OPTIMIZED FATIGUE PERFORMANCE OF MARTENSITIC STAINLESS STEEL AISI 440C USING DEEP ROLLING INTEGRATED INTO HARDENING PROCESS

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Abstract

The deep rolling process can be modified by annealing at appropriate temperature and time to optimize the fatigue performance of metallic materials. The hardening process of the martensitic stainless steel AISI 440C composes of quenching and double tempering processes. We suggest to integrate the deep rolling process into the hardening treatment because the heat from the tempering process possibly provides sufficient static strain ageing effects. It was found that the deep rolling process can be integrated fully into the hardening process of the martensitic stainless steel AISI 440C, especially in the middle of the double tempering processes. The heat of the tempering process after the deep rolling process leads to beneficial static strain ageing effects as a consequence of greater fatigue lives. Moreover, the maximum fatigue life was detected in this research, when the optimized annealing had been performed instead of the second tempering process.

Keywords: Fatigue; Deep rolling; Stainless steel; Surface treatment; Tempering.

1. Introduction

For highly stressed components in the automotive industry, fatigue performance is an important issue in numerous applications. It is well known that the fatigue strength as well as -life depends strongly on the surface integrity [1-4]. Thus, there are many ways to improve the fatigue performance by modification or treatment of the surface regions, i.e., thermochemical or mechanical surface treatments. Some investigations of thermochemical surface treatments, e.g., carbonitriding or boronizing processes are reported and focused on the fatigue as well as kinetics [5-8]. Mechanical surface treatments, e.g. shot peening, deep rolling or laser shock peening are well-known processes for fatigue life enhancement due to the generated near-surface work hardening layer and compressive residual stresses retarding the fatigue crack initiation and propagation [9-15]. However, the beneficial effects of mechanical surface treatments can be deteriorated under high loading and/or high temperature. Compressive residual stresses can be relaxed due to dislocation movement as well as rearrangement [16-20]. From these reasons, during service, a high stability of compressive residual stresses is desired. This can be achieved microstructurally by pinning dislocations. A strain ageing concept (formation of Cottrell clouds by solute atoms) can be used to pin as well as obstruct the dislocation movement [21-25]. If such a strain ageing concept can be applied to mechanically surface treated conditions, improved stability of compressive residual stresses should be expected. Consequently, the fatigue lifetime enhancement can be expected under stress-controlled fatigue. Dynamic or static strain ageing can be found in modified mechanical surface treatments, i.e. high temperature deep rolling or deep rolling followed by appropriated annealing as well as heating [26-29]. In [30], it is shown that fatigue lives of deep rolled metallic materials such as non-hardened normalized plain carbon steel or austenitic stainless steel can increase after appropriate annealing although near-surface compressive residual stresses were actually decreased. One simple idea of combined surface treatment is to integrate the deep rolling process into the hardening treatment (quenching followed by double tempering) of the martensitic stainless steel AISI 440C because the heat from the tempering process is able to provide the stain ageing effect.

Consequently, in this research, the fatigue performance optimization of martensitic stainless steel AISI 440C using deep rolling integrated into hardening treatment is investigated. The deep rolling process in our study is performed in different sequences, for example, deep rolling after double

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tempering (general usage) or deep rolling between the first and second tempering processes. Moreover, the appropriate annealing after deep rolling will also be investigated to optimize the fatigue lifetime of the martensitic stainless steel AISI 440C. In contrast to other studies [31-33], in this study stain ageing occurs after and not during plastic deformation, so the effects investigated here are caused by static and not by dynamic stain ageing.

2. Materials and experimental procedures

The martensitic stainless steel AISI 440C was delivered as annealed bars with a diameter of 12.5 mm. The chemical composition of this alloy is 1.04% C, 0.41% Si, 0.38% Mn, 0.021% P, 0.01% S, 12.15% Cr, 0.43% Mo and Fe balance (all values in wt.%). Specimens were prepared to a fatigue testing shape following the ASTM E466-96 standard. The loading direction during fatigue investigations corresponds to the extruded direction of the bar. All test specimens were hardened by solid solution treatment at a temperature of 1040 °C for about 45 min, then cooled in a nitrogen atmosphere. The tempering process was normally carried out at a temperature of 300 °C for about 2 hr. A yield stress of about 1,738 MPa with an elongation of 3.8 % was detected for the tempered martensitic stainless steel AISI 440C. The deep rolling process was performed using a single roller with a diameter of 40 mm [34] with the rolling force of about 0.75 kN, feed rate of 0.15 mm/min and rotating speed of 85 rpm. Rotary bending fatigue tests were conducted without mean stress ($R = -1$). The fatigue life presented in this paper is an average from 5 investigations at the same fatigue test condition. All residual stress measurements were performed by a standard X-ray diffractometer according to the $\sin^2\psi$-method using Cr-Kα-radiation, the {211}-Bragg peak of the ferrite phase and an elastic constant of $1/2s_2 = 6.16 \times 10^{-6}$ MPa^{-1} for stress determination. Depth profiles were obtained by successive electrolytical removal of material using an electro-polishing device with a dial gauge to mark the measurement point and to identify the depth. Stress correction was not carried out after electrolytical removal. All residual stresses were measured in longitudinal (extruded) direction of the specimens. The investigated conditions for the fatigue optimization of the martensitic stainless steel AISI 440C are shown in five categories as in table 1.

It should be noted that the TT condition is marked as a general usage. The classical deep rolling can usually be applied to improve the fatigue performance of the martensitic stainless steel as the TTD condition.

3. Results and discussion
3.1 Fatigue performance of the TT and TTD conditions

The martensitic stainless steel AISI 440C in the TT condition was fatigued at room temperature. The S-N curve of the TT condition is shown in Fig.1. Relatively high-stress amplitudes have been applied because of the high hardness, yield and tensile strength of the martensitic structure. Fatigue lifetime decreases with increasing stress amplitude. At the applied stress amplitude of 750 MPa, the fatigue life of about 91,000 cycles was detected. Whereas the fatigue life higher than 10^7 cycles was observed at the applied stress amplitude of about 550 MPa. The fatigue strength of the martensitic stainless steel AISI 440C presented in Fig. 1 is on a similar level than the fatigue strength of swaged and deep rolled copper alloy CuMn20Ni20 [35], but inferior to the fatigue strength of titanium alloys [36]. After deep rolling, near-surface hardness values and compressive residual stresses are generated as shown in Fig. 2. The maximum compressive residual stress of 1,350 MPa about 70 μm beneath the surface has been measured.

Figure 1. *The S-N curve of the referent (TT) condition of the martensitic stainless steel AISI 440C.*

Table 1. *The treatment conditions and abbreviation for the fatigue optimization of the martensitic stainless steel AISI 440C.*

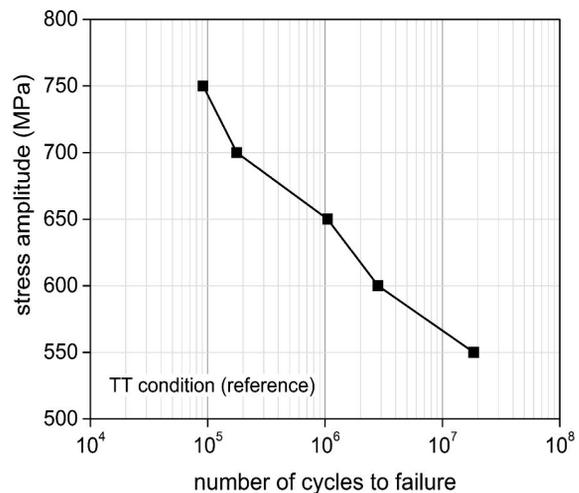| Categories	Details	Abbreviations
1	Quenched + Double tempered	TT
2	Quenched + Double tempered + Deep rolled	TTD
3	Quenched + Tempered 1st + Deep rolled + Tempered 2nd	TDT
4	Quenched + Tempered 1st + Deep rolled + Optimized	TDO
5	Quenched + Double tempered + Deep rolled + Optimized	TTDO

High compressive residual stresses of the martensitic structure after mechanical surface treatment are also reported in [37]. A case depth of the compressive residual stresses of about 0.8 mm was observed. These alterations at the surface and in near-surface regions are beneficial for the fatigue performance because they are able to inhibit as well as retard the crack initiation as well as propagation during cyclic loading [11-13]. Consequently, the fatigue life of the TTD condition dramatically increases from about 91,000 cycles of the reference to about 3 x 10^6 cycles at an applied stress amplitude of 750 MPa.
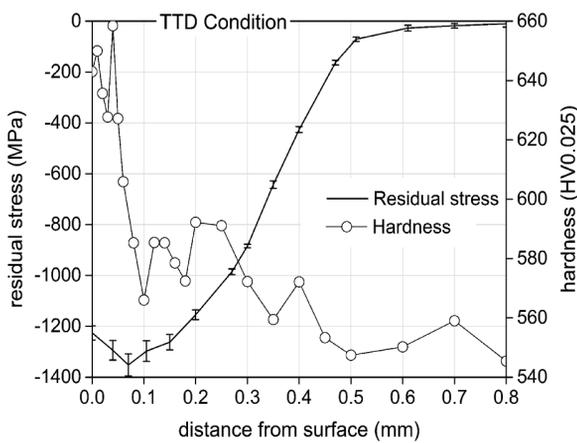

Figure 2. The residual stress and hardness depth profiles of the TTD condition of the martensitic stainless steel AISI 440C.

3.2 Deep rolling integrated into hardening process (TDT, TDO and TTDO conditions)

The deep rolling was performed in the middle of the double tempering processes (TDT condition). The heat of the second tempering process should basically provide more or less the static strain ageing effects to the deep rolled surface of the martensitic stainless steel AISI 440C. The TDT condition exhibits a slight fatigue lifetime of about 5.2 × 10^6 cycles at an applied stress amplitude of 750 MPa as compared to the TTD condition (3 × 10^6 cycles), whereas the compressive residual stress at the surface of the TDT condition is comparable to the TTD condition. It can be reasoned that, for the fatigue lifetime enhancement of the TDT condition, the static strain ageing effects from the second tempering process (300 °C for about 2 hr) applied after the deep rolling process. Dislocations are impeded by Cottrell-clouds of solute atoms and very fine carbides [21-27] occurring during the tempering process. Consequently, macroscopic compressive residual stresses and work hardening states at the surface and in near-surface regions of the TDT condition are more stable than that in the TTD

condition. However, the temperature of 300 °C for about 2 hr in the tempering process was possibly not an optimized annealing condition for the static strain ageing of the martensitic stainless steel AISI 440C. Therefore, different annealing conditions in a temperature range of 250 – 400 °C for about 1 or 2 hr were performed to find the optimized condition of the static strain ageing through the maximum fatigue lifetime at the stress amplitude of 750 MPa. It was found that the maximum fatigue lifetime of 6.2 × 10^6 cycles was observed when an annealing temperature of 350 °C for about 2 hr was performed as shown in Fig. 3, although a slight residual stress relaxation by 20% was observed as depicted in Fig. 4. That means that resulted in static strain ageing was promoted at the optimized annealing condition and brought the positive effects for fatigue lifetime enhancement of
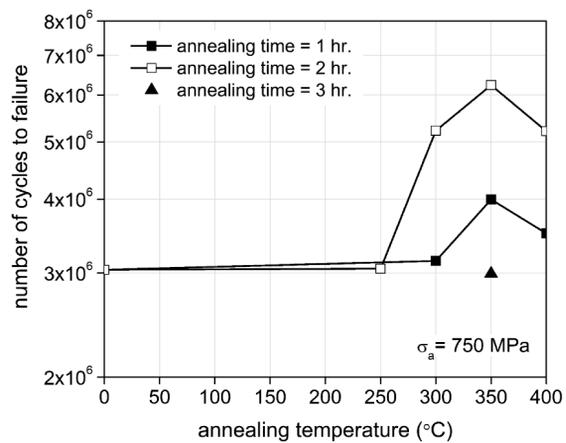

Figure 3. Fatigue optimization of the deep rolled martensitic stainless steel AISI 440 C using the annealing processes.
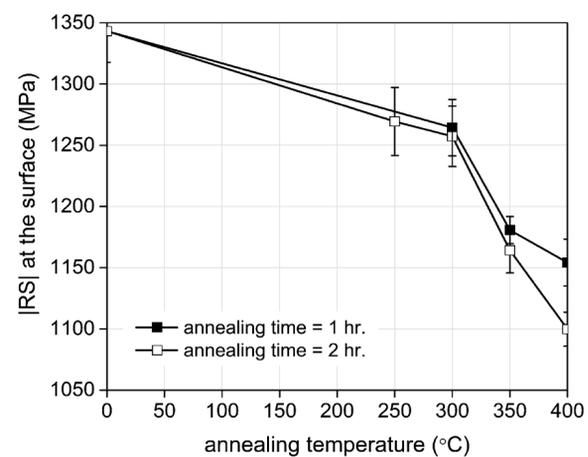

Figure 4. Residual stress relaxation at the surface of the deep rolled martensitic stainless steel AISI 440 C after the annealing.

the martensitic stainless steel AISI 440C in the TDO condition. The optimized annealing temperature of about 350 °C has also been reported in ref [30] for the strain ageing effects in various steels, where the Cottrell clouds of carbon solute atoms could be used to pin as well as obstruct the dislocation movements.

The residual stress depth profiles of the TTD and TDO conditions are shown in Fig. 5. Additionally, the optimized annealing condition was applied to the TTD condition as named the TTDO condition. A slight increase of fatigue lifetime of the TTDO condition was detected as compared to the TTD condition as shown in Fig. 6. However, the fatigue life of the TTDO condition decreased as compared to the TDO condition. It can be speculated that the carbide formation during the second tempering process possibly consumes the carbon solute atoms in the matrix. Consequently, the positive effects of the Cottrell clouds were only partially active. To confirm
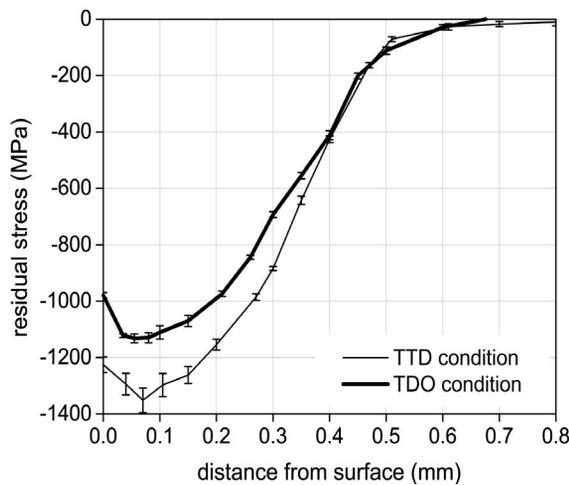
the underlying microstructural mechanisms during the tempering of the martensitic stainless steel AISI 440C, further microstructural characterization by TEM is needed.

4. Conclusion

To optimize the fatigue performance of the martensitic stainless steel AISI 440C, deep rolling integrated into the hardening process has been suggested and investigated. Several conclusions can be drawn from these studies.

1. The deep rolling process provides the beneficial effects, e.g. near-surface compressive residual stresses and increased hardness values which can inhibit as well as retard the fatigue crack initiation as well as propagation.

2. The deep rolling process can be integrated fully into the hardening process of the martensitic stainless steel AISI 440C, especially in the middle of the double tempering processes (TDT condition). The heat of the tempering process after the deep rolling process could provide the static strain ageing effects, consequently greater fatigue lifetime was observed as compared to the TTD condition.

3. An improved fatigue lifetime was detected, when the optimized annealing at a temperature of 350 °C for about 2 hr has been performed instead of the second tempering process (TDO condition).

Figure 5. *Residual stress depth profiles of the TTD and TDO conditions of the martensitic stainless steel AISI 440 C.*
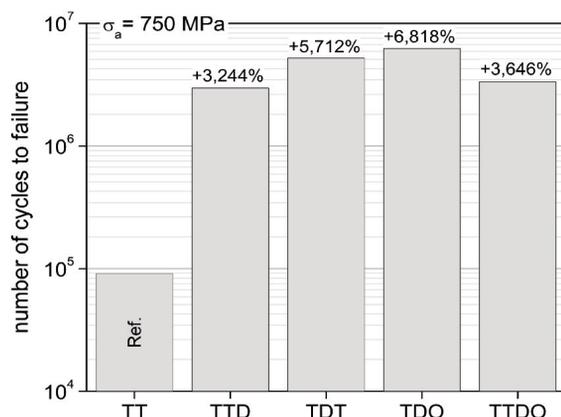

Figure 6. *Fatigue lives of the various treatment conditions of the martensitic stainless steel AISI 440 C at a given stress amplitude of 750 MPa.*

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POSTIZANJE OPTIMALNOG ZAMORA MATERIJALA OD MARTENZITNOG NERĐAJUĆEG ČELIKA AISI 440C POSTUPKOM OJAČAVANJA U KOJI JE UKLJUČEN I POSTUPAK DUBOKOG VALJANJA

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Apstrakt

Postupak dubokog valjanja se može modifikovati legiranjem na odgovarajućoj temperaturi, tokom određenog perioda da bi se postigao optimalni zamor metalnog materijala. Postupak ojačavanja martenzitnog nerđajućeg čelika AISI 440C uključuje postupak kaljenja i duplog temperovanja. Predlaže se uključivanje postupka dubokog valjanja u proces ojačavanja, pošto toplota dobijena tokom postupka temperovanja pruža dovoljan statički napon tokom procesa starenja. Ustanovljeno je da se postupak dubokog valjanja može u potpunosti uključiti u postupak ojačavanja martenzitnog nerđajućeg čelika AISI 440C, posebno nasred postupka duplog temperovanja. Toplota dobijena tokom postupka temperovanja, nakon dubokog valjanja, stvara koristan statički napon tokom procesa starenja kao posledicu većeg iskorišćenja zamora. Štaviše, maksimalna izdržljivost na zamor je ustanovljeno kada je izvršeno optimalno legiranje umesto drugog postupka temperovanja.

Kjučne reči: Zamor; Duboko valjanje; Nerđajući čelik; Površinska obrada; Temperovanje.