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Influence of carburized surface on plastic properties of steel during tempering

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1. Introduction

Carbon saturation of the surface, i.e. carburizing, is usually applied technology for machinery of low carbon steel. The carbon content of such steel is commonly 0.1–0.25% [1, 2]. Sometimes, carbon content can exceed 0.4% [1], when carburizing is applied for tools or the steel is alloyed with Cr, Ni, Mo and others [3, 4].

After carburizing, the specimens are quenched and tempered. The temperature of tempering mostly is low – 180–200°C. Sometimes refrigeration is applied between quenching and tempering on purpose to avoid coming of the retained austenite in the carburized layer [3].

The purpose of such thermochemical treatment is to obtain different hardness through the all cross-section of the specimen – the biggest at the surface and the less in the core. Thermo chemical treatment is widely used in engineering, e.g., automobile industry for such specimens as gears, tappets and others [3-5]. These specimens have great hardness of the surface that provides with high fatigue and wear resistance while the core remains tough, resistant to the impact loads.

The microstructure after annealing of low carbon steels (0.1–0.25% C) is ferrite and pearlite. After quenching from austenite zone, we have the microstructure of cubic martensite [6].

Surface carburizing of specimens gives rather multiplex microstructure: at the very surface the hypoeutectoid microstructure composes from pearlite and different amount of surplus carbides dependent on the degree of carbon saturation; next we have eutectoid microstructure of pearlite and lastly – hypereutectoid ferrite/pearlite microstructure with rising amount of ferrite till the microstructure reaches the phase composition of the core. During quenching of the carburized specimens, the martensite transformation at the low carbon core begins considerably earlier (M_s = 440-470°C) comparing to the transformation at carburized surface (M_s = 160-245°C) [7]. When austenite turns to martensite, the relative volume increases ~ 1% at the low carbon core and signally more at the carburized surface [8]. These transformations precede great internal stress varying during quenching. Because of this stress, on the condition of transformation plasticity, big deformations of quenching occur, especially, when the surface is carburized asymmetrically.

During the hardening of carburized specimens, they deform and precision is lost because of the volume mismatch, therefore, the vibration can occur in the elements coupling (e.g., coupling of gears) and resistance to the impact wear can decrease. Hardened deformed specimens could be fixed by polishing, but then the thickness of carburized layer is declined.

Hardened deformed specimens could be fixed during the low tempering under the effect of transformation plasticity when huge strains could be achieved under even small load because of temporal relaxation of atoms' binds [9].

This specimen presents the investigation of transformation plasticity phenomenon during tempering of hardened deformed specimens. The results obtained could be applied for the development of heat treatment technologies of carburized machinery.

2. Experimental

The chemical composition of used structural steel is listed in the Table 1.

Table 1

Chemical composition of steel, % (Fe balance)

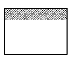
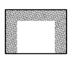
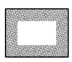
C	Mn	Si	Cr	Ni	S	P	Cu
0.19	0.51	0.24	0.12	0.04	0.014	0.013	0.04

The critical temperatures of steel with such chemical composition are: A_{c1} = 735°C, A_{c3} = 850°C [6, 10]. The phase composition of annealed steel is ferrite and pearlite.

Rectangular specimens were manufactured from steel rods of Ø12 mm diameter with the dimensions of 6 × 8 × 100 mm^3. The specimens were carburized at 930°C temperature 6 hours in the hard carburizer. Three schema of carburizing were chosen that are presented in the Table 2.

Table 2

Arbitrary marking of the schema of carburizing dependent on the number of carburized surfaces and average deflection after hardening of specimens

Arbitrary marking	Schema of specimen cross section		Initial average deflection of specimen y_0, mm
A		One surface is carburized	0.20 ($T_{hard.}$ = 800°C)
B		Three surfaces are carburized	0.11 ($T_{hard.}$ = 800°C)
C		Carburized all the surfaces	0.06 ($T_{hard.}$ = 800°C) 0.10 ($T_{hard.}$ = 860°C)

The recommended temperature of hardening after carburizing is 800-820°C [10]. We have chosen two temperatures of quenching – 800°C and 860°C, heating 8 min and cooling in the water. The hardness of the surface after hardening was measured (61-63 HRC units were obtained), the content of remained austenite was determined. The specimens carburized by the C schema and hardened under 860°C temperature, had 15–25% of retained austenite, that is very close to the data of the literature source [2]), and the initial deflection of specimen y_0 was gauged (Table 2). For the comparison, some specimens of the same grade of steel were hardened without carburizing. They reached the hardness of ~ 40 HRC units.

After hardening and measurement of HRC and content of retained austenite, the specimens were bent during low tempering on purpose to observe the transformation plasticity effect. The tempering temperature was 200°C, bending stress – 200 MPa, duration of tempering – 30 min. The equipment used for the experiment of bending during tempering is described in the earlier works [11]. During experiment of bending and tempering, the curve of specimen deformation was written measuring the deflection of transformation plasticity y_{tp} with the accuracy of 0.01 mm. After tempering, when the specimen is cooled down, the plastic deflection of specimen y_p was measured and remained deflection y_r was calculated estimating the initial hardening deflection y_0:

$$y_r = y_p + (\pm y_0) \quad (1)$$

For the observation of steel microstructure, cross-cuts were made from carburized and carburized and hardened specimens. The cross-cuts were etched with 4% HNO_3 solution in ethanol. The microstructure was examined by the optical microscope LMA with video camera YCH15. For the control, the approximate average content of carbon was determined in the specimen core using standard photographs of microstructures. It was obtained ~ 0.17-0.18% of carbon, so, this allows an assumption that only the surface was saturated with carbon.

Examining the microstructures, the approximate depth of carburizing was determined. Effective depth of carburizing was calculated [2]

$$\text{Depth} = 1 + 2 + 3/2 \quad (2)$$

where 1 is width of hipoeutectoid zone, μm; 2 is width of eutectoid zone, μm; 3 is hypereutectoid range going gradually to the microstructure of core, μm. In this way, the half of it is taken.

There was obtained that the depth of carburizing of specimens was approximately 1.80 mm.

3. Results and discussion

During bending of hardened steel specimens at 200°C tempering temperature, the character of the curves of transformation plasticity deflection y_{tp} is gradually declining; therefore, the possibility of steel creep during heating might be eliminated (Fig. 1). Especially this is obviously when the specimens are bent without carburizing. In this case, the hardening temperature has less influence on the deflection of transformation plasticity, though final deflection y_r was greater for 3% when hardening temperature was 860°C. This difference was more apparent when the specimens were symmetrically carburized. The difference increased till 20%. This could be explained by the difference of phase and chemical composition of steel after carburizing and hardening (Fig. 2). It was already obtained [11], that carbon increases transformation plasticity of steel (comparing with the not carburized specimen). The difference between values of y_r when hardening temperature is 860°C and 800°C, could be explained by such process: at higher hardening temperature the phase composition of steel composes from austenite that accommodates all dissolved carbon (and carbides in the surface layer), so, after hardening, we obtain tetragonal martensite and carbides at the surface layer and cubic martensite in the core of specimen.

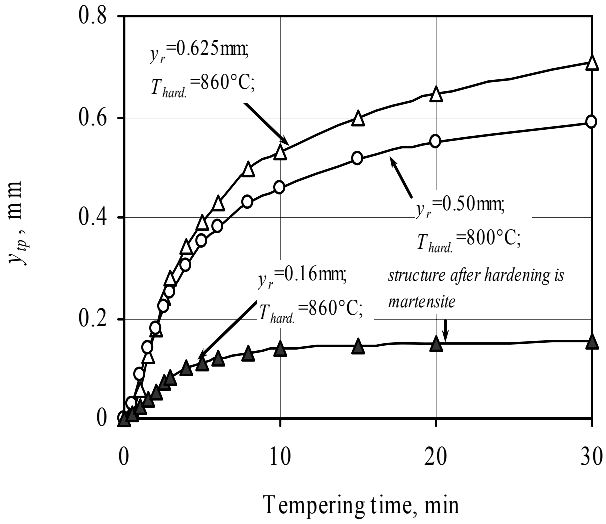
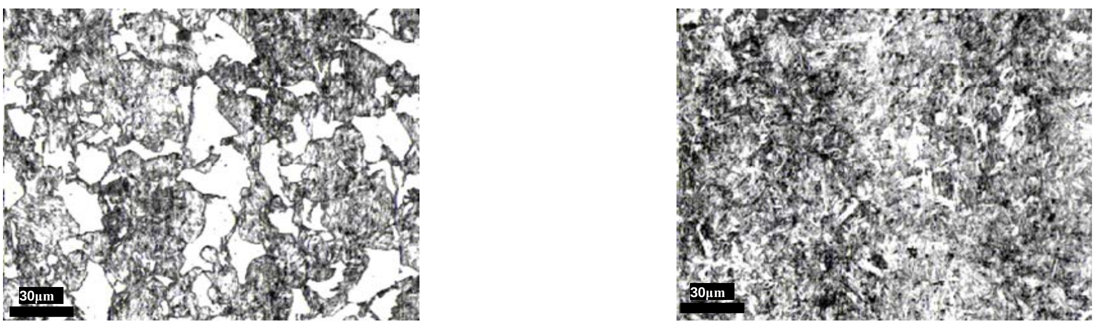
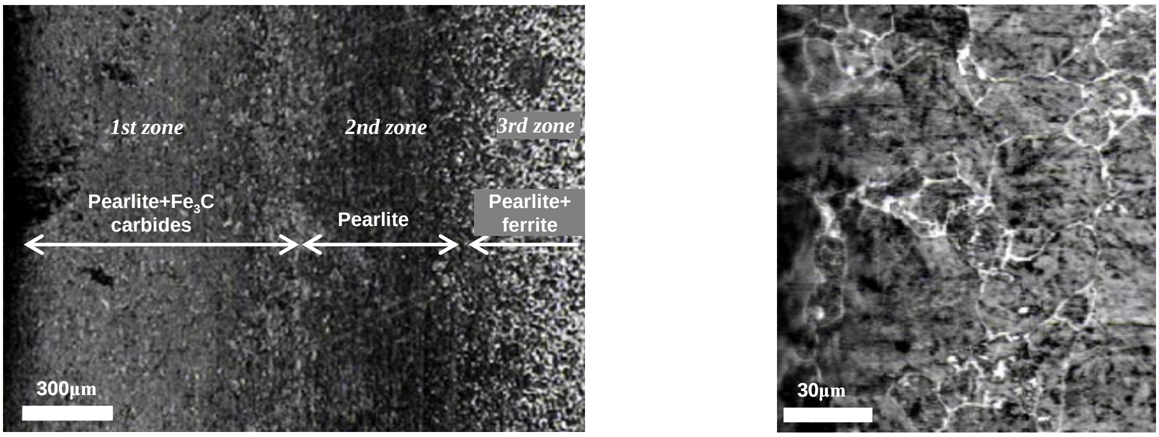


Fig. 1 The dependence of transformation plasticity of carburized and not carburized steel on duration of tempering: white triangles and circles – the specimens carburized symmetrically; black triangles and circles – not carburized specimens



a b

Fig. 2 Microstructure of steel after hardening and tempering: a – ferrite and martensite, when hardening temperature is 800°C; b – martensite, when hardening temperature is 860°C



a b

Fig. 3 Microstructure of carburized surface: a – three zones of carburizing; b – the very surface of carburized specimen composed from pearlite, retained austenite and carbides Fe_3C

The effect of transformation plasticity is observed when such transformations of tempering occur: carbon segregation from martensite, carbides formation and partitioning of retained austenite. The temperature of 200°C is sufficient for the partitioning of martensite; the character of curves of specimen bending shows that this process proceeds most intensively during the first 10-15 minutes. Later, this transformation diminishes (Fig. 1). The partitioning of retained austenite in the carbon steel occurs at the temperature range of 200-300°C [6], so, during the experiment this transformation could begin. It emerged that this has happened – the content of retained austenite has decreased till 25% when hardening temperature was 800°C and till 30% when hardening temperature was higher.

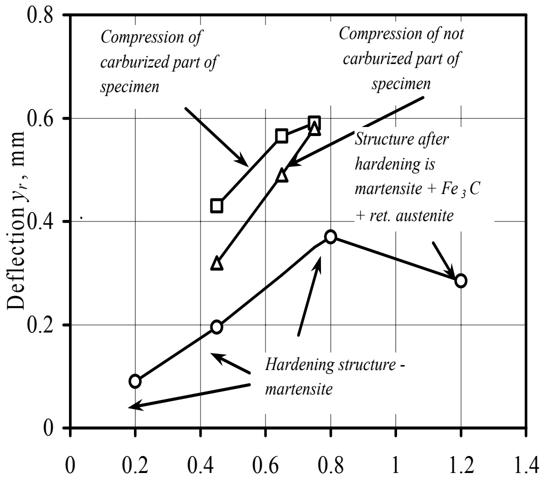


Fig. 4 Dependence of plastic deflection of specimen on the content of steel at 200°C tempering temperature when bending stress 200 MPa, hardening temperature 800°C (curves □, Δ). Hardening temperature of specimens $T = (20–30°C)+A_{cm}$, depending on the content of carbon [11] (curve o)

When hardening temperature was 800°C, the core of specimen has ferrite, therefore, during tempering at 200°C temperature of specimen with such microstructure, the transformation plasticity is less, because at this temperature ferrite doesn't undergo transformation.

Investigating the influence of carburized surface on steel transformation plasticity during tempering, it was interesting to calculate approximate average carbon content of the carburized specimens through all the volume (when schema of carburizing is A, B and C). Examining the microstructure of carburized layer (Fig. 3), three zones are obviously determined: hipoeutectoid (900 μm approximate width), eutectoid (600 μm approximate width), and hypereutectoid (350 μm approximate width) (Fig. 3, b).

The content of carbon was obtained at the zones (Fig. 3, a):

1 – at the hipoeutectoid – 0.8-1.2% C (we have chosen average 1.1%, because the microstructure has some carbides);

2 – at the eutectoid – 0.8% C;

3 – at the hypereutectoid – from ~ 0.7% until 0.45% C (as it is mentioned at the literature source [2]).

So, since the width of carburized layer is approximately 1.80 mm, the very approximate calculated average of carbon content depending on the carburizing schema, is:

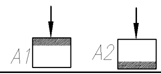
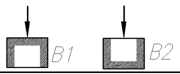
A schema – ~ 0.45% C; B schema – ~ 0.65% C;
C schema – ~ 0.75% C.

These approximate values could be compared with the earlier investigated specimens with homogenous microstructure and different carbon content: 0.2%, 0.45%, 0.8% and 1.2% C (Fig. 4) [11]. This picture presents the values of y_r dependent on carbon content (difference between the values of y_r comparing data of the experiment and data from the literature sources could be explained by different interval of time between hardening and tempering – this time interval has influence on the retained deflection [12, 13]). It is evident that when carbon content doesn't exceed 0.8% (when all carbon dissolves in austenite during heating), the dependence of y_r on carbon content is almost linear. Our results show very alike dependence. When carbon content increases until 1.2%, y_r value deviates from linear dependence because the microstructure has carbides Fe_3C and retained austenite that decrease transformation plasticity at 200°C temperature. Very small deviation from linear dependence of our results, increasing content of carbon, could be explained also by the origin of carbides and retained austenite in the surface layer.

Interesting results were obtained when asymmetrically carburized specimens were bent during tempering. The chart of bending is presented in the Table 3.

Table3

Marking of different bending chart

A chart	B chart
	

As Fig. 5 shows, the character of curves doesn't depend on order of bending, but it is evident, that the deflection of transformation plasticity is bigger when carburized layer is compressed, also the value y_r (Fig. 6). As it was already mentioned [6], the carburizing of specimen generates compressive stress at the surface and tensile stress in the core. This is obtained also in asymmetrically carburized specimens. Such distribution of stresses could be found on the volume mismatch ΔV of different steel phases when martensite has formed. Volume mismatch increases together with increasing of carbon content (Fig. 7), as it was determined in the heterogeneous microstructure of carburized specimens. Bending a specimen (according chart A1 and B1) that has compressed carburized surface and stretched not carburized surface, the compressive stress of internal load summarizes with structural compressive stress generated because of volume mismatch ΔV

$$y_{tp} = y_\sigma + y_{\Delta V(h)} + y_{\Delta V(t)} \qquad (3)$$

where y_σ is deflection of specimen obtained for the internal load; $y_{\Delta V(h)}$ is deflection of specimen obtained for the remained structural stress after hardening; $y_{\Delta V(t)}$ is deflection of specimen obtained during tempering because of volume mismatch in the core and in the carburized layers.

Analogically, not carburized surface is stretched because of structural stress and internal load. Bending asymmetrically carburized specimens according A2 and B2 chart, at the surface compressed by internal load the structural stretch stress proceeds as the surface stretched by the internal load is affected also by structural compressive stress.

Therefore, the deflection of transformation plasticity is obtained

$$y_{tp} = y_\sigma - y_{\Delta V(h)} - y_{\Delta V(t)} \qquad (4)$$

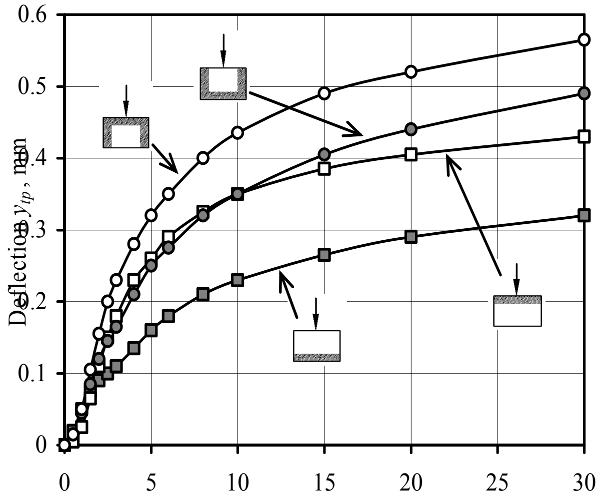


Fig. 5 Deflection of transformation plasticity bending the asymmetrically carburized specimens

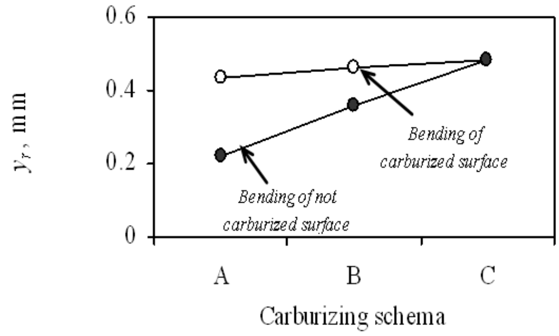


Fig. 6 Dependence of retained deflection of steel specimens on the schema of carburizing and bending

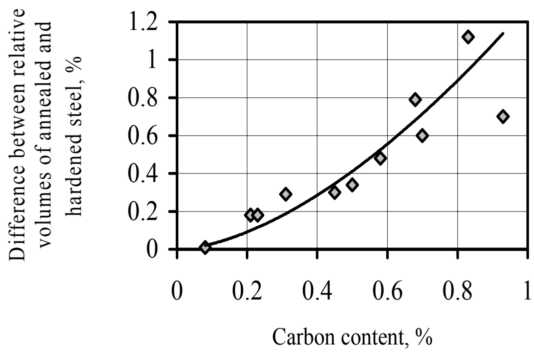


Fig. 7 Dependence between relative volume of steel, carbon content and phase composition

So, the values of y_{tp} and y_r of the specimens bent according A2 and B2 chart are greater than the ones of the specimens bent according A1 and B1 chart (Figs. 5 and 6). This effect might be evaluated with the purpose to temper asymmetrically carburized curved hardened specimens at the strained state.

4. Conclusions

Investigating the influence of carburizing on plastic properties of steel during low tempering, there was obtained:

1. Transformation plasticity depends on phase composition of low carbon steel after hardening – the amount of ferrite and carbides decrease this effect. Phase composition of steel after hardening depends on the temperature of quenching.

2. Calculated approximate average of carbon content of carburized specimens has shown that the value of retained plastic deflection y_r increases according to the linear dependence that is very alike during bending of specimens with the precise and equal content of carbon through all volume of the specimen.

3. Bending asymmetrically carburized specimens, the steel is more plastic because of structural stress generated by volume mismatch, in that case when the sign of this stress synchronizes with the sign of internal load.

4. The results of the experiment could be used for the development of heat treatment technologies of the carburized production.

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R. Kandrotaitė Janutienė

ĮANGLINTO PAVIRŠIAUS ĮTAKA PLIENO PLASTINĖMS SAVYBĖMS ATLEIDIMO METU

R e z i u m ė

Straipsnyje pateiktas plieno bandinių su įanglintu paviršiumi plastinių savybių tyrimas žemojo atleidimo metu. Įanglinti dirbiniai dažnai deformuojasi grūdinant, todėl pagrindinis tyrimo tikslas buvo patyrinėti vieną iš galimų detalių lyginimo būdų – kreivų bandinių lenkimą kaitinant atleidimo temperatūroje virsminio plastiškumo metu, kai net nedidelės išorinės apkrovos gali smarkiai deformuoti gaminį. Ištirta plieno plastiškumo atleidimo temperatūroje priklausomybė nuo anglies kiekio ir nesimetriško įanglinimo poveikis plieno virsminio plastiškumo efektui, įvertinant struktūrinius gniuždymo ir tempimo įtempius, atsiradusius dėl tūrinių pokyčių.

R. Kandrotaitė Janutienė

INFLUENCE OF CARBURIZED SURFACE ON PLASTIC PROPERTIES OF STEEL DURING TEMPERING

S u m m a r y

The specimen presents the investigation of plastic properties of carburized steel specimens during low tempering. Carburized specimens often deform during quenching, therefore, the principal aim of the experiment was to investigate one of the fixing ways of curved specimens – the bending of curved hardened specimens during tempering under the effect of transformation plasticity when even small internal load generates great deformations. The dependence between steel plasticity and carbon content at the tempering temperature was determined. The effect of asymmetrical carburization on steel transformation plasticity was examined evaluating the influence of structural compressive and tensile stress, which occurred because of volume mismatch.

Р. Кандротайте Янутиене

ВЛИЯНИЕ НАУГЛЕРОЖЕННОГО СЛОЯ НА ПЛАСТИЧЕСКИЕ СВОЙСТВА СТАЛИ ПРИ ОТПУСКЕ

Р е з ю м е

В настоящей работе проведено исследование пластических свойств науглероженных стальных образцов во время низкотемпературного отпуска. Науглероженные стальные изделия часто деформируются при закалке, поэтому основной целью настоящей работы было провести исследование одного из возможных способов правки изделий – изгиб образцов при нагреве на отпуск во время пластичности превращения, когда даже небольшое наружное нагружение может значительно деформировать изделие. Установлена зависимость пластичности стали при температуре отпуска от количества углерода. Исследовано влияние несимметричности науглероживания на эффект пластичности превращения с оценкой структурных напряжений растяжения и сжатия, возникающих при изменении удельного объема.

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