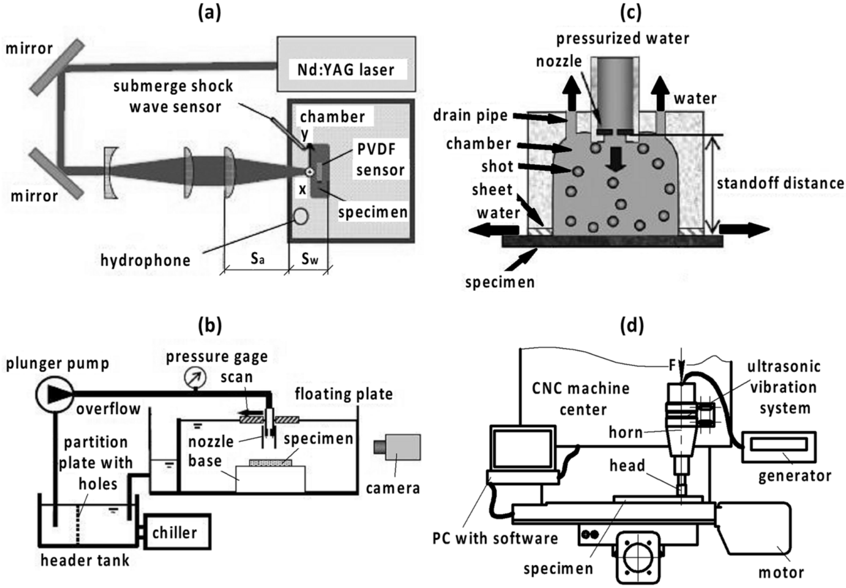
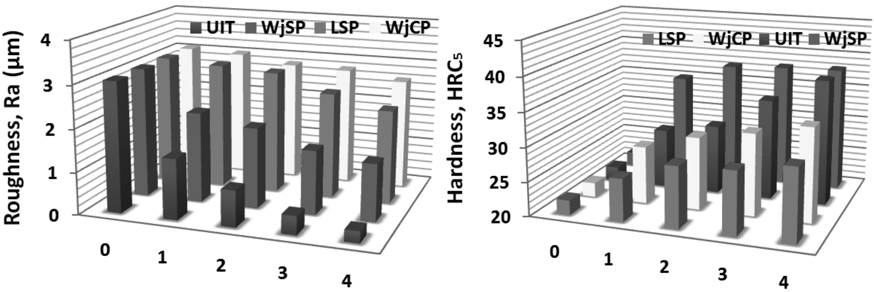


Fig. 1 – Scheme of the LSP (a), WjCP (b), WjSP (c), and UIT processes (d).

The surface roughness was determined by a tester MarSurf PS1. The surface hardness was estimated using a tester Computest SC at a load on indenter of 5 kgf. The residual stress was measured by a standard X-ray diffraction technique according to the $\sin^2 \psi$-method.

The evolutions of the arithmetic mean parameter *Ra* of the surface roughness after application of the studied mechanical surface treatments are shown in Fig. 2a for different applied regimes. Compared to the initial/unpolished specimens (~3 μm), owing to the severe plastic deformation the treatment induced *Ra* magnitudes were always lowered although in different extents. The surface roughness analysis shows that the higher the duration of the WjCP, WjSP, UIT processes or the higher the pulse number density at the LSP the lower the surface roughness becomes. In comparison with the initial state, the *Ra* magnitudes of the processed specimens were respectively decreased by approx. 28%, 15%, 56%, and 91% after the LSP, WCP, WSP, and UIT processes. The most remarkable decrease in *Ra* roughness parameter (0.27 μm) was observed after the UIT process.

The experiments show that the surface hardness (HRC) increases relative to the untreated specimen regardless of the treatment type (Fig. 2b). The registered hardening extents grow with on-going treatments but at different rates. The WjCP and WjSP processes of the used intensities demonstrate a saturation of the strain induced hardening of the surface at the levels of ~28–30 HRC and ~37 HRC, respectively. On the contrary, the hardening ability of the LSP and UIT processed specimens has not been exhausted for the studied regimes, and the surface hardness seemingly can be further increased. The UIT process led to the highest surface hardness (38.28 HRC) among the studied peening treatments.



(a) (b)

Fig. 2 – Surface roughness (a) and hardness (b) of AISI 304 steel in the initial state (regime 0) and after LSP, WjCP, WjSP, and UIT processes applied in regimes 1–4 (see Table 1)

Fig. 3 shows the magnitudes of residual stresses registered by X-ray method in the near-surface layers of as-treated specimens. The results confirmed that all the surface treatments generated compressive residual stresses.

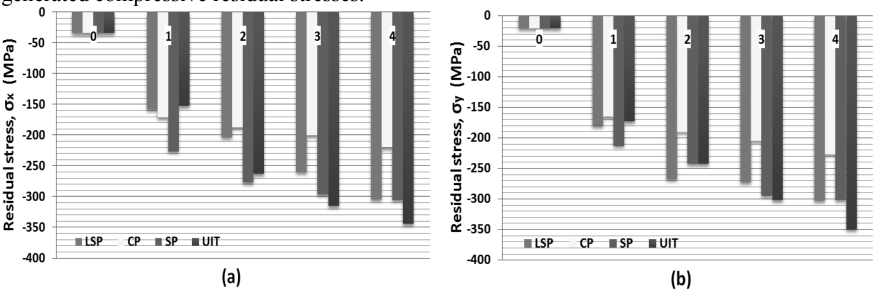


Fig. 3 – Residual stress in the X (a) and Y (b) direction of the specimens of AISI 304 steel in the initial state (regime 0) and after WjCP, LSP, WjSP, and UIT applied in regimes 1–4 (see Table 1)

Thus, based on the above-mentioned experimental studies and taking the efficiency of each process into account the mechanical surface treatments induced surface roughness, hardness and residual stress of AISI 304 stainless steel, the following regimes were further applied: LSP2, WjSP2, WjCP2, and UIT4. These regimes result in increase in the HRC surface hardness (LSP2 ~30.7%, WjCP2 ~38.4%, WjSP2 ~69.6%, UIT4 ~73.2%) and reduction in the *Ra* roughness parameter (LSP2 ~5.5%, WjCP2 ~7.8%, WjSP2 ~38.2%, UIT4 ~91.1%) in comparison with the initial state, providing the compressive residual stress in the near-surface layer (LSP2 –470 MPa, WjCP2 –377 MPa, WjSP2 –519 MPa, UIT4 –693 MPa), which are known to be beneficial for different operative properties, such as enhanced anti-corrosion performance, wear resistance and prolonged fatigue life.

Вплив механічних поверхневих обробок на шорсткість, твердість та залишкові напруження нержавіючої сталі 08Х18Н10

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Анотація. *Досліджено вплив лазерної ударної обробки, кавітаційної обробки, дробоструминної обробки та ультразвукової ударної обробки на шорсткість, твердість та залишкові напруження поверхні нержавіючої сталі 08Х18Н10. З огляду на формування нового поверхневого рельєфу, параметри шорсткості Ra стали нижчими після ультразвукового та дробоструминного зміцнення, ніж після лазерного і кавітаційного зміцнення. Ультразвукова обробка призвела до найвищої поверхневої твердості серед досліджуваних обробок. Оптимальні режими визначалися з урахуванням мінімальних величин шорсткості поверхні і максимальних величин поверхневої твердості і залишкових напружень. У порівнянні з вихідним станом, ці режими призводять до збільшення поверхневої твердості HRC (LSP2 ~30,7%, WjCP2 ~38,4%, WjSP2 ~69,6%, UIT4 ~73,2%) і зменшення параметра шорсткості Ra (LSP2 ~5,5%, WjCP2 ~7,8%, WjSP2 ~38,2%, UIT4 ~91,1%) забезпечуючи залишкові напруження стиснення (LSP2 –470 MPa, WjCP2 –377 MPa, WjSP2 –519 MPa, UIT4 –693 MPa).*

Ключові слова. *Деформаційне зміцнення, шорсткість, твердість, залишкові напруження, лазерна ударна обробка, кавітаційна обробка, дробоструминна обробка, ультразвукова ударна обробка*

Влияние механических поверхностных обработок на шероховатость, твердость и остаточные напряжения нержавеющей стали 08Х18Н10

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Аннотация. *Исследованы влияние лазерной ударной обработки, кавитационной обработки, дробеструйной обработки и ультразвуковой ударной обработки на шероховатость, твердость и остаточные напряжения поверхности нержавеющей стали 08Х18Н10. Вследствие формирования нового рельефа поверхности, параметры шероховатости Ra стали ниже после ультразвукового и дробеструйного упрочнения, чем после лазерного и кавитационного упрочнения. Ультразвуковая обработка привела к самой высокой твердости поверхности среди изученных обработок упрочнения. Оптимальные режимы были определены с учетом минимальных величин шероховатости поверхности и максимальных величин поверхностной твердости и остаточных напряжений. По сравнению с исходным состоянием, эти режимы приводят к увеличению твердости поверхности HRC (LSP2 ~30,7%, WjCP2 ~38,4%, WjSP2 ~69,6%, UIT4 ~73,2%) и снижению параметра шероховатости Ra (LSP2 ~5,5%, WjCP2 ~7,8%, WjSP2 ~38,2%, UIT4 ~91,1%) обеспечивая остаточные напряжения сжатия (LSP2 –470 MPa, WjCP2 –377 MPa, WjSP2 –519 MPa, UIT4 –693 MPa).*

Ключевые слова. *Деформационное упрочнение, шероховатость, твердость, остаточное напряжение, лазерная ударная обработка, кавитационная обработка, дробеструйная обработка, ультразвуковая ударная обработка*

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