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Influence of Sulfur on the Anisotropy of the Plastic Properties in Structural Steel

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Abstract—The influence of the preparation of structural steels on the anisotropy of the plastic properties is investigated. With increase in sulfur content, the banding and anisotropy of mechanical properties such as the impact strength is considerably increased. For example, in high-quality steel with the limiting sulfur content, the impact strength differs by a factor of 6–8 in the longitudinal and transverse directions.

Keywords: structural steel, steel composition, sulfur content, fiber configuration, mechanical anisotropy, impact strength

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Most defects of steel appear in ingot solidification, which may be accompanied by the formation of shrinkage cavities, porosity, gas bubbles, chemical inhomogeneity (segregation), dendritic inhomogeneity, etc. (Fig. 1a). In subsequent treatment of the ingots (mainly in hot rolling), most defects change their shape and size, with the formation of fibers extending along the direction of rolling. The fiber structure is due to chemical inhomogeneity of the ingot or the presence of nonmetallic inclusions [1, 2]. Plastic nonmetallic inclusions (sulfides and silicates) are extended on hot rolling, whereas brittle inclusions break down to form rows oriented in the direction of metal flow (Fig. 1b).

With chemical inhomogeneity of the ingot, the fiber structure arises on account of the deformation of alternating lean regions (the dendrite axes) and enriched regions (between the dendrites). Banding is then seen in the microstructure. This is especially characteristic of cemented steels (Fig. 2). The fiber structure results in anisotropy of the steel's mechanical properties. If the cast alloy is isotropic—in other words, if it has practically the same properties in different directions, the hot-deformed steel will have better mechanical properties along the fiber and inferior transverse properties. If there is no difference in strength between the longitudinal and transverse fibers, the relative construction will decrease by 20–30% [3].

We note anisotropy of the steel's mechanical properties in terms of the impact strength in the case of longitudinal and transverse fibers. In samples with fibers inclined at 45°, the impact strength is 10–25% less than in the case of longitudinal fibers and half as much as for transverse fibers [4].

The anisotropy of the steel's mechanical properties plays a key role in ensuring the maximum performance

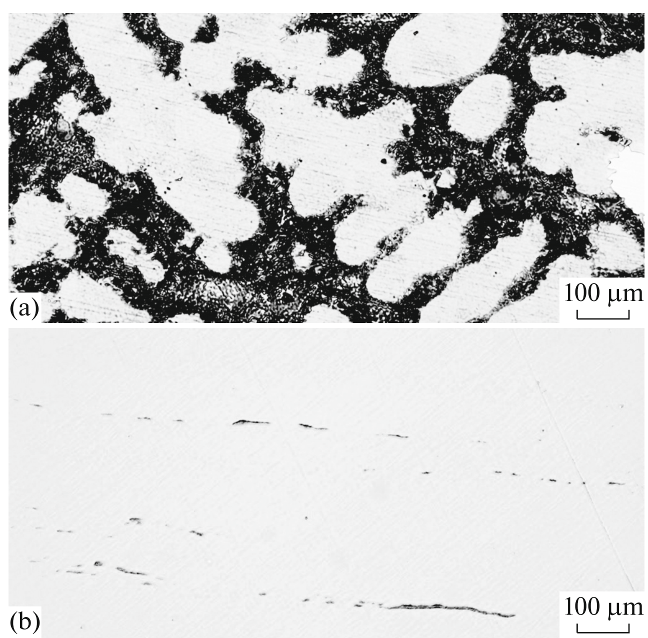


Fig. 1. Defects of steel: (a) dendritic inhomogeneity of the ingot; (b) nonmetallic inclusions.

of highly stressed parts. This is particularly important for drill bits operating in a highly abrasive medium at 1000 rpm with a transmitted torque of up to 2500 N m and a dynamic factor of up to 1.5. The drill (cutter) has a complex configuration with numerous stress concentrators [5, 6]. In order to prevent housing failure and tooth fracture, the steel employed must be plastic and ductile with high fatigue strength, In other words, it must be able to withstand the cyclic application of large dynamic loads in drilling a borehole. However, the teeth and supporting surfaces of the drill must be characterized by maximum wear resistance in drilling hard and abrasive rock. That calls for very hard steel, which is generally brittle. The requirements on drill components may be met by appropriate disposition of the fibers over the cross section of the part in hot bulk stamping.

Structural anisotropy largely determines the performance of gears operating with a bulk stress–strain state of the teeth. For gears whose life is limited by the fatigue strength in tooth flexure, the configuration with the fibers along the generatrix of the tooth is best. However, this configuration is undesirable for gears whose life is limited by the resistance to deep contact fatigue of the tooth's active surfaces [7]. These two contradictory requirements complicate the selection of the best steel.

Comprehensive study of the influence of particular nonmetallic inclusions on the steel's mechanical or fatigue properties is impractical on account of the many relevant variables (the composition, size, and shape of the inclusions, the number of inclusions, etc.). Usually, research is conducted for a model metal produced so that one type of inclusions predominates. In the classification of steel, the quality is mainly judged on the basis of the limiting permissible content of phosphorus and sulfur (State Standard GOST 4543–71). The content of those impurities mainly determines the steel properties. In the present work, we investigate the influence of the steel's sulfur content on the plastic properties of rolled sheet. In practice, the sulfur is mainly present in sulfides of iron and manganese.

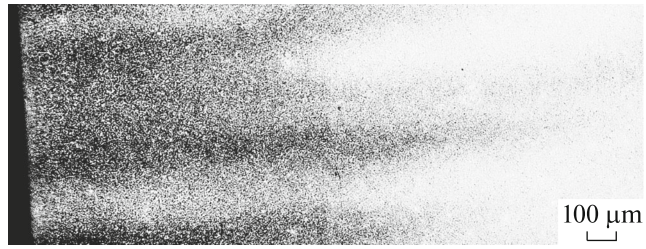


Fig. 2. Banding in cemented layer. Etching in accordance with [4].

Samples of 25ХГНМ, 20ХН3А, 14ХН3МА, and 21ХГНМА steel are investigated. Tensile tests are conducted in accordance with State Standard GOST 1497–84. The impact strength at normal temperature is determined on sample of type I according to State Standard GOST 9454–78, on a PSWO 30 pendulum hammer. Metallographic data are obtained by means of MIM-8M and Neophot 32 optical microscopes at 100-fold magnification. The steel is also examined by means of a Vega II LMU scanning electron microscope (Tescan, Brno, Czech Republic). Metallographic sections are investigated after etching in a special reagent [4]. Table 1 presents the chemical composition of the steels. Table 2 presents their mechanical properties, including the results of impact flexure tests for longitudinal and transverse samples. The sulfur content (0.004–0.014%) corresponds to superhigh-quality steel according to State Standard GOST 4543–71.

The results show that increase in sulfur content from 0.004 to 0.014% has practically no effect on the mechanical properties of the structural steels. However, the sulfur content has considerable influence on the anisotropy of the plastic properties in the longitudinal and transverse directions of the fibers. With 0.013–0.014% S, the transverse ductility is considerably decreased, and hence the anisotropy is increased.. In that case, $\Delta = KCU_{lo}/KCU_{trans} = 6.5–7.5$. Larger Δ

Table 1. Chemical composition (wt %) of steels

Manufacturer	Steel	C	Si	Mn	P	S	Cr	Ni	Mo
ZAO MZ Petrostal'	25ХГНМ	0.21–0.215	0.23–0.29	0.90–0.93	0.011–0.015	0.013–0.014	0.90–0.91	0.78–0.82	0.19
OAO Izhstal'	20ХН3А	0.21	0.29	0.415	0.006	0.008	0.71	2.72	0.008
	14ХН3МА	0.13–0.15	0.28–0.34	0.70–0.81	0.005–0.009	0.005–0.008	1.39–1.50	3.115–3.29	0.12–0.13
	21ХГНМА	0.21	0.32	0.87	0.005	0.004	0.52	0.50	0.41

Table 2. Mechanical properties of steels

Steel	Melt	σ_u, N/mm^2	σ_y, N/mm^2	δ, %	ψ, %	*KC*U,* J/cm^2	S, %	Δ
25ХГНМ	64541	1280	1150	13	54	157/24	0.013	6.5
	75485	1200	1090	13	51	158/21	0.014	7.5
20ХН3А**	Э82587	1080	1000	14	68	140/46	0.008	3.0
14ХН3МА	7Э82764	1395	1300	16	56	147/79	0.005	1.9
	7К7066	1490	1345	19	70	190/95	0.007	2.0
	7К7190	1120	920	13	56	140/58	0.008	2.4
21ХГНМА	13К20797	930	800	24	73	95/67	0.004	1.4

*Values in longitudinal/transverse direction.
**Tempering at 200°C; $\Delta = KCU_{lo}/KCU_{trans}$.

corresponds to higher carbon content in the steel (Table 2). With decrease in sulfur content to 0.004–0.008 wt %, the anisotropy of the impact strength is considerably decreased: Δ = 1.4–3.0 (Fig. 3). This finding must be taken into account in selecting steel and the smelting technology for critical components operating in a multiaxial stress–strain state.

The microstructure of longitudinal 20ХН3А steel sample 3 (Fig. 4a) with low sulfur content (0.008%) has slight banding. The distance between the bands is around 100 μm, and the mean difference in microhardness of the bands and the axes of the microfiber is 17 $HV_{0.5}$ (1.5 *HRC*). In Fig. 4b, we show the microstructure of a longitudinal 25ХГНМ steel sample with 0.013% S used in the impact strength tests; this sample has pronounced banding (the first sample in Table 2). The distance between the bands is around 150–400 μm, and the mean difference in microhardness of the bands and the axes of the microfiber is 50 $HV_{0.5}$ (5 *HRC*).

Viewing broken transverse 25ХГНМ steel samples on a scanning electron microscope, we note considerable chemical inhomogeneity over the sample cross section (Fig. 5). In addition, the fracture includes individual extended inclusions of manganese sulfide oriented in the direction of the fibers in the case of

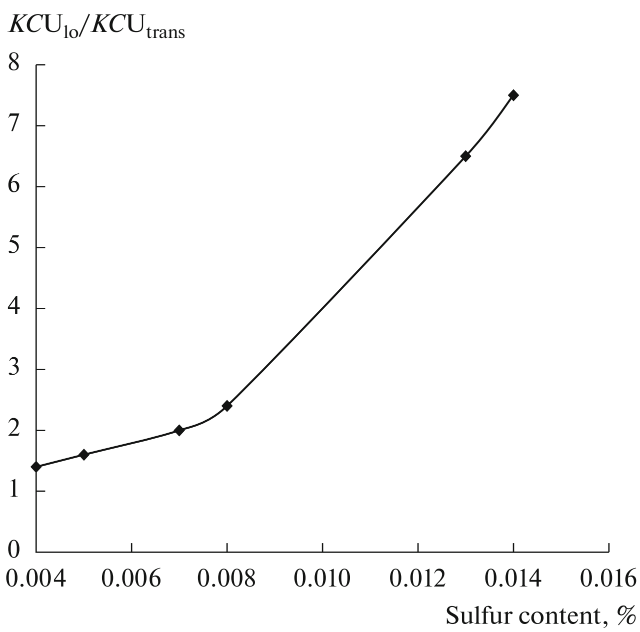


Fig. 3. Influence of the sulfur content on the anisotropy of the impact strength in structural steels.

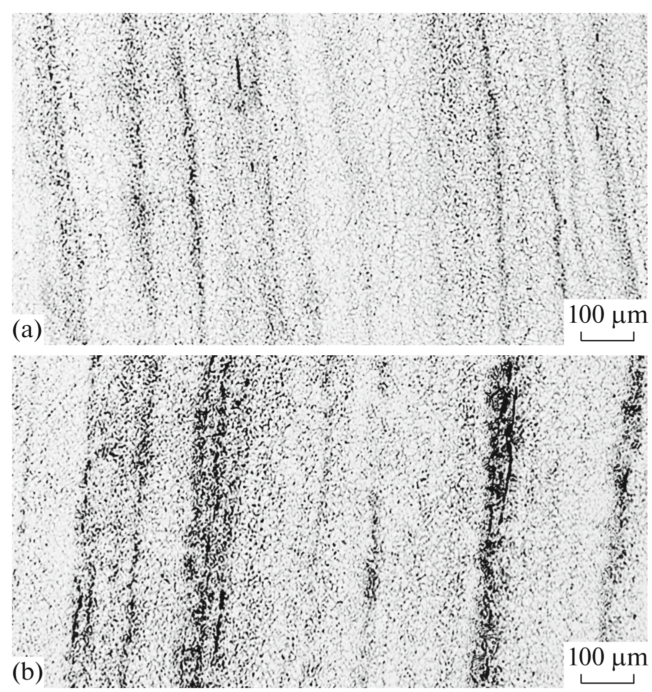
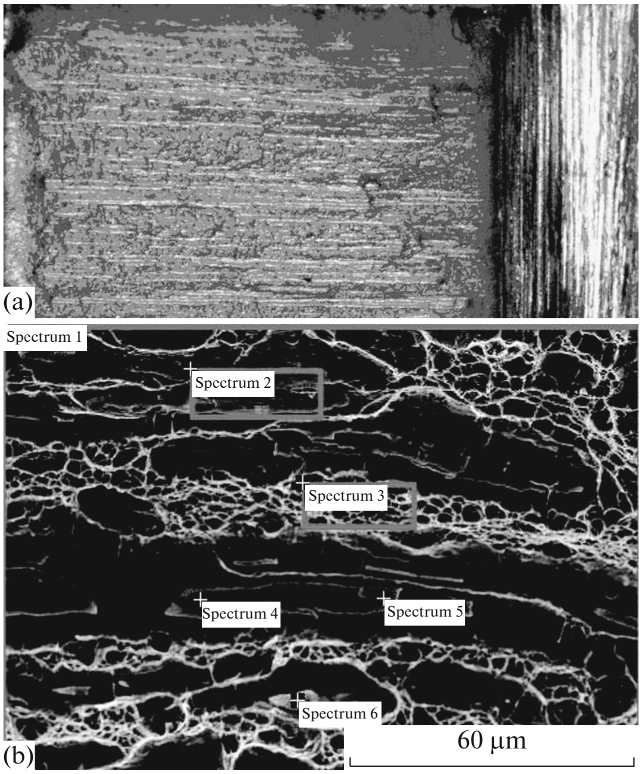


Fig. 4. Microstructure of longitudinal samples: (a) 20ХН3А steel, sample 3; (b) 25ХГНМ steel, sample 1. Etching in accordance with [4].



(c)

Spectrum	C	Al	Si	S	Cr	Mn	Fe	Ni
1	**3.58**	–	0.37	1.09	0.78	2.08	**90.15**	**1.95**
2	9.68	–	**0.51**	–	0.71	13.91	74.24	0.95
3	12.32	–	–	**0.16**	0.79	**0.71**	84.55	1.47
4	**39.41**	**0.82**	–	–	**2.13**	4.59	52.64	**0.42**
6	12.75	**0.11**	**0.13**	**29.30**	**0.58**	**42.16**	**14.97**	–

* Spectrum 5—100% Fe.

Fig. 5. Fracture of a transverse 25ХГНМ steel sample (a, b) and elementary composition (%) of characteristic sections of the fracture (c). Magnification: ×10 (a); ×2000 (b). In the table (c), the figures in boldface are the minimum and maximum contents of each element. Spectrum 5 corresponds to 100% Fe.

samples with 0.014% S. For 20ХН3А steel samples with 0.008% S, no MnS inclusions are observed.

CONCLUSIONS

(1) A relationship has been established between the sulfur content in structural steels and the anisotropy of the plastic properties in the longitudinal and transverse directions of the fibers.

(2) In superhigh-quality structural steels with 0.014% S, the impact strength in the longitudinal and transverse directions may differ by a factor of 6–8. To reduce the anisotropy of the impact strength, the sulfur content in the steel must be no more than 0.01%.

(3) The results will prove useful in selecting steel and its production method for critical components operating in a multiaxial stress–strain state.

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