Journal of
Marine Science and Technology

Volume 24 | Issue 3 Article 23

INFLUENCE OF SHOT-PEENING-INDUCED RESIDUAL STRESSES ON POST-NECKING BEHAVIOR OF TEMPERED ULTRAHIGH-STRENGTH LOW ALLOY 300M STEEL

Shing-Hoa Wang
Department of Mechanical and Mechatronic Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C

Yi-Ming Jen
Department of Mechanical and Mechatronic Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C., ymjen@mail.ntou.edu.tw

Yu-Cyuan Lin
Department of Mechanical and Mechatronic Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C

Bee-Fong Wu
Yung Heng Machinery and Electric Industry Company, New Taipei City, Taiwan, R.O.C.

Hsiu-Chuan Hsu
Department of Mechanical and Mechatronic Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C.

See next page for additional authors

Recommended Citation

Wang, Shing-Hoa; Jen, Yi-Ming; Lin, Yu-Cyuan; Wu, Bee-Fong; Hsu, Hsiu-Chuan; and Yeh, Ji-Jung (2016) "INFLUENCE OF SHOT-PEENING-INDUCED RESIDUAL STRESSES ON POST-NECKING BEHAVIOR OF TEMPERED ULTRAHIGH-STRENGTH LOW ALLOY 300M STEEL," *Journal of Marine Science and Technology*: Vol. 24: Iss. 3, Article 23.
DOI: 10.6119/JMST-015-1130-1
Available at: https://jmstt.ntou.edu.tw/journal/vol24/iss3/23

Journal of Marine Science and Technology, Vol. 24, No. 3, pp. 581-588 (2016)
DOI: 10.6119/JMST-015-1130-1

INFLUENCE OF SHOT-PEENING-INDUCED RESIDUAL STRESSES ON POST-NECKING BEHAVIOR OF TEMPERED ULTRAHIGH-STRENGTH LOW ALLOY 300M STEEL

Shing-Hoa Wang[1], Yi-Ming Jen[1], Yu-Cyuan Lin[1], Bee-Fong Wu[2], Hsiu-Chuan Hsu[1], and Ji-Jung Yeh[3]

Key words: shot peening, 300M steel, post-necking, elongation, residual stress.

ABSTRACT

The effect of the tempering temperature and shot peening time on the uniaxial post-necking behavior of 300M steel (silicon-modified AISI 4340 steel) was experimentally investigated in this study. Normalized specimens were divided into two groups: one tempered at 280°C and the other tempered at 302°C. The specimens were shot-peened for various durations to study the effect of the shot peening time on their mechanical properties. Experimental results showed that the shot-peening-induced compressive residual stress in the specimens tempered at 302°C was greater than that in the specimens tempered at 280°C, and the optimum compressive residual stress was obtained by shot peening for 5 min. Although the tempering temperature and shot peening time did not influence the yield and ultimate strengths, the total and post-necking elongations of the specimens decreased with the shot peening time. The necking behavior in the specimens tempered at 302°C was more apparent than that in the specimens tempered at 280°C. In this paper, the influence of the shot peening time on the post-necking behavior is elucidated on the basis of work hardening resulting from shot peening, and the effect of the tempering temperature on the necking behavior is interpreted in terms of the presence of residual stress.

Paper submitted 07/13/15; revised 11/12/15; accepted 11/30/15. Author for correspondence: Yi-MingJen (e-mail: ymjen@mail.ntou.edu.tw).
[1] *Department of Mechanical and Mechatronic Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C.*
[2] *Yung Heng Machinery and Electric Industry Company, New Taipei City, Taiwan, R.O.C.*
[3] *Institute of Nuclear Energy Research, Atomic Energy Council, Longtan, Taoyuan, Taiwan, R.O.C.*

I. INTRODUCTION

An understanding of the mechanical properties of metals under various loading conditions is crucial for the engineering applications in structural design and manufacturing. Steel materials can have several microstructures, such as ferrite/pearlite, bainite, martensite, and austenite microstructures, and each microstructure is associated with distinct mechanical properties (Carlson et al., 1979; Chai and Laird, 1987; Callister and Rethwisch, 2011). Therefore, the optimum strength can be obtained for any one or a combination of these structures. Generally, quenching and tempering are well-established techniques used for increasing the strength of steel, and this increase is mainly due to the finely dispersed precipitation of alloy carbides during tempering (Huang and Tomas, 1971). Despite being the strongest among all steel microstructures, the martensite microstructure is rarely used without being tempered because the large internal stresses resulting from the transformation reduce the material's ductility (Horn and Ritchie, 1978; Kwon et al., 1988). Low-temperature tempering is appropriate for reducing these stresses considerably. However, in low-temperature tempering, dislocation rearrangement and annihilation are accompanied by carbide precipitation, which transforms the tetragonal martensite microstructure into the fine ferrite microstructure. From a commercial viewpoint, the martensitic steels used in past studies must have been tempered in the temperature range of 200°C-250°C. To obtain steel with the optimum strength and toughness, the steel should be austenitized at 982°C (1255 K) and tempered in the range of 204°C-316°C (477-589 K) (Youngblood and Raghavan, 1977).

Shot peening is a widely used process for improving the fatigue strength of metal components (Marsh, 1993; Miller, 1993). In this process, the surface of the components is bombarded with a stream of spheroidal shot with sufficient kinetic energy to induce plastic strain in the subsurface layer. The resulting compressive residual stress field (CRSF) near the surface prevents fatigue crack initiation and retards fatigue crack propagation. Furthermore, recent studies have demonstrated that shot peening and other plastic deformation treatments increase the fatigue strength. Residual stresses effectively retard microcrack propagation, but have only a slight influence on fatigue crack initiation (Kloos et al., 1987; Wagner et al., 1993; Song and Wen, 1999; Batista et al., 2000). Moreover, although the hardening of the plastically deformed layer of materials (Molzen and Hornbach, 2001) after shot peening treatment increases the fatigue strength, no study has quantified this effect. Overlapping indentations or dimples have been found to develop during shot and hammer peening treatments. Uniform residual compressive stresses in the surface layer can suppress intrusions and extrusions and delay fatigue damage.

The shot peening process has been employed to increase the fatigue resistance of metal materials (Diepart, 1994; de los Rios et al., 1995). The compressive residual stress induced in the surface layers of the materials inhibits the nucleation and propagation of fatigue cracks. An increase in the shot peening intensity increases the maximum compressive residual stress and the width of the CRSF. When a CRSF is present, the shot peening treatment pushes crack sources beneath the surface in most medium and high cycle cases. In specimens that have either been shot peened in a low cycle or not been shot peened, cracks originate from the surface. The presence of a CRSF improves the fatigue resistance of AISI 4340 steel (Torres and Voorwald, 2002).

Numerous previous studies have investigated the effect of shot peening on the fatigue properties. However, analyses of the effect of shot peening on the monotonic tensile property have been rare. The objective of the present study was to investigate the effect of the shot peening time on tensile post-necking behavior. The effect of shot peening time on the necking behavior was focused on in particular because necking deformation first occurs in the interior of shot-peened specimens. Necking deformation differs considerably from the failure mechanism in fatigue tests, in which the damage initiates on the specimen surface. Various shot peening times were considered in the experimental program for evaluating the effect of the shot peening time on the post-necking behavior. Furthermore, the effect of the tempering temperature on the necking and post-necking behavior of 300M steel was also studied. The residual stress was measured and used for interpreting the influence of the shot peening time and tempering temperature on the post-necking behavior.

II. MATERIALS AND EXPERIMENTAL DETAILS

In this study, 300M steel specimens were employed (silicon-modified AISI 4340 steel). The composition of the specimen material was similar to that of the material used for producing armored combat vehicles, for which high strength and toughness are fundamental design requirements. Table 1 shows the chemical composition of the 300M specimens in terms of weight percentage, as analyzed using a glow discharge spectrometer. The specimen composition is essentially similar to that of AISI 4340, but modified with 1.6 wt% silicon. Moreover, it has slightly higher carbon and molybdenum content and contains vanadium.

Table 1. Chemical composition of 300M steel.

(wt.%)

C	Mn	Si	Cr	Ni	Mo	Cu	S	P	V
0.41	0.81	1.61	0.83	1.86	0.38	0.04	0.001	0.005	0.065

The base material of the specimens was normalized first. Previous studies have shown that most inclusions in AISI 4340 steel are of MnS particles (Murty et al., 1975). However, the inclusion concentration can be considerably reduced through vacuum arc remelting (VAR) (Hickey and Anticil, 1985). The 300M steel employed in the present study was normalized at 927°C (1200 K) for 1 h through VAR prior to delivery.

The specimens were machined according to ASTM E292-01 to the standard shape and dimensions. The length of the gage section was 24.5 mm, and the diameter of the solid cylinder in the gage section was 6.4 mm; an arc with a radius of 4.7 mm was introduced between the grip and the gage sections. All specimens were austenitized in a vertical tube furnace at 871°C (1144 K) for 30 min and then directly oil quenched at 40°C (313 K). The quenched specimens were divided into two groups. The specimens in one group were tempered twice at 280°C (553 K) for 2 h, and those of the other group were tempered twice at 302°C (575 K) for 2 h. According to the datasheet provided by the material supplier, the optimum tempering temperature was between 550 and 600 K, implying that the 300M steel had higher hardness than that tempered at other temperatures. Hence, to investigate the effect of the tempering temperature on the post-necking behavior, in addition to the frequently employed tempering temperature of 302°C (575 K), 280°C (553 K) was also considered in the experimental program. The entire heat treatment process is depicted in Fig. 1. Before mechanical testing, the heat-treated specimens were divided into four groups, and the groups were shot peened for various durations: 0, 5, 10, and 15 min. A preliminary study revealed that shot peening times longer than 15 min resulted in a rough dimpled surface, which decreased the specimen strength considerably. Shot peening was performed using 170 grit steel shot in an air-blast machine under a peening pressure of 5 bar. The peening strength for a bent standard shot peened sheet of dimensions 2.4 × 19 × 76 mm must be equivalent to the arc height, which is in the range of 0.178-0.254 mm.

The hardness of the studied specimens was measured using a Future-Tech Rockwell-type hardness tester with a 150-kg load. To examine the effect of the shot peening time on the residual stress magnitude, the residual stress of the studied specimens was measured by X-ray diffraction. A Siemens D5000 X-ray diffractometer and the Siemens Stress/AT software were used for the stress measurements, the parameters

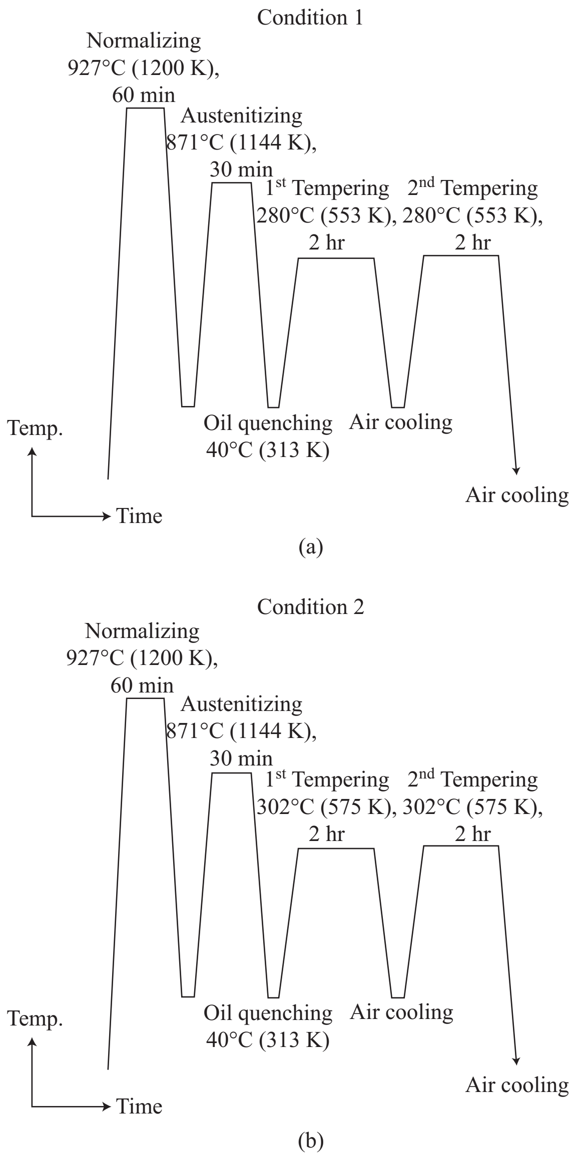

Fig. 1. Heat treatment schematic diagram with different tempering temperatures: (a) tempered at 280°C (553K) (b) tempered at 302°C (575 K).

for which are listed in Table 2. A monochromatic beam of X-rays is diffracted from the surface of a stressed sample at a large diffraction angle (2θ). In Table 2, the angle ψ , which defines the orientation of the sample surface, is the angle between the normal to the surface and the bisector between the incident and the diffracted beams. It is also the angle between the normal to the diffracting lattice planes and the sample surface. Diffraction occurs at the angle of 2θ, which is defined by Bragg's law, and 2θ is the diffraction angle. Any change in the lattice spacing d results in a corresponding shift in the diffraction angle 2θ. To measure the stress in various directions at the same point, the sample was rotated about its surface normal to ensure that the direction of interest was in the diffraction plane.

Table 2. Parameters used in the X-ray diffraction technique.

X-ray diffractometer	Siemens D5000 model
goniometer geometry	Omega (Ω)
Characteristic X-ray	Cr-Kα
Lattice plane	(2 1 1)
Diffraction angle (2θ)	156°
Psi (ψ) tilt	-41.41°, -33.9°, -25.66°, -14.46°, 0.00° 20.70°, 30.00°, 37.76°, 45.00°
Scanning range	152.5°~159.5°
Step width	0.05°/ step
Acquisition time	3 sec / step
Tube voltage	45 KV
Tube current	35 mA
Young modulus	225200 MPa
Poission coefficient	0.3

Quasi-static tensile tests were conducted using a MTS material testing system. All the specimens were axially loaded at room temperature until they fractured with a strain rate of $1 \times 10^{-3}\ s^{-1}$. The axial strain was then measured using a strain-gage extensometer with a nominal gage length of 20 mm. For the specimens with the same shot peening time condition, the tensile tests were performed three times to obtain reliable results. Moreover, the optical microstructures were etched using the etchant Nital (consisting of 3% HNO_3 and 97% CH_3COOH) after standard mechanical polishing. The fracture surfaces were cut from the fractured specimens and the topographical features were examined under a high-resolution field-emission scanning electron microscope (Hitachi S-4800) operated at 5.0 kV.

III. RESULTS AND DISCUSSION

1. Microstructure of the Tempered 300M Steel

In the as-quenched conditions after being austenitized, the steel specimens had the highest strength and hardness, but the lowest ductility. The lattice structure of steel changes from face-centered cubic (γ phase) to body-centered tetragonal (martensite) during the formation of the martensite platelets, and a large amount of distortion occurs simultaneously. This phenomenon leads to a rapid increase in the strength and hardness of the steel. However, adequate tempering can relieve the stress and increase the ductility and toughness. An enlarged view of the microstructure observed using the scanning electron microscope is shown in Fig. 2. Clearly, the microstructure tempered at 302°C shows finer martensite than that tempered at 280°C. This led to the slightly higher hardness of the specimen tempered at 302°C, as shown in Table 3. The optimum tempering temperature determined in the present study is similar to that presented in a previous research (Horn and Ritchie, 1978), and the oil-quenched 300M steel tempered at approximately 300°C exhibited the optimum mechanical properties.

Table 3. Rockwell and Brinell hardness for two tempering conditions.

Tempering Temp.		HRc (HB)
Cond. 1	280°C (553 K)	52 (512)
Cond. 2	302°C (575 K)	54 (543)

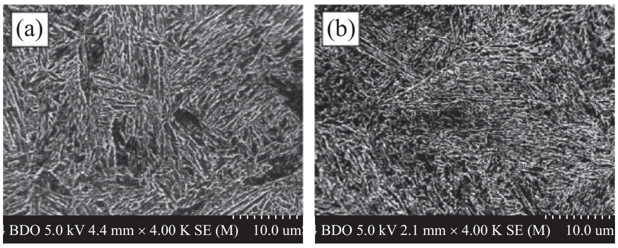

Fig. 2. SEM view of the heat treatment microstructures for 300M steel tempered at (a) 280°C and (b) 302°C.

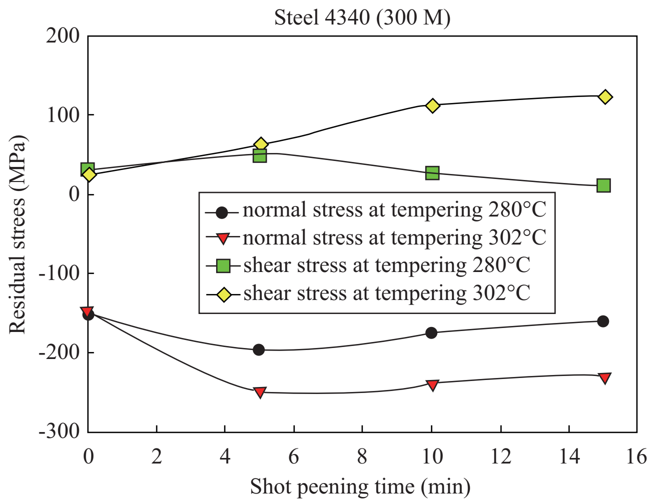

Fig. 3. Effect of the shot peening time on the measured residual stress for the specimens tempered at two different temperatures.

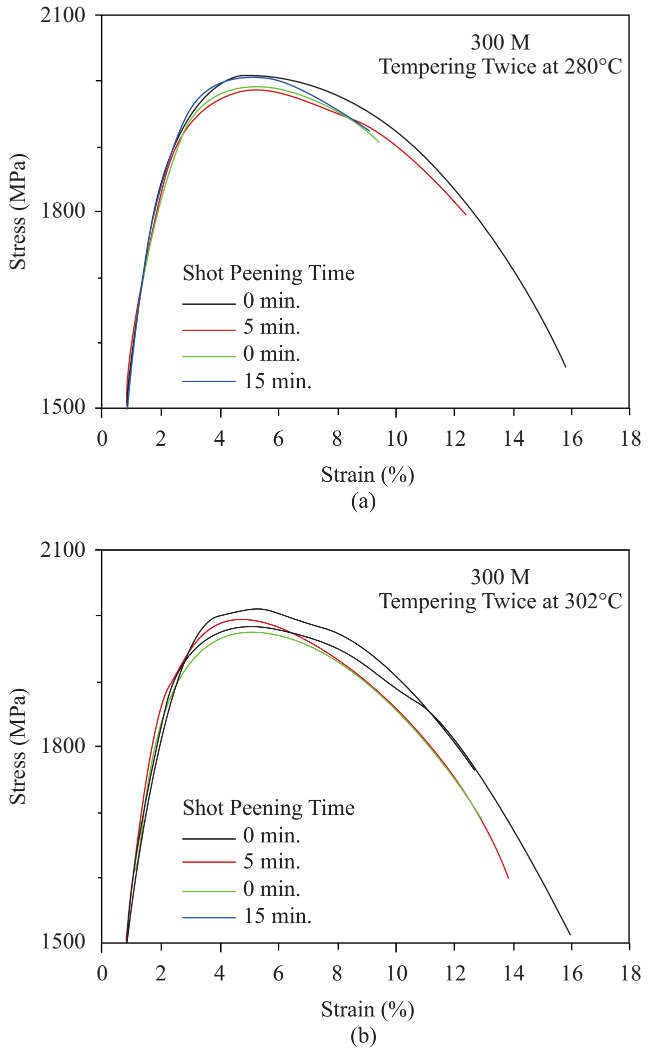

Fig. 4. Tensile stress-strain curves (above 1500MPa) for the specimens subjected to four different shot peening times. The samples were twice tempered at (a) 280°C (553K) and (b) 302°C (575K).

2. Effect of Shot Peening Time on Surface Residual Stress

Fig. 3 shows the effect of the shot peening time on the measured surface residual stress in the tempered 300M steel specimens. Both normal and shear residual stresses are shown in the figure. Evidently, the maximum compressive residual stress was obtained for the shot peening time of 5 min for the specimens tempered at both temperatures. The residual stress remained unchanged at longer shot peening times. Furthermore, for a given shot peening time, the compressive residual stress of the specimens tempered at 302°C was greater than that of the specimens tempered at 280°C, implying that the effect of residual stress induced by the shot peening treatment was stronger in the specimens tempered at 302°C.

4. Effect of Shot Peening Time on Mechanical Properties ahead the Ultimate Stress Points

Figs. 4(a) and 4(b) show the effect of the shot peening time on the stress-strain curves for the 300M steel specimens tempered at 280°C and 302°C, respectively. The experimental results show that the elastic moduli of the studied specimens were unaffected by shot peening and that the uniform strain region was relatively small. This implies that the heat-treated 300M steel specimens achieved the ultimate tensile strength very quickly. Because the elastic behavior of all the studied specimens were similar, only the part of the stress-strain curves beyond 1500 MPa are presented in Figs. 4(a) and 4(b). The measured ultimate tensile strength and yield strength of the specimens tempered at different temperatures and shot peened for different durations are listed in Table 4. The values listed in the table are the average value obtained from three quasi-static tensile tests. The table shows that the tempering temperature had no effect on the yielding strength and ultimate strength of the 300M steel materials. Furthermore, the measured values of the properties accord with those reported in a

Table 4. Mechanical properties of the studied 300M steel specimens.

Tempering temperature, Degree (Kelvin)	Shot peening time, minutes	YS, MPa	UTS, MPa	Total elongation, %	Post-necking elongation, %	Strain hardening exponent, *n*
280°C (553 K)	0	1642	2008	16	10.4	0.44
	5	1625	1986	12	7.3	0.48
	10	1612	1991	8	4.5	0.49
	15	1625	2006	7	4.1	0.5
302°C (575 K)	0	1645	1983	16	11.1	0.37
	5	1647	1992	13	9.3	0.43
	10	1618	1975	11	8.3	0.43
	15	1618	2010	10	6.6	0.48

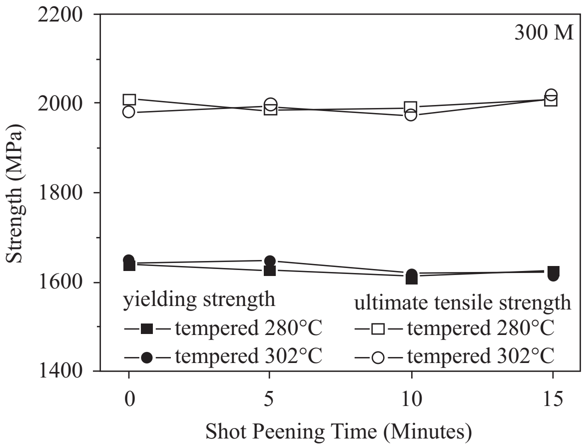

Fig. 5. Comparison of the shot peening time influence on the ultimate tensile strength and yielding strength for the specimens tempered at two different temperatures.

previous study on 300M steel (Youngblood and Raghavan, 1977), in which the tensile strength and yield strength were approximately 1900 and 1500 MPa, respectively. Fig. 5 shows the effect of the shot peening time on the ultimate tensile strength and yield strength of the 300M steel specimens tempered at the two temperatures. The ultimate tensile strength and yield strength appear to be independent of the shot peening time.

The true stress-strain curves of the 300M steel specimens conform closely to the Ludwik relationship $\sigma = K\varepsilon^n$, where K is the strength coefficient and n is the strain hardening exponent. These two constants completely describe the shape of the true stress-strain curves. The value of K indicates the strength of the material and the magnitude of forces required for forming. The value of n is correlated with the slope of the true stress-strain curve (i.e. the rate of work hardening), and it serves as a measure of the ability of the material to inhibit the localization of deformation. The parameter n can be obtained by fitting the relationship between the stress and strain obtained in the tensile tests with a power law curve. The exponent

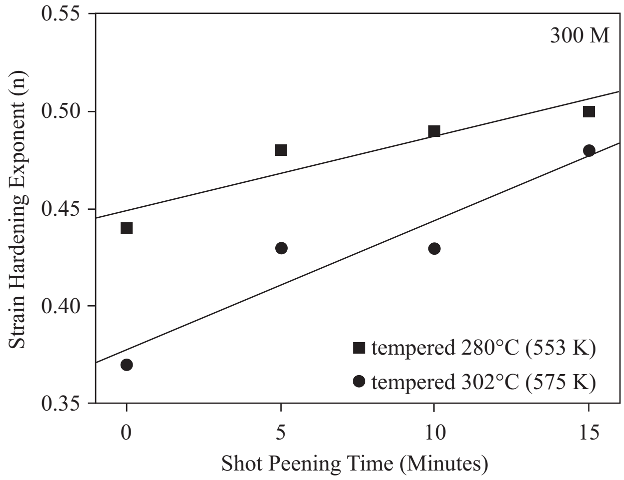

Fig. 6. Effect of the shot peening time on the strain-hardening exponent *n* for the specimens tempered at two different temperatures.

n is the slope of the curve in a log-log plot. The stress must not exceed the tensile instability stress σ_{crit}, which corresponds to the maximum load in simple tension and marks the end of uniform straining (thus, $\sigma_{crit} = K\varepsilon_{crit}^n$). Table 4 lists the values of the strain hardening exponents for the studied specimens. Fig. 6 shows the effect of the shot peening time on n for the studied 300M steel specimens tempered at the two temperatures. In the figure, the strain hardening exponent increases with the shot peening time for both of the tempered specimens. The increasing trend for the specimens tempered at 302°C is considerably steeper compared with that for the specimens tempered at 280°C. Furthermore, despite the finer martensite composition, the strain hardening exponent for the specimens tempered at 302°C is lower than that for the specimens tempered at 280°C, indicating that those tempered at 280°C were harder than those tempered at 302°C. High hardness was observed in the specimens tempered at both temperatures at longer shot peening durations. Because the strain hardening exponent of a material is correlated with its resistance to necking, necking behavior was expected to be more evident in the specimens tempered at 302°C than in those tempered at 280°C. Furthermore, the necking behavior of the two types of specimen becomes less apparent with longer shot peening durations. This is discussed in detail in the following section.

4. Effect of Shot Peening Time on Necking Behavior

When the applied stress exceeds the ultimate tensile stress, the deformation is localized in the necked region of the specimen, and the material in this region is no longer subject to purely uniaxial tensile stress, but to a complex system of triaxial tensile and shear stress in which the maximum stress occurs at the center of the necked region. This phenomenon has been detailed in a previous paper (Wigley, 1971).

Table 4 shows the total and post-necking elongations in the tensile tests performed on the studied specimens. The total elongation was dominated by local post-necking elongation.

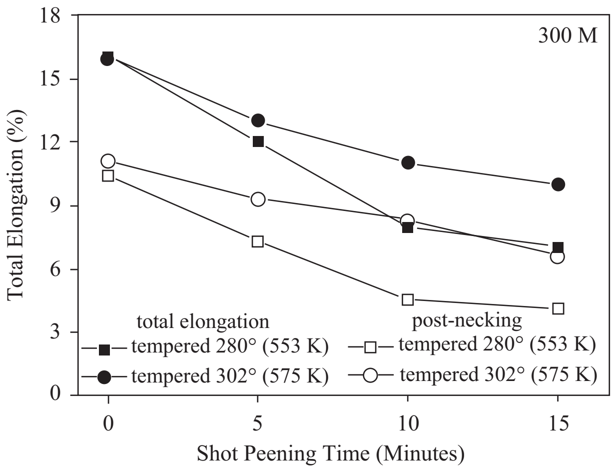

Fig. 7. Comparison of the shot peening time influence on the elongations for the specimens tempered at two different temperatures.

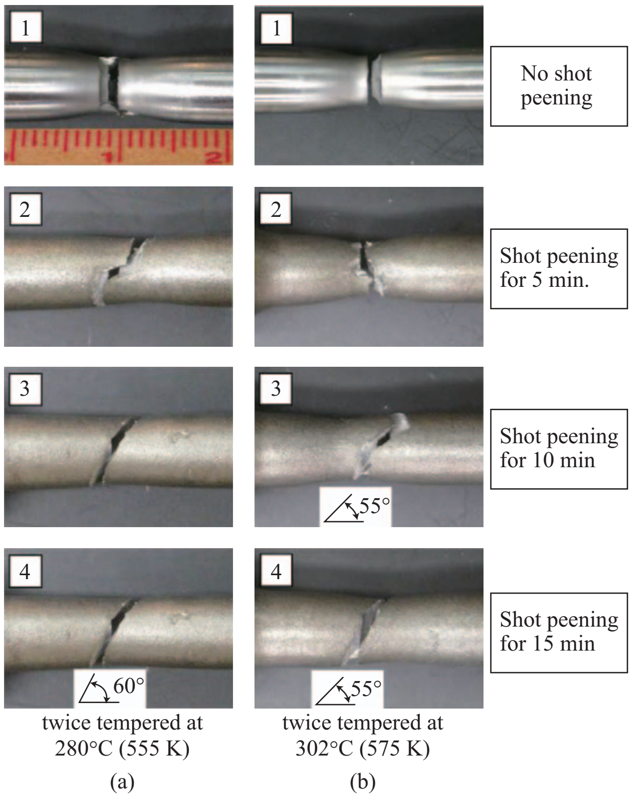

Fig. 8. Comparison of the shot peening time influence on the local necking shape for studied specimens tempered at (a) 280°C (553K) and (b) 302°C (575 K). Shot peening time for (1) unpeened, (2) 5 minutes, (3) 10 minutes, and (4) 15 minutes.

The influence of the shot peening time on the total elongation and post-necking elongation of the studied 300M steel specimens tempered at the two temperatures is shown in Fig. 7. The total and post-necking elongations decrease considerably with the peening time. Moreover, the elongation of the specimens tempered at 302°C is greater than that of the specimens tempered at 280°C. The relationship between the elongation and

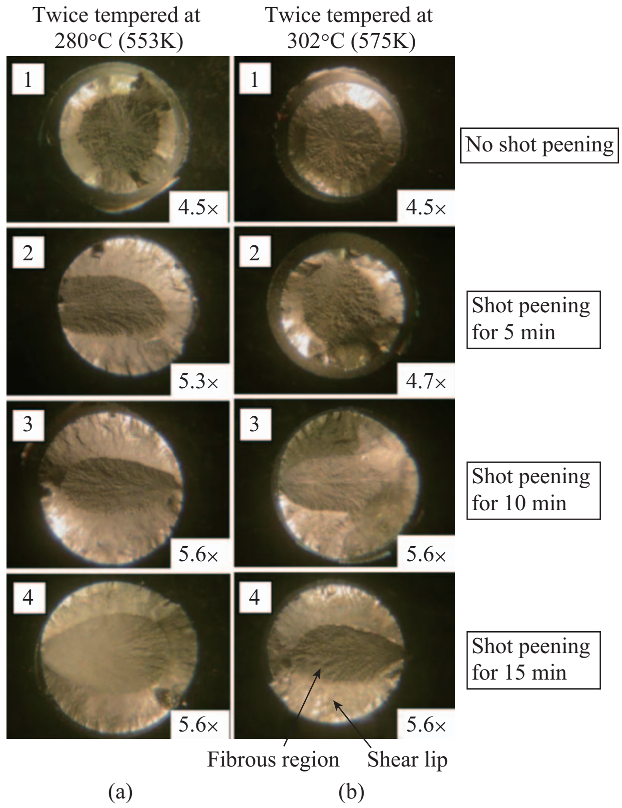

Fig. 9. Comparison of the shot peening time influence on the fractographs for 300M steel specimens tempered at (a) 280°C (553 K) and (b) 302°C (575 K).

shot peening time corresponds to that between the strain hardening exponent and shot peening time. Work hardening plays a crucial role in determining the elongation behavior because of the finer martensite structure of the specimens tempered at 302°C compared with that of the specimens tempered at 280°C (Fig. 2).

Fig. 8 shows photographs of the local necking shapes of the studied specimens. In the specimens tempered at 280°C and 302°C, the necking behavior becomes less apparent with longer shot peening durations. The observation is similar to the decrease in elongation with longer shot peening times (Fig. 7). Furthermore, necking is more prominent in the specimens tempered at 302°C than in the specimens tempered at 280°C. This difference was verified by comparing the elongation behavior of the two specimens in Fig. 7. Furthermore, for the specimens tempered at 280°C and 302°C (without shot peening), the failure surfaces exhibited the typical ductile "cup-and-cone" mode with local necking, which was dominated by normal tension and characterized by void formation and coalescence in the interior of the specimens; the shear lips are evident in the outer rim of the specimens, as shown in Figs. 8(a)-1 and 8(b)-1. At longer shot peening times, the fibrous region shrank considerably and the failure mode changed from the cup-and-cone mode to a shear dominant mode. For the specimens tempered at 280°C, the degree of obliqueness of the shear plane is ap-

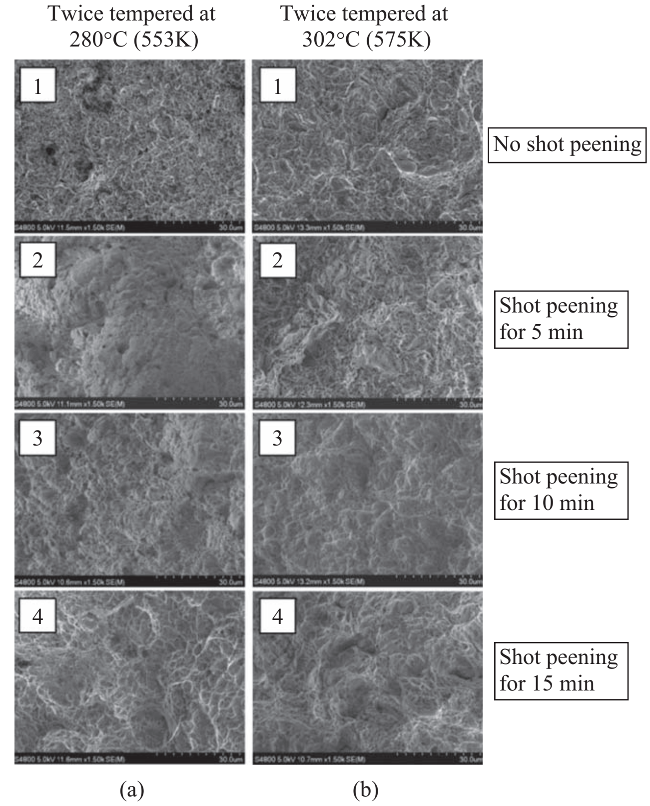

Fig. 10. Fractographic comparison of fibrous region in the center of tensile rupture for 300M steel specimens tempered at (a) 280°C (553K) and (b) 302°C (575 K). Shot peening time for (1) no peening, (2) 5 minutes, (3) 10 minutes, (4) 15 minutes.

proximately 60° relative to the longitudinal axis (Figs. 8(a)-3 and 8(a)-4); for the specimens tempered at 302°C (Figs. 8(b)-3 and 8(b)-4), this value is 55°.

Fig. 9 shows photographs of the fracture surfaces of the studied specimens. Clearly, at longer shot peening times, the fibrous region portion became smaller, and the necking behavior was less apparent. Furthermore, the necking behavior was less apparent in the specimens tempered at 280°C compared with that in the specimens tempered at 302°C. For example, necking was almost absent in the specimens tempered at 280°C after 15 min of shot peening. Work hardening resulting from shot peening is the main reason for the transition of failure mode during shot peening. Ductile fracture occurs through a shear fracture across a slip plane when the material is more work hardened. In other words, the necking behavior is weakened when the material hardness increases because of cold working or shot peening.

Because the compressive residual stress in the specimens tempered at 302°C was larger than that in the specimens tempered at 280°C, owing to the equilibrium, large tensile residual stress was induced in the interior of the specimen tempered at 302°C. This tensile stress contributed to the plastic deformation and linkage of voids in the fibrous region, and the necking behavior was enhanced. This mechanism can explain the difference in the necking behavior between the specimens tempered at 280°C and those tempered at 302°C.

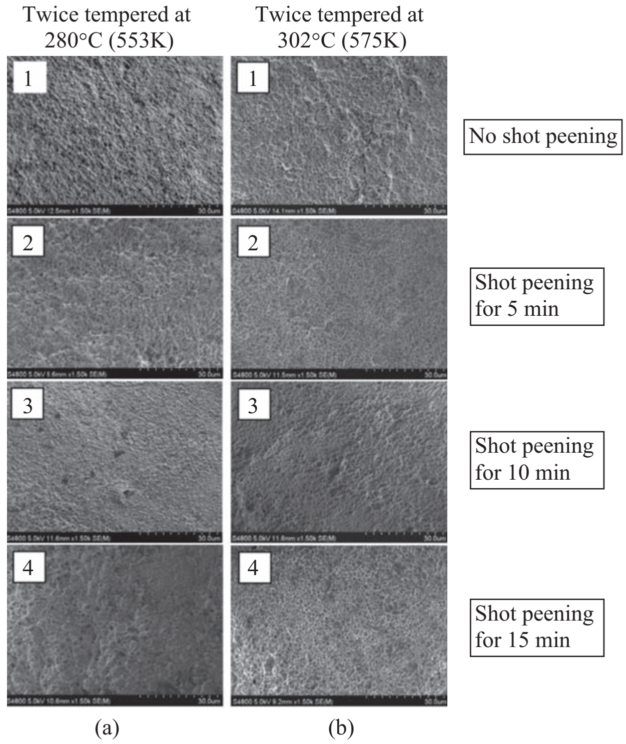

Fig. 11. Fractographic comparison of the subsurface of smaller shear lip in tensile rupture for 300M steel specimens tempered at (a) 280°C (553 K) and (b) 302°C (575 K). Shot peening time for (1) no peening, (2) 5 minutes, (3) 10 minutes, (4) 15 minutes.

Figs. 10 and 11 show SEM fractographs of the fibrous region and shear lip region of the fractured specimens, respectively. In the figures, the fracture surfaces of the fibrous region are characterized by fine dimples in the unpeened specimens tempered at 280°C (Fig. 10(a)-1) and by shallow dimples mixed with quasi-cleavages in the unpeened specimens tempered at 302°C (Fig. 10(b)-1). The photographs in Fig. 10 show that the fibrous surfaces of the tempered specimens shot peened for different durations are characterized by rough dimples, among which some smeared dimples are due to the shear friction between two slanted fracture surfaces. Fig. 11 shows fine and delicate dimples nucleated in the shear lip region located in the outer rim of the rupture surface.

IV. CONCLUSIONS

The effect of the tempering temperature and shot peening time on the mechanical properties of 300M steel in uniaxial tensile tests was studied. The conclusions of this study are summarized as follows:

1. The compressive residual stress induced by shot peening the 300M steel specimens tempered at 302°C was larger than in the specimens tempered at 280°C, and the optimum shot peening time was 5 min for both types of specimen.

2. The tempering temperature and shot peening time had no influence on the yield strength and ultimate strength of the 300M steel specimens.
3. The strain hardening exponent for the 300M steel specimens tempered at 280°C was higher than that for the specimens tempered at 302°C. Moreover, the strain hardening exponents for the studied specimens increased with the shot peening time.
4. The total and post-necking elongations of the studied specimens decreased with longer shot peening times. The work hardening resulting from shot peening weakened the necking behavior weak and decreased the elongations.
5. More apparent necking behavior and larger elongations were observed in the specimens tempered at 302°C than in those tempered at 280°C. The dissimilar necking behavior between the specimens tempered at the two temperatures was primarily attributed to the residual stress.
6. To summarize, the failure mode, necking behavior, and characteristic fractographs of the fibrous/shear lip region were influenced in a complex manner by the work hardening and residual stress resulting from shot peening.

REFERENCES

Batista, A. C., A. M. Dias, J. L. Lebrun, J. C. Le Flour and G. Inglebert (2000). Contact fatigue of automotive gears: evolution and effects of residual stresses introduced by surface treatments. Fatigue and Fracture of Engineering Materials and Structures 23, 217-228.

Callister, M. D. and D. G. Rethwisch (2011). Material Science and Engineering. John Wiley & Sons, New York.

Carlson, M. F., B. V. Narasimha Rao and G. Thomas (1979). The effect of austenitizing temperature upon the microstructure and mechanical properties of experimental Fe/Cr/C steels. Metallurgical and Materials Transactions A 10, 1273-1284.

Chai, H. F. and C. Laird (1987). Mechanisms of cyclic softening and cyclic creep in low carbon steel. Materials Science and Engineering 93, 159-174.

de los Rios, E. R., A. Walley, M. T. Milan and G. Hammersley (1995). Fatigue crack initiation and propagation on shot-peened surfaces in A316 stainless steel. International Journal of Fatigue 17, 493-499.

Diepart, C. P. (1994) Modeling of shot peening residual stresses practical applications. Materials Science Forum 163-65, 457-464.

Hickey, C. F. and A. A. Anticil (1985). Split heat mechanical property comparison of ESR and VAR 4340 steel. Journal of Heat Treating 4, 177-183.

Horn, R. M. and R. O. Ritchie (1978). Mechanisms of tempered martensite embrittlement in low alloy steels. Metallurgical and Materials Transactions A 9, 1039-1053.

Huang, D. H. and G. Tomas (1971). Structure and mechanical properties of tempered martensite and lower bainite in Fe-Ni-Mn-C steels. Metallurgical and Materials Transactions A 2, 1587-1598.

Kloos, K. H., B. Fuchsbauer and J. Adelmann (1987). Fatigue properties of specimens similar to components deep rolled under optimized conditions. International Journal of Fatigue 9, 35-42.

Kwon, H., J. C. Cha and C. H. Kim (1988). The effect of grain size on fracture behaviour in tempered martensite embrittlement for AISI 4340 steel. Materials Science and Engineering 100, 121-128.

Marsh, K. J. (1993). Shot peening-techniques and applications. EMAS publishing, London.

Miller, K. J. (1993). Materials science perspective of metal fatigue resistance. Materials Science and Technology 9, 453-462.

Molzen, M. S. and D. Hornbach (2001). Shot peening and heat treatment reduce stress. Welding Journal 80, 38-43.

Murty, Y. V., J. E. Morral, T. Z. Kattamis and R. Mehrabian (1975). Initial coarsening of manganese sulfide inclusions in rolled steel during homogenization. Metallurgical and Materials Transactions A 6, 2031-2035.

Song, P. S. and C. C. Wen (1999). Crack closure and crack growth behaviour in shot peened fatigued specimen. Engineering Fracture Mechanics 63, 295-304.

Torres M. A. S. and H. J. C. Voorwald (2002). An evaluation of shot peening, residual stress and stress relaxation on the fatigue life of AISI 4340 steel. International Journal of Fatigue 24, 877-886.

Wagner, L., C. Müller and J. K. Gregory (1993). Effect of surface rolling and shot peening on notched fatigue strength in Al 2024. In: Surface engineering: [papers presented at the International Conference on Surface Engineering, 1993, Bremen, Germany], edited by Mayr P., DGM-Informationsges, Oberursel, 181-186.

Wigley, D. A. (1971). Mechanical properties of metals at low temperature. Springer, New York.

Youngblood, J. L. and M. Raghavan (1977). Correlation of microstructure with mechanical properties of 300M steel. Metallurgical and Materials Transactions A 8, 1439-1448.