ACTA STEREOL 1994; 13/2: 433-438
PROC 6ECS PRAGUE, 1993
ORIGINAL SCIENTIFIC PAPER

QUANTITATIVE DESCRIPTION OF DUAL-PHASE STEEL MICROSTRUCTURE

Jan CWAJNA, Janusz SZALA and Jerzy HERIAN*

Silesian University of Technology
Department of Materials Science
Department of Mechanics and Plastic Working Technology*
Krasińskiego 8, PL-40-018 KATOWICE, POLAND

ABSTRACT

The effect of prior cold working on dual-phase steel C-Mn-Si-V type microstructure was analysed with an application of quantitative metallography and statistical methods. The paper includes a proposal of terminology and notation unification of stereological parameters. Some improvements and supplements of dual-phase (D-P) steel microstructure description are suggested. The diagrams and empirical equations showing the effect of prior cold work ratio on volume fraction, size, shape and distribution of phases are presented. The main conclusion drawn from the performed investigations is that the magnitude of prior cold working significantly affects size and shape distributions of both ferritic grains and martensitic islands as well as the inhomogeneity of martensitic islands distribution. It was found that prior cold work ratio of 65-75%, leading to the significant refinement of microstructure and its homogenization, ensures the best combination of D-P steel strength and ductility.

Key words: dual-phase steel, prior cold working, quantitative metallography.

INTRODUCTION

In the investigations of the cause-effect chain: chemical composition - processing → microstructure → properties of D-P steels the quantitative metallography methods are commonly applied. The structural features assessed and stereological parameters used in these studies are presented in Table 1. This table includes a proposal of terminology and notation unification, as well as corrected formulas for stereological parameters calculation because in the literature a large diversity in this matter and some inaccuracies occur (Gurland, 1979; Lanzillotto et al., 1982; Burford et al., 1985 and Fonstein et al., 1985). This may be one of the reasons for unequivocal opinions on the efficiency of the chosen processing route upon the D-P steel microstructure and properties and also on the role of microstructural factors in these steels. It particularly refers to the ferrite grain size and arrangement of structural constituents (Burford et al., 1985; Lanzillotto et al., 1982 and Yang et al., 1985).
Quantitative description of D-P steels microstructure makes it possible to determine the empirical microstructure → properties relationships (Table 2). The analysis of these equations as well as the formulas included in this table, resulting from the theory of two-phase granular materials (the modified rule-of-mixtures), leads to the following conclusions:

- volume fraction of martensite, affecting all stereological parameters of D-P steel microstructure (Table 1) is microstructural factor of fundamental importance in these steels,
- ferrite grain and martensite island size are generally characterized by means of average grain size; the mentioned above equations can be valid only for steels with homogenous microstructure,
- mean free path in ferrite is a commonly applied parameter for the description of phase arrangement,

Table 1. Stereological parameters of dual-phase steel microstructure.

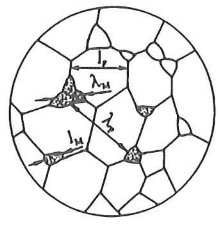
Ferrite	Martensite	Explanations and notes
Feature of microstructure - stereological parameter		
Phase composition - volume fraction of phases		
$(V_V)_F$	$(V_V)_M$	
Microstructural refinement - total specific surface $S_V = (S_V)_F + (S_V)_M + (S_V)_{F-M}$ $[mm^2/mm^3]$		
Specific surface of ferrite grain/martensite islands boundaries		
$(S_V)_F = 2(P_L)_{F-F} + (P_L)_{F-M}$	$(S_V)_M = 2(P_L)_{M-M} + (P_L)_{F-M}$	
Specific surface of interphase boundaries $(S_V)_{F-M} = 2(P_L)_{F-M}$ $[mm^{-1}]$		
Size distribution of ferrite grains and martensite islands **Relative specific surface**		"F" - Ferrite "M" - Martensitic islands P_L - number of grain boundaries intercepted by the secant of unit length F-F boundaries between ferritic grains M-M boundaries between martensitic islands M-F interface boundaries ferrite - martensite
$(S_R)_F = (S_V)_F / (V_V)_F$	$(S_R)_M = (S_V)_M / (V_V)_M$	
Average grain/islands size: - mean intercept length		
$\bar{l}_F$; $\bar{l}_F \approx 4(V_V)_F/(S_V)_F$ $[mm]$	$\bar{l}_M$; $\bar{l}_M \approx 4(V_V)_M/(S_V)_M$ $[mm]$	
- mean plane section area		
$\bar{A}_F$ $[mm^2]$	$\bar{A}_M$ $[mm^2]$	
Grain / islands size inhomogeneity measure - equivalent coefficient of variation		s(l) - empirical standard deviation of chords length s(A) - empirical standard deviation of plane sections area Obtained by the comparison of grain size distribution of investigated material with the grain size distributions of a set of turncated octahedra of the same size (Maliński et. al, 1991)
$(v_L)_F = S(l)_F / \bar{l}_F$, or $(v_A)_F = S(A)_F / \bar{A}_F$	$(v_L)_M = S(l)_M / \bar{l}_M$, or $(v_A)_M = S(A)_M / \bar{A}_M$	
- stereological measure of grain size inhomogeneity		
$(M_l)_F$ or $(M_A)_F$	$(M_l)_M$ or $(M_A)_M$	
Shape of ferrite grains and martensite islands **Parameters of shape factor distribution**		n_i - number of grains / islands of a given shape factor $\zeta = 4\pi A / P^2$ A_{A_i} - area fraction of grains / islands occupied by grains of a given shape factor ζ
$(n_i)_F = f(\zeta)_i$ $(A_{A_i})_F = f(\zeta)_i$	$(n_i)_M = f(\zeta)_i$ $(A_{A_i})_M = f(\zeta)_i$	
Arrangement of structural constituents Contiguity parameter $C_M = \frac{(S_V)_M}{(S_V)_M + (S_V)_{F-M}}$		C_M=0 phase is completly dispersed C_M=1 phase is fully aglomerated (continuous) $0 < C_M < 1$ phase is partially connected or partially continuous
Mean free path in ferrite $\lambda_F = 4(V_V)_F/(S_V)_{F-M}$ $[mm]$	Mean free path in martensite $\lambda_M = 4(V_V)_M/(S_V)_{F-M}$ $[mm]$	
Conectivity, continuity parameters $\Delta = (S_V)_M / (S_V)_F$ $\delta = (S_V)_{F-M} / (S_V)_F$		dual structure: $\Delta \to \infty$, $(S_V)_{F-F}=0$ $C_M \to 1$ and $(V_V)_M \approx 0.2$
Islands distributions inhomogeneity factor $v(A_A) = s(A_A) / \bar{A}_A$; $v(A_A)=0$ for homogenous structure **Anisotropy factor** $\eta = F_H / F_V$; $\eta = 1$ for isometric structure		Factors determined by systematic scanning and variance analysis method (Wiśniewski et al., 1992) F_H, F_V - horizontal and vertical variability

Table 2. Selected example of relationships between the microstructure and properties of dual-phase steels.

Property	Relationship	Explenation	Reference
Yield strength	$\sigma_y = \sigma_F[1 - C_M(V_V)_M] + \sigma_m C_M(V_V)_M$	σ_F - effective in situ yield stress of ferrite under plastic constraint σ_M - average in situ stress in martensite	Gurland, 1979
True plastic strain	$\sigma - \sigma_0 = \frac{\varepsilon_p}{m}\frac{d\sigma}{d\varepsilon_p} = \frac{\beta'}{m}(\varepsilon_p)^m (V_V)_M^q (\lambda_F)^n$ m ≈ 0.47; n ≈ -0.22; q ≈ 0.67	σ_0 - friction stress ε_p - strain $d\sigma/d\varepsilon_p$ - strain hardening rate β' - constant	Lanzillotto, 1982
	$\sigma - \sigma_0 = M^{3/2}\left[\alpha G\sqrt{\frac{48\, b(V_V)_M\varepsilon_p}{\pi\lambda_M}} + \left(\frac{16\pi b}{\alpha^2\varepsilon_p\lambda_M}\right)^{1/8}\alpha G(V_V)_M\sqrt{\frac{16\, b\varepsilon_p}{\pi\lambda_M}}\right]$ $\sigma - \sigma_0 = 63.9\sqrt{\frac{\varepsilon_p(V_V)_M}{\lambda_M}} + 36.8(V_V)_M\sqrt{\frac{\varepsilon_p}{\lambda_M}}$	M - Taylor's coefficient of orientation = 2.738 for bcc structure σ_0 - constant = yield stress ε_p - strain G - shear modulus = 80700 [Mnm^{-2}] b - Burgers vector = 0.248 µm α - constant	Lanzillotto et al., 1982
Yield stress	$\sigma_{0.2} = 122 + \left\{16.4 + 432\left[(V_V)_M \bar{d}_M\right]^{1/2}\right\}(\bar{d}_C)^{-1/2}$ where: $d_C = \left[1 - (V_V)_M\right](\bar{d}_F)^{1/2} + (V_V)_M(\bar{d}_M)^{1/2}$		Reuben et al., 1984
Strain hardening rate	$\frac{d\sigma}{d\varepsilon} = 0.78\, k\frac{Gb^{1/2}}{\varepsilon^{1/2}}\sqrt{\frac{(V_V)_M}{\bar{l}_M}}$ $\frac{d\sigma}{d\varepsilon} = \left[k_1\sqrt{(V_V)_M} + k_2(V_V)_M\right]\sqrt{\frac{1}{\lambda_F}}$	k,k_1, k_2 - constants ε - strain G - shear modulus b - Burgers vector	Fonstein et al., 1985
	$\frac{d\sigma}{d\varepsilon_{0.2}} = \left[71.4\sqrt{(V_V)_M} + 41.1(V_V)_M\right]\sqrt{\frac{1}{\lambda_M}}$		Lanzillotto et al., 1982
Fracture toughness	$G_C = C\frac{\sigma_{0.2}\lambda_M}{(V_V)_M^{1/3}}$	C - constant	Fonstein et al., 1985
Crack tip opening displacemant	$\delta_C = \lambda_M - 2R = 2R\left[\left(\frac{\pi}{4(V_V)_M}\right)^{1/3} - 1\right]$	R - mean radius of martensite islands	

although it does not reflect precisely the various types of distribution inhomogeneity of martensite islands in D-P steel microstructure.

This is why in Table 1 certain suggestions of the improvements of D-P steel microstructure quantitative description are presented. They have been derived from our experience in the range of grain size and particle inhomogeneity distribution evaluation (Cwajna, 1991; Maliński et al., 1991 and Wiśniewski et al., 1992). In order to find out whether these modifications may introduce any new data into the theory of D-P steel properties, the examinations of the effect of industrial scale processing, schematicly shown in Fig. 1., on D-P steel microstructure were performed. This is a modern technology, leading to a significant microstructure refinement and homogenization. However, the prior cold working (PCW) does not affect significantly the volume fraction of martensite (Hussein et al., 1985; Yang et al., 1985; Shirasawa et al., 1987 and Skohorodova et al., 1989).

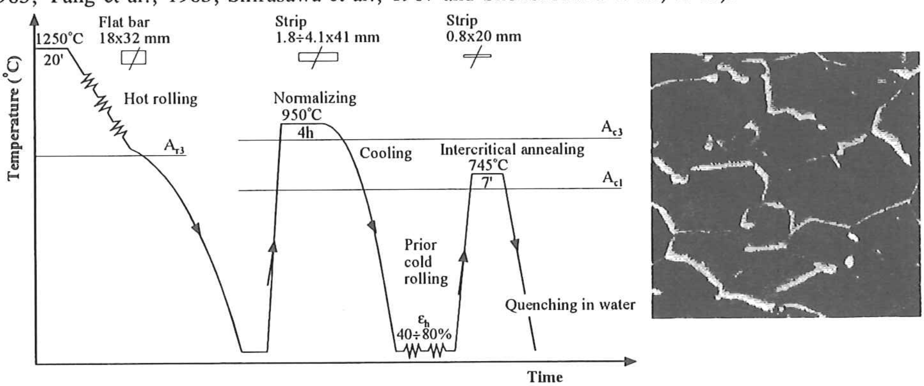


Fig. 1. Scheme of processing of investigated dual-phase steel strips.

MATERIAL AND TESTING METHODS

A plain carbon steel with the composition of: 0.14%C, 1.40%Mn, 0.54%Si, 0.13%V, 0.45%Al, 0.0022%B, 0.09%Cr, 0.04%Ni, 0.015%P and 0.016%S was used in the form of strips. The strips were cold rolled with the ratio of prior deformation ranging from 40% to 80% reduction of thickness. Flat tensile specimens with a 50 mm gange length were machined from the rolled strips. The specimens were then annealed for 7 minutes within the intercritical range (745°C) before quenching in water to obtain the dual-phase microstructure. Tensile testing was performed with a MTS machine. Undeformed tensile specimen heads were cut out of the specimens showing mechanical properties closest to the mean values calculated upon the 10-specimen basis. Transverse cross section of each specimen was polished - Petrodisc M and eatched in 2 pct nital. The microstructure was examined with a scaning electron microscope at magnification of 5000x and quantitatively evaluated with a MORPHOPERICOLOR image analyser. Volume fraction and specific surface of structural constituents were determined with relative error smaller than 5%. Other stereological parameters, indicated in Table 1, were assessed with similar accuracy.

RESULTS AND CONCLUSIONS

The results of quantitative evaluation of the examined strips microstructure are shown in Fig. 2 - 7. The Student's test have suggested that the prior cold working has no direct influence upon the volume fraction of martensite, and significantly affects all other considered parameters of ferrite and martensite; the examples of the empirical equations are collected in Table 3.

Following are the conclusions that can be drawn from the analysis of these data:

1. PCW causes some refinement of the D-P steel microstructure [S_V↑] associated with the decrease of ferrite average grain size [$(S_R)_F$↑; $\bar{l}_F$↓] and martensite islands dispersion increase [$(S_R)_M$↑; $\bar{A}_M$↓], as well as by obvious changes of grain/island size distribution.

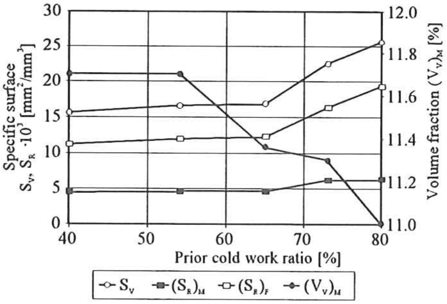


Fig. 2. Effect of prior cold work ratio on martensite volume fraction and microstructural refinement of dual-phase steel.

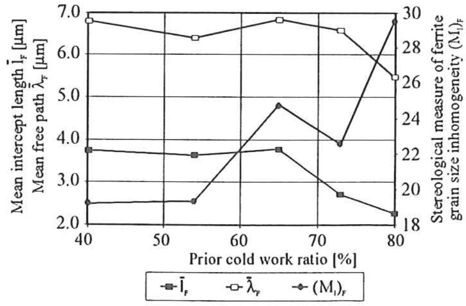


Fig. 3. Effect of prior cold work ratio on ferrite grain size and mean free path in ferrite of dual-phase steel.

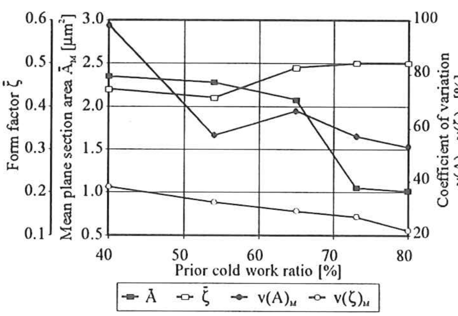


Fig. 4. Effect of prior cold work ratio on size and shape of martensite islands.

Factors $v(A_A)_M$ and η were determined by systematic scanning and variance analysis method (Wiśniewski et al., 1992) with the application of measuring frame of 0.07μm² area

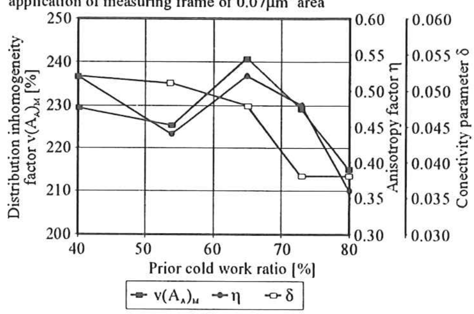


Fig. 5. Effect of prior cold work ratio on arrangement of martensite islands.

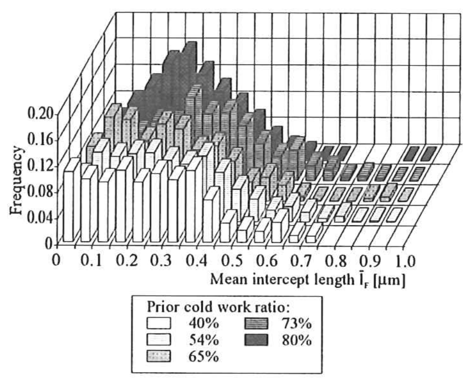


Fig. 6. Effect of prior cold work ratio on ferrite grain size distribution of dual-phase steel.

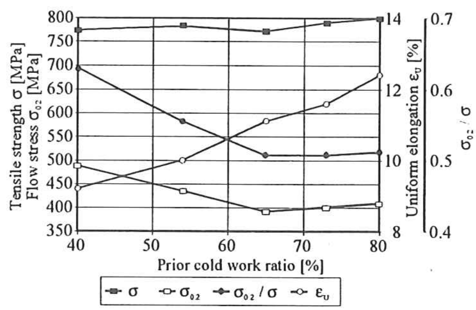


Fig. 7. Effect of prior cold work ratio on mechanical properties of dual-phase steel.

Table 3. Examples of empirical equations presenting the effect of prior cold work ratio on stereological parameters of structural constituent of dual-phase steel.

Empirical equation	Coefficient of correlation r	Significance level p
$S_V = 4231.2 + 243.4\varepsilon$	0.876	<0.05
$(S_R)_M = 2088.3 + 49.9\varepsilon$	0.848	<0.05
$(S_R)_F = 2142.9 + 193.6\varepsilon$	0.877	<0.05
$\bar{l}_F = 5.48 - 0.036\varepsilon$	0.820	<0.05
$(M_l)_F = 8.561 + 0.233\varepsilon$	0.849	<0.05
$\delta = 0.07 - 0.0004\varepsilon$	0.907	<0.05

Note: ε - prior cold working ratio

2. Non-monotonic variation of grain size inhomogeneity $[(M_L)_F \uparrow\downarrow]$ and martensite $[v(A)_M \uparrow\downarrow]$ demonstrate that the PCW ratio is a controlling variable of D-P steel microstructure inhomogeneity.
3. PCW ensures desirable transition of martensite islands form $[\bar{\zeta}\uparrow$ and $v(\zeta)\downarrow]$.
4. PCW tends to decrease the martensite islands distribution inhomogeneity $[v(A_A)_M\downarrow]$, but at the same time - to increase the microstructure anisotropy $[\eta\downarrow]$.

Taking into consideration the microstructure refinement and homogeneity the PCW ratio in the range from 65% to 75% seems to be the most suitable.The changes of D-P steel microstructure, associated with the substructure and properties alterations of both martensite and ferrite (Lanzillotto et al., 1982, Burford et al., 1985 and Hussein et al., 1985) increase the strength significantly and improve the deformation behaviour of D-P steel (Fig. 7). These findings prove that the improvements and supplements of D-P steel microstructure quantitative description suggested in the paper seems to be indispensable.

ACKNOWLEDGEMENTS

The work was supported by Polish Committee for Scientific Research, under grant No 7 0830 91 01.

REFERENCES

Ashby MF. Strengthening methods of crystals. Halsted Press Div, John Wiley and Sons, Inc, New York, 1971.

Burford DA, Matlok DK, Krauss D. Effect of microstructural refinement on the deformation behavior of dual-phase steels. In: Proc. 7th Int. Conference on "Strength of Metals and Alloys", Montreal, Canada, 1985; 1: 189-194.

Cwajna J. Tool alloys microstructure quantitative evaluation and its application. DSc Thesis. Zeszyty Naukowe Politechniki Śląskiej, "Hutnictwo" z. 39, Gliwice; 1991.

Fonstein NM, Borcov AN, Tscherniavskij KS. Stereologiczeskoje opisanije struktury dwuchfaznych stalej. Zawodskaja Laboratorija, 1985; 12: 34-37.

Gurland JA. Structural approach to the yield strength of two-phase alloys with coarse microstructures. Materials Science and Engineering, 1979; 40: 59-71.

Hussein AA, El-Bradie ZM. Effect of prior cold work on dual phase steel. In: Proc. 7th Int. Conference on "Strength of Metals and Alloys", Montreal, Canada, 1985; 2: 539-544.

Maliński M, Cwajna J, Chrapoński J. Grain size distribution. Acta Stereol, 1991; 10/1; 73-82.

Shirasawa H, Thomson JG. Effect of hot band microstructure on strength and ductility of cold rolled dual phase steel. Trans. Iron A Steel Inst. Jap, 1987; 27/5: 360-365.

Skorohodova LG, Fonstein NH, Niestierenko AM, Storozeva LM. Wlijanije struktury i čistoty ferritno-martienzitnoj stali na jeje plastičnost. IVUZ Czernaja Mietallurgia, 1989; 3: 47-101.

Wiśniewski A, Szala J, Cwajna J. The systematic scaning and variance analysis method for evaluation of cluster structures. Acta Stereol, 1992; 11/Suppli: 617-623.

Yang DZ, Matlock DK, Krauss D. Effect of cold rolling and intercritical annealing on microstructure and deformation of Mn-Si-C steel. In: Proc. 7th Int. Conference on "Strength of Metals and Alloys". Montreal, Canada, 1985; 1: 183-188.