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ISSN 0543-5846
METABK 45 (1) 51-55 (2006)
UDC - UDK 539.377:669–122.2:620.17=111

DEVELOPMENT OF BAKE HARDENING EFFECT BY PLASTIC DEFORMATION AND ANNEALING CONDITIONS

Received - Primljeno: 2004-12-29
Accepted - Prihvaćeno: 2005-07-20
Preliminary Note - Prethodno priopćenje

The paper deals with the classification of steel sheets for automotives industry on the basis of strength and structural characteristics. Experimental works were aimed to obtain the best possible strengthening parameters as well as work hardening and solid solution ferrite hardening, which are the result of thermal activation of interstitial carbon atoms during paint-baking of auto body. Hardening process coming from interstitial atoms is realized as two-step process. The first step is BH (bake hardening) effect achieved by interaction of interstitial atoms with dislocations. The Cottrels atmosphere is obtained. The second step of BH effect is to produced the hardening from precipitation of the carbon atoms in ε-carbides, or formation of $Fe_{32}C_4$ carbides. WH (work hardening) effect is obtained as dislocation hardening from plastic deformations during sheet deep drawing. Experimental works were aimed at as to achieve such plastic material properties after cold rolling, annealing and skin-pass rolling, which would be able to classify the material ZStE220BH into the drawing categories at the level of DQ – DDQ. As resulting from the experimental results, the optimal treatment conditions for the maximal sum (WH+BH) = 86 MPa are as follows: total cold rolling deformation ε_{cold} = 65 %, annealing temperature $T_{anneal.}$ = 700 °C.

Key words: *plastic properties, auto body steel sheet, bake hardening, work hardening, cold rolling, annealing*

Razvoj pećnog otvrdnjavanja plasičnom deformacijom i žarenjem. U radu se raspravlja o klasificiranju čeličnih limova za automobilsku industriju na bazi čvrstoće strukturalnih karakteristika. Cilj eksperimenata je bio dobivanje najboljih mogućih parametara očvršćivanja kao i parametara otvrdnjavanja obradom, te otvrdnjavanja krute otopine ferita koje su rezultat termičkog djelovanja intersticijalnih atoma ugljika tijekom pečenja zaštitnog premaza na karoseriji auta. proces se realizira kao dvostupanjski proces. Prvi korak je otvrdnjavanje pečenjem (BH = bark hardening), koji nastaje međusobnim djelovanjem intersticijalnih atoma s dislokacijama. Dobiva se Cottrelova atmosfera. Drugi korak učinka BH je postizanje otvrdnjavanja iz precipitacije ugljičnih atoma u ε-karbidima, nastajanjem karbida $Fe_{32}C_4$. Otvrdnjavanje obradom se dobiva dislokacijom otvrdnjavanja iz plastične deformacije tijekom dubokog izvlačenja limova. Cilj eksperimenta je bio dobiti takva plastična svojstva nakon hladnog valjanja, žarenja, i polirajućeg valjanja po kojima bi se materijal ZstE 220 BH mogao svrstati u kategorije izvlačenja na nivou od DQ – DDQ. Kao rezultat obavljenih eksperimenata optimalni tretmani za maksimalnu sumu (WH+BH) = 86 MPa su slijedeći: totalno deformiranje hladnim valjanjem ε_{cold} = 65 %, temperatura žarenja T_{anneal} = 700 °C.

Ključne riječi: *plastična svojstva, čelični lim za karoseriju auta, otvrdnjavanje u peći, otvrdnjavanje obradom, hladno valjanje, žarenje*

INTRODUCTION

Steel sheets for production of auto bodies, doors and the other parts are supplied in thickness of h = 1 - 2 mm as hot-rolled and pickled strips and in thickness of $h \leq 0,7$ mm as cold rolled and annealed strips. Auto body weight reduction can be realized by increasing of strength, formability and good weld ability of steel sheets. The development of strength and structural properties is documented in Figure 1. Percentage distribution of hot and cold rolled steel sheets for auto body parts, after the yield strength criteria, is shown in Figure 2. [1, 2].

In ULSAB conception more than 90 % auto body parts are made from high strength steel (HSS), advance HSS

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Steel sheets for weight reduction of autobody

HSS (High strength steels) $R_{p0,2}$ = 180 – 550 MPa (F, AF)

Steel types			$R_{p0,2min}$ / MPa
HSLA	HR	S315MC-S550MC (QStE340TM-QStE550TM)	340-550
	CR	H240LA-H400LA (ZStE260-ZStE420)	260-400
BH	CR	ZStE180BH-ZStE300BH	180-300
IS	CR	ZStE220i-ZStE300i	220-300
P	CR	ZStE220P-ZStE300P	220-300
IF	CR	-	220-260

AHSS (Advanced high strength steels)

Multi-phase steels		$R_{p0,2min}$ / MPa	structure
DP	Dual phase steels	350-650	F+M
CP	Complex phase steels	350-700	F+B+M
RA	Residual austenite with TRIP effect	400-800	F+B+RA

UHSS (Ultra high strength steels) R_e > 550 MPa

Steel types			$R_{e,min}$ / MPa
HSLA	HR	S600MC-S700MC	600-700
M	HR	-	>550

Remarks:
HR - hot rolled; F-ferrite; B-bainite
CR - cold rolled; AF-acicular ferrite; M-martensite; RA-residual austenite

Figure 1. **Development of strength and structural properties of autobody sheets**
Slika 1. **Razvoj čvrstoće i konstrukcijskih svojstava limova za karoseriju**

(AHSS) and ultra HSS (UHSS). High strength properties and good draw ability of steel sheets are the function of strengthening mechanisms controlled by technological production parameters [3 - 10] such as temperature, strain, strain rate, time and chemical composition of steel.

BH (bake hardening) steels are used mainly for the sheets designed of large size pressings of external panels, for which the excellent stability is required after deep-drawing and painting works. The main advantage of BH

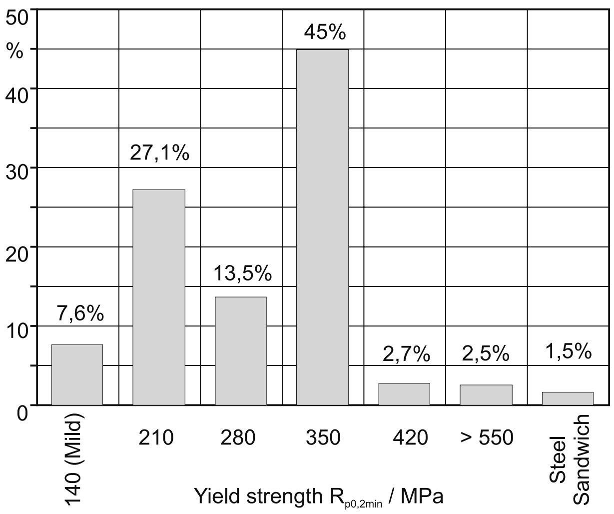

Figure 2. **Application of steel sheets for auto body in ULSAB [1]**
Slika 2. **Primjena čeličnih limova u autoindustriji u ULSAB [1]**

sheets lays in their low yield strength and high formability parameters before deep-drawing. While after deep-drawing and painting works, the deformation - thermal strengthening take place and consequently the yield strength is increasing by about 30 - 90 MPa.

The first strengthening effect of BH process is related to the hot mechanical ageing, which is controlled by the diffusion of the carbon and nitrogen atoms to the dislocations generated during deep-drawing. The artificial ageing process is controlled through thermal activation of carbon atoms, which are dissolved in deformed ferrite and subsequently, during paint baking, due to the diffusion movement, which takes place around dislocations and forms Cottrel atmosphere. The authors [11] assumed the strengthening effect coming from Cottrel atmosphere at the level of $\Delta\sigma_{Cottrel}$ ~ 35 MPa. The second strengthening effect of BH process is caused by the precipitation hardening of carbon atoms in ε-carbides, or formation of $Fe_{32}C_4$ carbides. The authors [12] described yield strength at the increasing of BH during paint baking as followed:

$$\Delta\sigma_{BH} = \Delta\sigma_{Cottrel} + \Delta\sigma_{precipitation\ strengthening} \quad (1)$$

BH effect is obtained from interstitial atoms of carbon or nitrogen. The nitrogen diffusion in ferrite at room temperature is very fast and material ageing is quick. Therefore solid solutions strengthening by nitrogen atoms cannot be taken into account.

The diffusion ability of carbon in ferrite at room temperature, with comparison of nitrogen is considerably lower and therefore ageing process is preferentially controlled by thermal activation of carbon atoms. Except of carbon content in steel, the interesting elements with favorable influence on BH effect are also Mn and Si, but very important is P content. The phosphorus is segregated on ferrite grain boundaries during annealing as protection against the cementite nucleation on ferrite grain boundaries. The preferential carbon diffusion into the dislocation areas is a result of phosphorus influence.

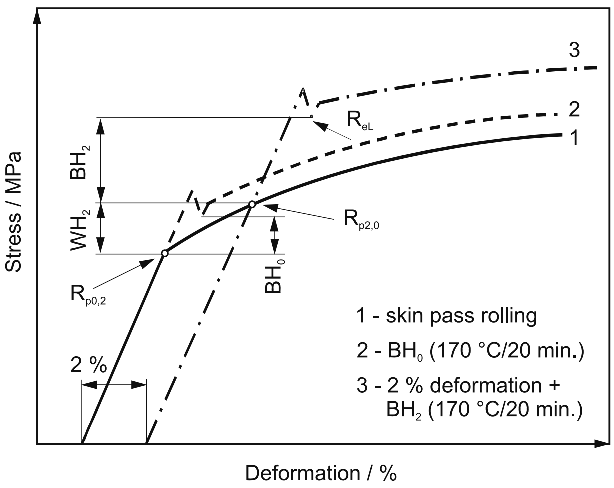

Figure 3. **Schedule for tensile test [10]**
Slika 3. **Plan vlačnog ispitivanja [10]**

The calculation of BH and WH effects is possible according to the scheme given in Figure 3. [12] and by the following formula [12]:

$$BH_2 = Re_L - R_{p2,0} \quad (2)$$

$$WH_2 = R_{p2,0} - R_{p0,2} \quad (3)$$

where:

Re_L - low level of yield strength,
$R_{p0,2}$ - yield strength for deformation 0,2 %,
$R_{p2,0}$ - yield strength after 2 % deformation.

EXPERIMENTAL MATERIAL AND PROCEDURES

The experimental studies were made on steel sheets ZStE 220 BH with chemical composition given in Table 1. The experimental works were done as laboratory cold rolling on DUO206 rolling mill and laboratory annealing in electric resistance furnace. The static tensile strength test was performed at room temperature using ZWICK Z050 equipment in accordance with STN EN 10002-5 standard.

Table 1. **Chemical analysis of experimentally tested steel sheet**
Tablica 1. **Kemijska analiza eksperimentalno ispitivanog čeličnog lima**

C / %	Mn / %	Si / %	P / %	S / %	Al / %	N_2 / %
0,038	0,20	0,27	0,054	0,012	0,051	0,006

Experimental schedule was realized according to the scheme shown in Figure 4. The boundary conditions of experiments were as followed: cold deformations $\varepsilon_1 \in \langle 55;75 \rangle$ / %, annealing temperature $T_{ann} \in \langle 680;720 \rangle$ / °C, holding time at annealing temperature t_{ann} = 1 h, skin-pass cold deformation ε_H = 2 %, predeformation by testing machine ε_2 = 2 %, paint baking simulation: t_{pb} = 20 min, T_{pb} = 170°C. The results of static tensile strength tests are expressed as following parameters: P = $R_m/R_{p0,2}$; KUT = P·A80; IT = 1000·r_s·n_s.

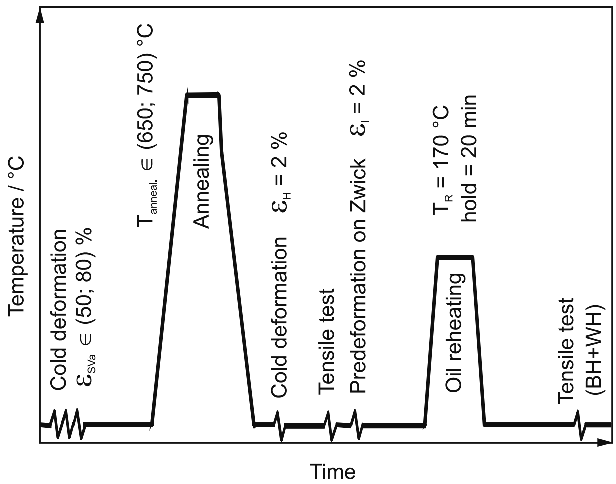

Figure 4. **Experimental schedule for BH of steel**
Slika 4. **Eksperimentalni plan za BH čelik**

RESULTS AND DISCUSSION

The first step of investigation was optimization of cold deformations and annealing conditions for obtaining suitable cold drawability of sheets. The results of laboratory experiments are given in Figure 5., Figure 6., Figure 7.,

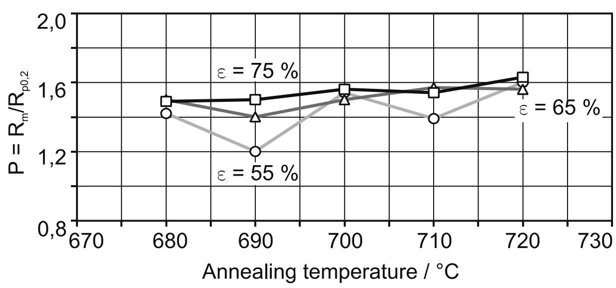

Figure 5. **Dependence of parameter *P* as function of annealing temperature and deformation**
Slika 5. **Ovisnost parametra *P* kao funkcije temperature žarenja i deformacije**

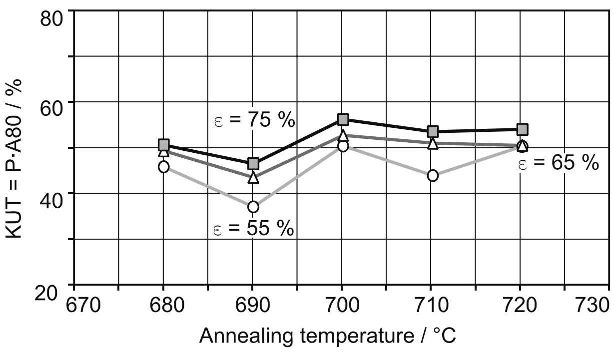

Figure 6. **Dependence of parameter *KUT* as function of annealing temperature and deformation**

Slika 6. **Ovisnost parametra *KUT* kao funkcije temperature žarenja i deformacije**

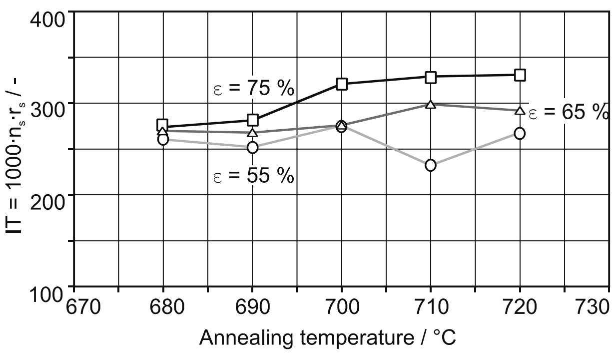

Figure 7. **Dependence of parameter *IT* as function of annealing temperature and deformation**

Slika 7. **Ovisnost parametra *IT* kao funkcije temperature žarenja i deformacije**

from which follows: materials coefficients P, KUT and IT are stabilized and suitable for deformations of ε_1 = 65 % and ε_1 = 75 %, and for annealing temperatures over 700 °C. We assume, that the secondary recrystallization is dependent on

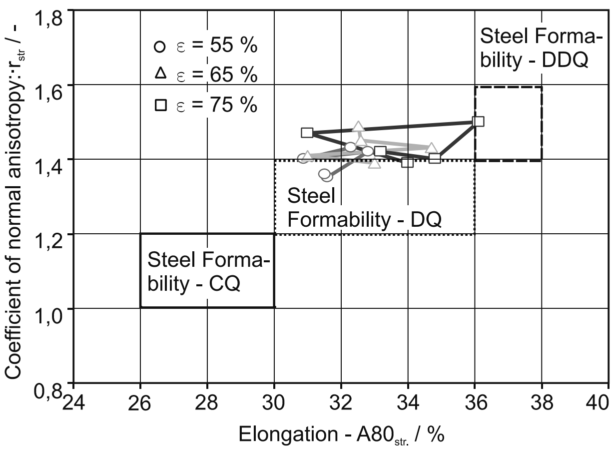

Figure 8. **Coefficient of normal anisotropy as function of elongation**

Slika 8. **Koeficijent normalne anizotropije kao funkcije izduživanja**

annealing temperature and the level of cold deformations. When the cold deformation was of ε_1 = 65 % and annealing temperature was in the range of T_{ann} = 680 - 690 °C, then the material's values were not suitable for sheet formability, because the recrystallization process is not finished in whole volume of sheet specimens. For the stabilization of values of formability parameters, following treatment conditions are acceptable: cold rolling deformation ε_1 = 65 - 75 % and annealing temperature $T_{ann} \geq$ 700 °C.

As it is shown in Figure 8., except for experimental condition: ε_1 = 75 %, T_{ann} = 700 °C where sheet drawability of DDQ category can be attained, all other investigated conditions provide sheet drawability of DQ category.

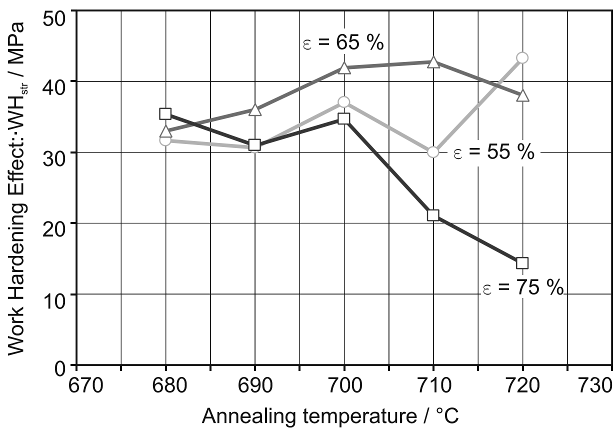

Figure 9. **Work hardening effect as function of annealing temperature**

Slika 9. **Učinak otvrdnjavanja obradom kao funkcije temperature žarenja**

Next experimental programme was oriented towards the investigation of cold plastic deformations and annealing temperatures influence on WH and BH effects. Experimental results are shown in Figure 9. and Figure 10. Work hardening

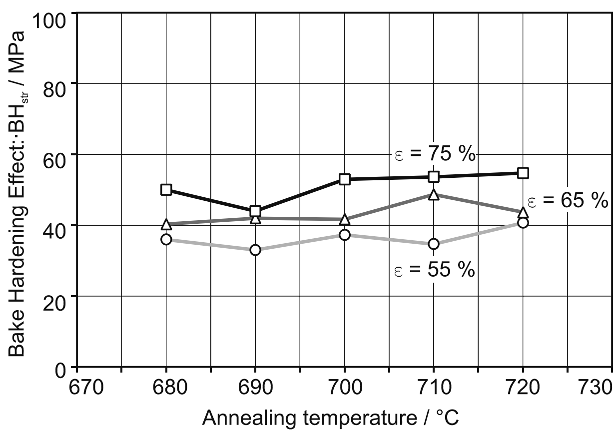

Figure 10. **Bake hardening effect as function of annealing temperature**

Slika 10. **Učinak otvrdnjavanja pečenjem kao funkcija temperature** effect (WH) was obtained in interval WH = 15 - 43 MPa. Maximum of WH was achieved for annealing temperatures of T_{ann} = 700 °C and 710 °C and cold plastic deformation of ε_1 = 65 %. When the annealing temperature reached the level $T_{ann} \geq$ 700 °C for of ε_1 = 75 %, then WH was decreasing. This fact is depending on better conditions to relaxation of internal energy of material. Bake hardening effect (BH) was obtained in interval BH = 38 - 56 MPa. Maximum of BH was achieved for cold plastic deformation of ε_1 = 75 % and annealing temperature of $T_{ann} \geq$ 700 °C. Minimum of BH was achieved for cold plastic deformation of ε_1 = 55 % and whole range the investigated annealing temperatures.

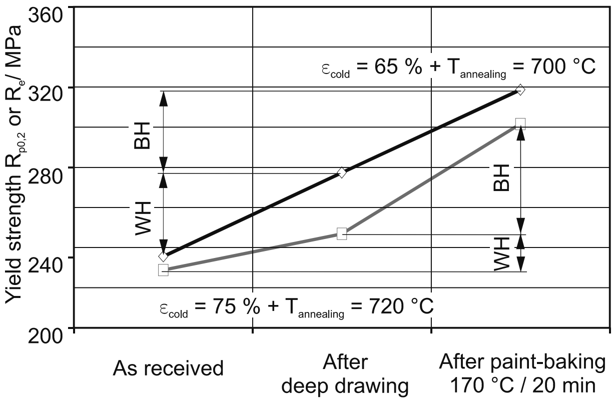

Figure 11. **Dependence of strengthening on treatment conditions**
Slika 11. **Ovisnost čvrstoće o načinu obrade**

The final result is that the sum of strengthening is in the range of (WH + BH) = 63 - 86 MPa. The summary of strengthening effects, as the dependence on treatment conditions, is shown in Figure 11. The analysis of strengthening mechanism to obtain different level of BH and WH effects is given in Table 2. Based on the data given in Table 2., it is possible to select deformation and annealing conditions to obtain various levels of final strength and plastical steel sheet properties achieved by the strengthening mechanism.

Table 2. **Analysis of strengthening mechanisms**
Tablica 2. **Analiza mehanizma očvršćavnja**

Experimental conditions	Strengthening mechanisms				Total sum
	BH-effect			WH- effect	
	Solid solution + dislocation hardening by Cottrell atmosphere pinning of dislocations	Precipitation hardening by $Fe_{32}C_4$ / MPa	Σ BH / MPa	Dislocation hardening	Σ (BH + WH) / MPa
ε_{cold} = 65 / % + T_{ann} = 700 / °C	35 MPa	5	40	42	82
ε_{cold} = 75 / % + T_{ann} = 720 / °C	35 MPa	20	55	18	73

CONCLUSIONS

Based on the literature data as well as own experimental results it is possible to make the following conclusions:

- good drawability of steel sheet is obtained applying the following conditions:
  - cold plastic deformation has to maximum value ε_1 = 75 %,
  - annealing temperature must be in the range of T_{ann} = 700 - 720 °C;
- maximum of summary effects WH + BH were obtained for the following conditions:
  - cold plastic deformation ε_1 = 65 %,
  - annealing temperature T_{ann} = 700 °C.

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Acknowledgement

The article was prepared with the financial supporting of GAV-SR-VEGA to project No. 1/8079/01.