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THE EFFECT OF NON-METALLIC INCLUSIONS ON MECHANICAL PROPERTIES OF A TOUGHENED HYPOEUTECTOID LOW-ALLOY STEEL

WPŁYW WTRĄCEŃ NIEMETALICZNYCH NA WŁASNOŚCI MECHANICZNE ULEPSZONEJ CIEPLNIE NISKOSTOPOWEJ STALI PODEUTEKTOIDALNEJ

The main objective of this work was to determine the effects of non-metallic inclusions on mechanical properties of a hypoeutectoid low-alloy steel designed for screws. The investigations were carried out on screws obtained in as-toughened condition. The investigated steels were delivered by three different suppliers and differed in the content of non-metallic inclusions. The volume fractions of non-metallic inclusions were evaluated on polished cross-sections using the point counting method. Irrespective of the content of non-metallic inclusions the investigated steels exhibited similar hardness and yield strength. Interestingly however, the highest ultimate tensile strength (UTS) was accompanied by the highest volume fraction of non-metallic inclusions.

W pracy przedstawiono wyniki badań wpływu zawartości wtrąceń niemetalicznych na własności mechaniczne śrub wykonanych ze stali niskostopowej po ulepszaniu cieplnym. Badania przeprowadzono na różniących się zawartością wtraceń niemetalicznych śrubach pochodzących od trzech dostawców. Udział wtrąceń niemetalicznych określono na wypolerowanych zgładach metalograficznych stosując metodę punktową. Twardość oraz granica plastyczności badanych stali była na zbliżonym poziomie, niezależnie od zawartości wtrąceń niemetalicznych. Granica wytrzymałości na rozciąganie była natomiast nieznacznie wyższa dla stali o największej zawartości wtrąceń niemetalicznych.

1. Introduction

Despite numerous studies in the field of inclusions engineering [1] (a term introduced in the recent years to define the effects of the type, size and density of non-metallic inclusions on steel properties) further research is necessary to better understand the influence of non-metallic inclusions on cracking of many specific steel grades. Inclusions may have a positive effect on ductility when microvoids nucleate around inclusions and crack propagation requires coalescence of these voids. As this process is controlled by the properties of the matrix it is of crucial importance that the steel is toughened in order to attain an optimum combination of high tensile strength and yield strength with good ductility.

Extensive research on methods of restricting the content of non-metallic inclusions in structural steels as well as on modification of their morphology to improve the steel properties is still being carried out [2-5] notwithstanding that the recent metallurgical technologies assure very low levels of non-metallic inclusions to meet the strict requirements of relevant standards, such as DIN 50 602 or ASTM E45-97 [6]. Although a lot of attention has been paid to the role of non-metallic inclusions in initiation of cracking [7-9] and fatigue wear [9-11] it still remains necessary to investigate the complex interrelations between the content of non-metallic inclusions and the steel performance under application conditions. Such a research is also needed to verify the theories proposed recently to explain the influence of non-metallic inclusions on steel properties [1,12] and, consequently, the numerical models based on these theories [13].

The main objective of this study is to establish the effect of non-metallic inclusions content of a toughened, low-alloy hypoeutectoid steel on mechanical properties of screws made thereof.

2. Experimental procedure

The research was conducted on screws made of 35B2+Cr steel received from three different suppliers. Their chemical compositions are presented in Table 1.

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TABLE 1

Chemical composition of the investigated steels (in wt. %)

steel	C	Si	Mn	P	S	Mo	Ti	Cu	Al	B	N
1	0.37	0.07	0.75	0.009	0.010	0.008	0.030	0.030	0.036	0.0040	0.0070
2	0.38	0.08	0.73	0.010	0.005	0.006	0.035	0.046	0.042	0.0033	0.0077
3	0.37	0.08	0.68	0.008	0.012	–	–	0.050	0.042	0.0027	0.0048

The screws were austenitized at 860°C for 60 min., oil quenched, tempered at 450°C for 100 min. and, subsequently, subjected the Vickers hardness test, static tensile test and microstructural studies.

The tensile test was carried out at room temperature on full size screws, according to ISO 6892, using ZD 40k machine. The loaded length of the threaded part of the screw was equal to its diameter. The ultimate tensile strength and yield strength were determined.

In order to avoid mixing up screws received from different suppliers the tests were performed on screws having the same diameter (M16) and different lengths, i.e. M16x140, M16x160 and M16x200 screws were made of steels no. 1, no. 2 and no. 3, respectively.

The volume fraction of non-metallic inclusions (V_v) was evaluated on polished crosssections using the point counting method. A 441-point grid was translated in a random manner over crosssectional images, taken at a 630x magnification, in order to analyse 55 fields of view for each sample.

3. Results and discussion

The results of the tensile test, presented in Table 2, indicate that the highest UTS exhibit screws made of steel no. 1 which contain the highest amount of non-metallic inclusions. It is noteworthy that steel no. 2 shows the lowest scatter of both UTS and yield strength results. The difference in yield strength between the investigated steels is very small and statistically insignificant. The hardness is also similar (see Table 2). Therefore it can be assumed that non-metallic inclusions have a negligible effect on lowering the yield strength of toughened screws (see Table 3).

TABLE 2

Mechanical properties of the investigated steels after toughening

steel	HV30	YS [MPa]	UTS [MPa]
1	366 (357÷377)	308 (300÷317)	1106 (1098÷1113)
2	358 (343÷373)	316 (313÷319)	1064 (1060÷1068)
3	360 (355÷371)	321 (312÷330)	1074 (1067÷1081)

TABLE 3

Volume fractions of non-metallic inclusions

steel	volume fraction [%] *
1	0.299±0.054
2	0.270±0.025
3	0.210±0.020

*The scatter intervals were estimated at 0.9 confidence level

As it is seen in Figure 1, the microstructures of the toughened steels are very similar except for steel no. 1 which exhibits slightly finer grain size compared to the other two steels. Interestingly, the fine-grained microstructure of steel no. 1 has no effect on the field strength which is virtually the same as in steels nos. 2 and 3. It is worthy of notice that the mechanical properties of the investigated steels meet the standards which must be kept up in the production of screws.

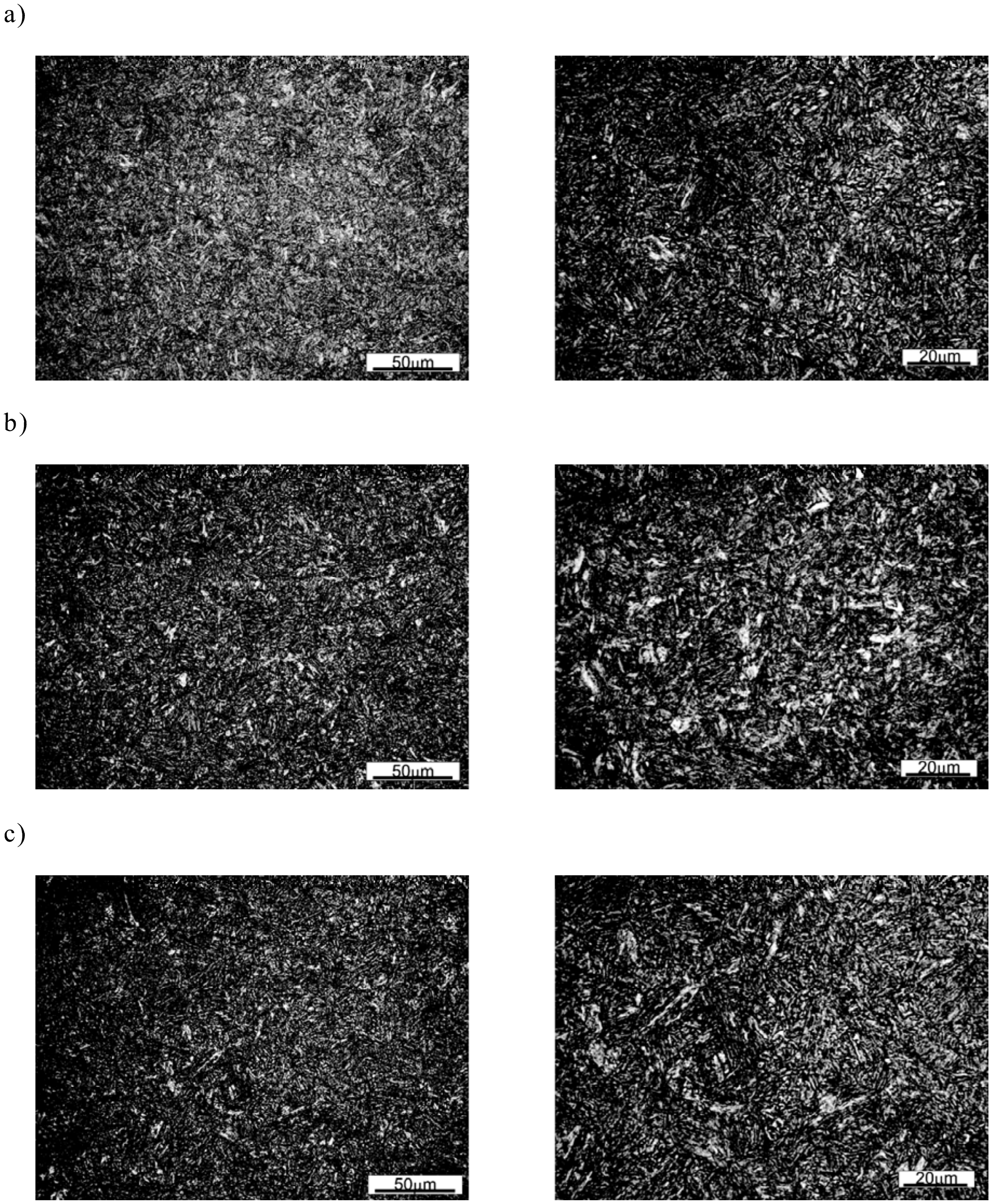

Fig. 1. Microstructure of the investigated steels after toughening: a) steel no. 1, b) steel no. 2, c) steel no. 3. Etched with 2% nital

Typical morphologies of non-metallic inclusions are shown in Figure 2. As seen in Figure 2a, sulphides were present in the form of inclusions elongated towards the direction of deformation. They were darker as compared to nitrides and brighter than oxides (Fig. 2a-c). A small number of nitrides were present in the tested steels. They were uniformly distributed and had a characteristic angular (so called "correct") shape (Fig. 2b). The most difficult challenge was to distinguish indigenous oxides from exogenous inclusions. It was therefore assumed that indigenous oxides should be seen as finely dispersed inclusions (Fig. 2b,c), whereas the large fuzzy-shaped inclusions should have an exogenous origin (Fig. 2c). The classic oxide strings were not observed.

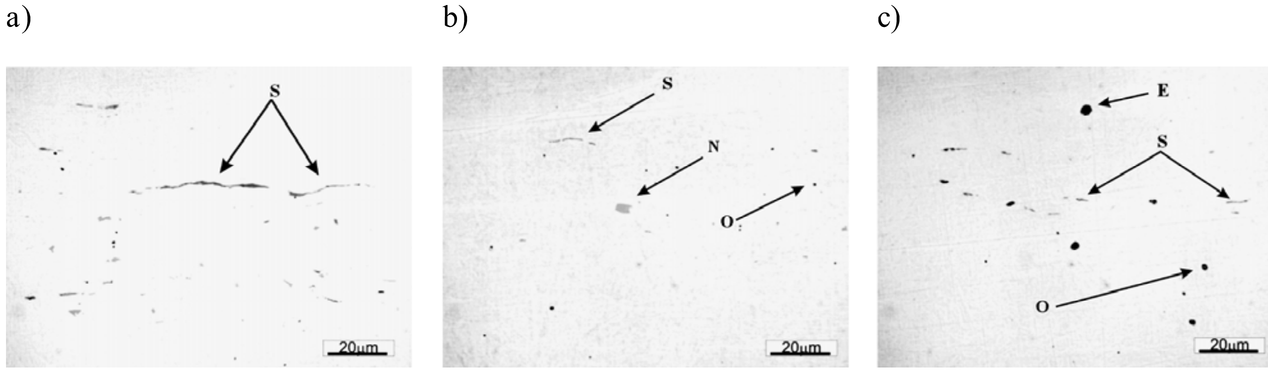

Fig. 2. Non-metallic inclusions in screws made of: a) steel no. 1, b) steel no. 2, c) steel no. 3 (O – oxides, S – sulphides, N – nitrides, E – exogenous inclusions). The longer side of each micrograph is parallel to the screw axis

It should be noted that inclusions described above as exogenous may partly be indigenous inclusions of silicates, but their correct identification with a light microscope is difficult. For simplicity, these inclusions are considered as exogenous in this work.

The volume fractions of non-metallic inclusions are given in Table 3.

4. Conclusions

The present study has demonstrated that:

- The mechanical properties of the tested steel met the requirements of the relevant standard PN EN ISO 898-1.
- The variation in yield strength and hardness between the investigated steels is very small and statistically insignificant.
- The highest ultimate tensile strength exhibit screws made of steel no. 1 which, coincidentally, has the highest volume fraction of non-metallic inclusions.
- There is a statistically significant difference in the volume fraction of non-metallic inclusions in screws made of nominally the same steel grade but obtained from different producers.
- Sulphides are present as elongated, fibrous inclusions parallel to the screw axis (direction of plastic deformation).

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