ISSN1027-5495. Functional Materials, 32, No.3 (2025), p. 423-428
doi:http://dx.doi.org/10.15407/fm32.03.423 © 2025 — STC "Institute for Single Crystals"

Resistance of manganese steel to hydrogen sulfide embrittlement

A. Borusiewicz[1], T. Olszewski[1], D. Hlushkova[2], V.Volchuk[3], A. Uzhva[2], I. Kyrychenko[2]

[1] International Academy of Applied Sciences in Łomża , 19 Studencka Str., 18-400 Łomża , Republic of Poland
[2] Kharkiv National Automobile and Highway University, 25 Yaroslava Mudrogo Str., 61002 Kharkiv , Ukraine
[3] Prydniprovska State Academy of Civil Engineering and Architecture, 24a Architect Oleh Petrov Str., 49000 Dnipro, Ukraine

Received May 22, 2025

This study investigates the effect of hydrogen sulfide (H_2S) environments on the mechanical properties and microstructural evolution of 30G2 manganese steel used for coupling pipes. Tensile tests were performed on specimens in the initial state and after 720 hours of exposure to an H_2S-saturated medium following the MSKR 01-85 procedure. The as-received steel demonstrated superior strength (σ_B = 842 MPa, σ_T = 736 MPa) and ductility (δ_5 = 19.6%, ψ = 65.6%) compared to standard 30G2 values, indicating thermostrengthening . After prolonged H_2S exposure, strength parameters decreased only slightly (by 2–3%), while ductility dropped more noticeably (by 10–13%), but remained acceptable for pipeline applications. Fractographic analysis revealed a transition from a ductile–brittle to a more brittle fracture behavior with the presence of hydrogen-induced cracks. The findings confirm the suitability of modified 30G2 steel for oil and gas pipelines operating in aggressive H_2S environments, and suggest that further optimization of alloying and heat treatment could enhance resistance to hydrogen embrittlement.

Keywords : 30G2 steel, hydrogen sulfide, hydrogen embrittlement, mechanical properties, fracture, oil and gas pipelines.

Стійкість марганцевої сталі до сірководневого окрихчування. *А. Борусевич, Т. Ольшевський, Д.Б. Глушкова, В.М. Волчук, А.В. Ужва, І.Г. Кириченко.*

У роботі представлені результати дослідження впливу сірководневого середовища (H_2S) на структуру та механічні властивості марганцевої сталі 30Г2, що широко застосовується в промисловості. Проведено випробування на розтягування зразків у вихідному стані та після витримки у H_2S-середовищі (720 годин, методика МСКР0І-85). Встановлено, що вихідні властивості сталі (σ_B=842 МПа, σ_T=736 МПа, δ_5=19.6%, ψ=65.6%) значно перевищують стандартні для 30Г2, вказуючи на термозміцнення. Після впливу H_2S характеристики міцності знижуються незначно (2-3%), а пластичність - на 10-13%, залишаючись задовільною. Фрактографічний аналіз показав перехід від в'язко-крихкого до більш крихкого характеру руйнування з наявністю водневих тріщин. Результати підтверджують придатність модифікованої сталі 30Г2 для нафтогазових трубопроводів в агресивних середовищах, з рекомендаціями щодо оптимізації складу та термообробки для підвищення стійкості до H_2S.

1. Introduction

The influence of heat treatment has a beneficial effect on the properties of metals and alloys [1-3], which allows to increase their service life [4, 5]. The structure of many metallic materials undergoes transformations after heat treatment [6-8]. The exploitation of hydrogen sulfide-containing oil and gas fields requires the use of pump and compressor pipes resistant to hydrogen sulfide cracking. Heat treatment of steels improves the performance properties of steels used in aggressive environments with hydrogen sulfide (H_2S). Particular attention in materials science is paid to the study of the behavior of steels in aggressive environments containing hydrogen sulfide (H_2S), which causes hydrogen embrittlement and stress corrosion cracking [9]. These processes lead to the formation of cracks with self-similar (fractal) morphology [10-16], which requires the use of various analysis methods, including fractal theory, optical and electron microscopy, and numerical modeling [17-22]. Tests for resistance to hydrogen sulfide cracking are carried out using the MSCR 01-85 method (presumably an analogue of NACE TM0177), which provides for testing at a constant strain rate in a H2S-containing environment [9]. This method allows one to evaluate the resistance of steels to degradation caused by hydrogen embrittlement and to identify changes in their mechanical properties.

This paper presents the results of a study of the effect of an aggressive hydrogen sulfide environment (H_2S) on the structure and mechanical properties of 30G2 manganese steel. The tests included an analysis of mechanical characteristics (strength, yield strength, relative elongation and contraction) in the initial state and after exposure to a H_2S environment, as well as a study of fracture surfaces to assess the nature of the fracture and microstructural changes. The data obtained emphasize the importance of optimizing the composition and heat treatment of 30G2 steel to improve its performance in aggressive environments.

2. Material and methods

The chemical composition of manganese steel 30G2 was studied (Table 1).

Mechanical tests of manganese steel were performed according to ISO 6892-1:2019 on longitudinal samples with a diameter of 6 *mm* (Fig. 1).

The results of determining the mechanical properties of the steel under study in the initial state are given in Table 2. The material of all pipes has relatively high plasticity characteristics.

Before tensile testing, the samples were kept for 720 hours in a saturated hydrogen sulfide-containing environment, in accordance with the MSKR 01-85 method. The MSKR 01-85 method requires keeping steel samples in a saturated hydrogen sulfide environment for 720 hours,

Geometrical characteristics	d_0	l_0	l	D_1	D	r	r_1	h_1	h_2
Dimensions, mm	6	30	42	8	15	1	3	6	4

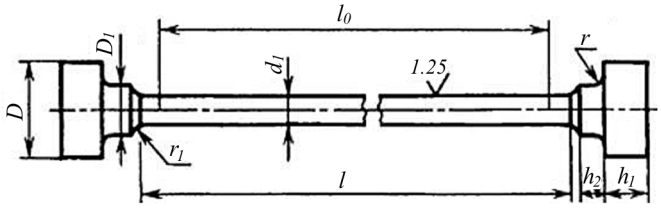

Fig. 1. Geometric characteristics of manganese steel specimens for mechanical tensile testing

Table 1. Chemical composition of manganese steel 30G2

C	Si	Mn	Ni	S	P	Cr	Cu
0.26 - 0.35	0.17 - 0.37	1.4 - 1.8	up to 0.3	up to 0.035	up to 0.035	up to 0.3	up to 0.3

Table 2. Mechanical properties of samples made of manganese steel 30G2

Sample number	Tensile strength σ_2 MPa	Yield strength $\sigma_{„}$ MPa	Relative elongation δ5,.%	Relative narrowing ., %
1	838	734	20.0	66.7
2	840	730	20.5	65.8
3	835	729	21.0	67.0
4	841	735	19.5	65.0
5	845	738	19.0	65.5
6	846	740	19.0	64.9
7	850	745	18.0	64.0

followed by tensile testing at a constant strain rate. The tests were carried out at a tensile rate of 1 mm/min. Comparison of mechanical properties before and after exposure to H_2S allows us to assess the degree of hydrogen embrittlement and the susceptibility to hydrogen sulfide cracking.

The microstructure of the material was studied using optical and scanning electron microscopes.

3. Results and discussion

The mechanical properties of the studied samples in the initial state show high strength and ductility (Table 2), which is typical for manganese steels of type 30G2, where manganese (1.4–1.8%) improves strength, toughness and weldability.

Based on the values of the material characteristics in the initial state and after exposure to a hydrogen sulfide-containing environment, their relative change was calculated using the formula:

$$\Delta i,\% = \frac{0_A - 0_u}{0_u} \times 100\% .$$

where 0_A 0_u e the values of the assessed characteristic for the material, respectively, in the initial state and after exposure to hydrogen sulfide.

Before testing in a hydrogen sulfide environment, samples of 30G2 steel were subjected to heat treatment according to the following regime:

- Quenching: 860–880°C, holding for 1–2 hours, cooling in oil.
- Tempering: 620–650°C, holding for 1–2 hours, air cooling, to ensure hardness ≤ 22 HRC and resistance to hydrogen sulfide cracking.

After exposure to hydrogen sulfide, the plasticity indices, although reduced, remain at a sufficiently high level for all samples; the strength characteristics, however, decrease insignificantly. The results of testing the samples after holding without load in a hydrogen sulfide-containing environment are given in Table 3.

The next stage was the study of the microstructure of pipes made of manganese steel 30G2, processed according to the given methods. The structure of the outer and inner surfaces of the pipe walls was studied (Fig. 2 - Fig. 5).

The structure of the pipe at the outer (Fig. 4) and inner (Fig. 2, Fig. 5) surfaces is tempered martensite and tempered lower bainite. The amount of tempered martensite at the outer surface is 80%. Upper bainite (up to 10%) is observed at the inner surface in certain areas.

Table 3. Mechanical properties in tension of samples made of 30G2 steel after holding without load in a hydrogen sulfide-containing environment according to the MCKP 0 I -85 method

Sample number	Tensile strength σ_B MPa	Limit of fluidity σ_T MPa	Relative elongation δ_5 ,%	Relative narrowing ψ, %
1	810	705	19.0	61.5
2	815	710	18.5	60.0
3	800	699	20.0	63.0
4	820	715	17.0	58.7
5	826	722	16.5	57.0
6	831	730	15.0	55.8
7	834	735	14.0	54.9

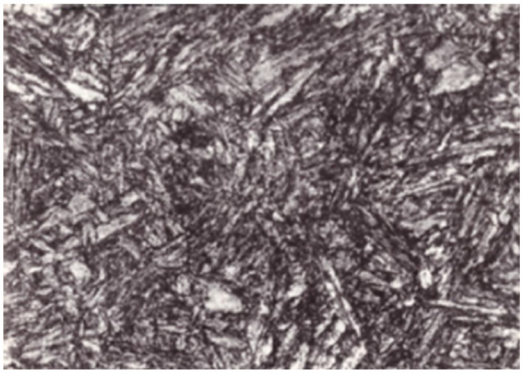

Fig. 2. Microstructure of the pipe material at the inner wall, ×1000

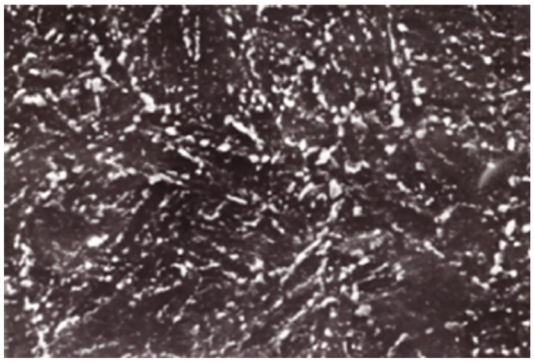

Fig. 3. Microstructure of the pipe material at the outer surface, ×5000

Fig. 4. Microstructure of the pipe material in the middle of the wall thickness, ×2500

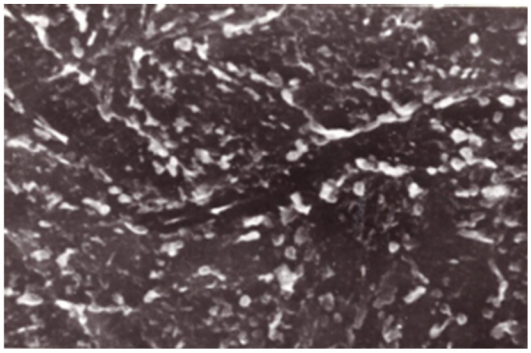

Fig. 5. Microstructure of the pipe material at the inner surface, ×10000

As we move away from the outer surface towards the middle of the wall, the amount of tempered bainite increases, areas of tempered upper bainite appear, and a ferrite network appears along the grain boundaries (Fig. 2; Fig. 4), the occurrence of which is apparently explained by insufficient cooling rate.

The relief of the ferrite regions and the significant number, especially at the inner surface of the pipe, of dark precipitates, which are apparently insufficiently formed carbides, suggest that the tempering processes have not been completed completely.

The strength characteristics of 30G2 steel samples, which were kept for 720 hours in a saturated H_2S environment according to the MSKR 01-85 method (Table 3), decrease insignificantly (2–3%), and the ductility – by 10–13%, but remains at a sufficiently high level (>14% for elongation, >54% for narrowing). A decrease in the ultimate strength σ_{in} and the yield strength σ_T by 2–4% is minimal and not critical for operation. This indicates good resistance of 30G2 to strength degradation in a H2S environment, despite its tendency to temper brittleness.

The fracture surfaces of the samples were examined for the initial state of the material and after holding the samples for 720 hours in a hydrogen sulfide-containing environment corresponding to the MOKR 01-85 method without load. For the material in the initial state, the fracture has a ductile-brittle nature (Fig. 6, column I). In the central ductile zone, there is a significant number of small cracks that have arisen on inclusions and, apparently, along grain boundaries. Holding the material in a hydrogen sulfide-containing environment led to the appearance of hydrogen cracks and general embrittlement of the fracture (Fig. 6).

Fractographic analysis revealed a transition from a ductile-brittle fracture in the initial state to a more brittle one after exposure to H_2S, which confirms the accumulation of hydrogen in the steel structure and its influence on crack formation.

The fracture is ductile-brittle with a central ductile zone containing small cracks at inclusions and grain boundaries (Fig. 6, column I). This is typical for 30G2 with a ferrite-pearlite structure: manganese stabilizes the viscosity, but sulphide inclusions (MnS) and grain boundaries serve as crack initiators.

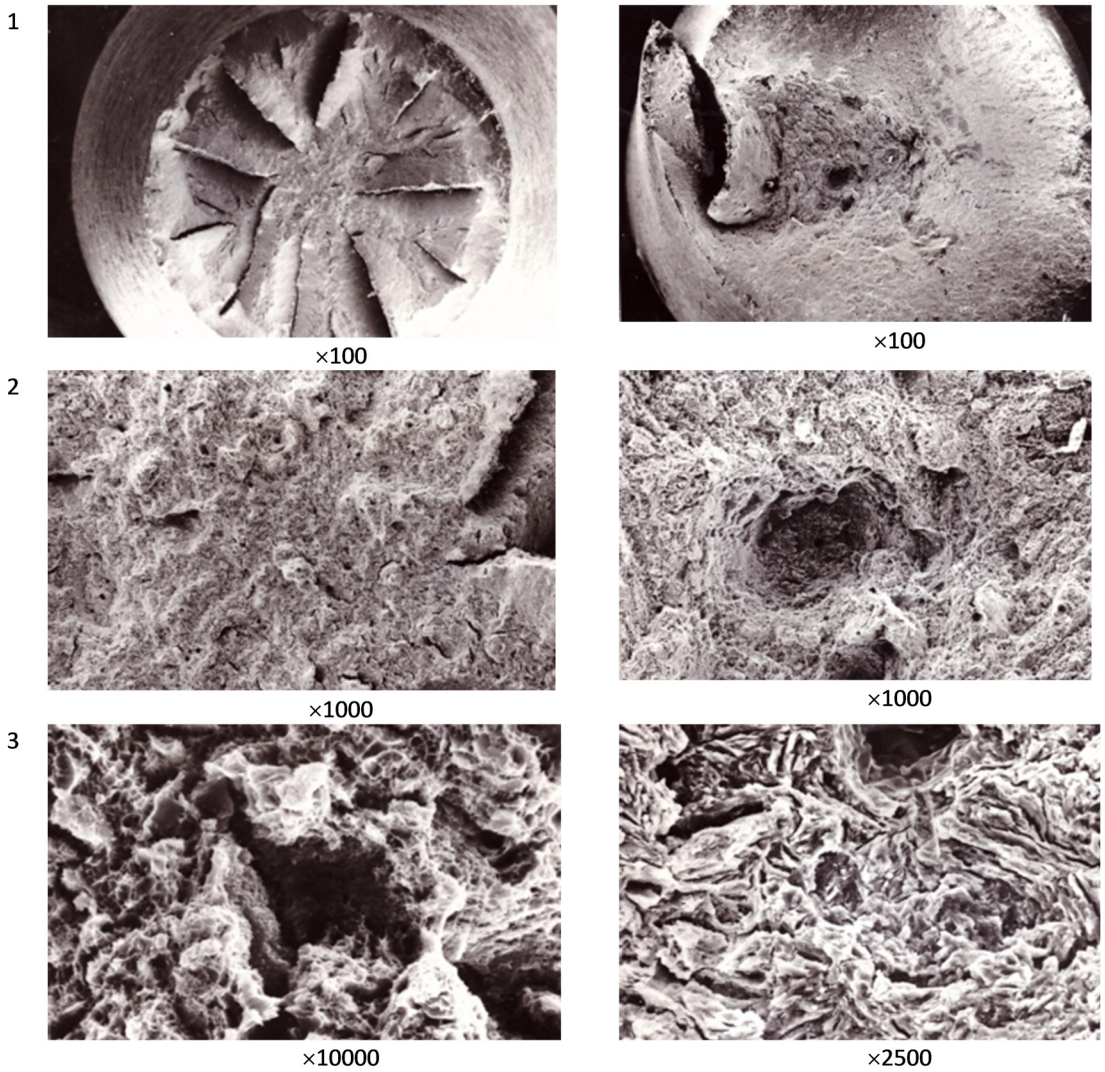

Fig. 6. Fracture surfaces of tensile-tested samples of 30G2 steel in the initial state (Fig. 6, column 1) and after holding without load in a hydrogen sulfide-containing environment (Fig. 6, column 2)

After exposure to H_2S, hydrogen cracks and general fracture embrittlement appear (Fig. 6). H_2S dissociates, releasing atomic hydrogen, which penetrates into 30G2 steel, accumulating on defects and causing intergranular cracking. This explains the decrease in ductility and increase in brittleness.

4. Conclusion

1. The mechanical properties of coupling pipes made of manganese steel 30G2 in the initial state are characterized by high strength ($\sigma_B \approx 842$ MPa, $\sigma_T \approx 736$ MPa) and good ductility ($\delta_5 \approx 19.6\%$, $\psi \approx 65.6\%$). These indicators exceed the standard values for steel 30G2, which indicates thermal strengthening of the material.

2. After holding the samples in a saturated hydrogen sulfide environment for 720 hours, the decrease in strength characteristics is only 2–3%, which indicates the resistance of 30G2 steel to strength degradation under H_2S conditions.

3. The greatest changes are observed in plastic properties: relative elongation and contraction decrease by 10–13%, which is associated with hydrogen embrittlement and the formation of intergranular cracks. However, even after exposure to H_2S, plasticity remains satisfactory for operation ($\delta_5 > 14\%$, $\psi > 54\%$).

4. Fractographic analysis revealed a transition from a ductile-brittle fracture in the initial state to a more brittle one after exposure to H_2S, which confirms the accumulation of hy-

drogen in the steel structure and its influence on crack formation.

5. In general, modified steel 30G2 demonstrates satisfactory resistance to hydrogen sulfide exposure and can be considered as a promising material for oil and gas pipelines in aggressive H2S environments.

References

1. V. Maslova, R. Nastase, G. Veryasov, N. Nesterenko, E. Fourré, C. Batiot-Dupeyrat, *Progress in Energy and Combustion Science*, **101**, 101096 (2024) https://doi.org/10.1016/j.pecs.2023.101096
2. G.I. Zaginaylov, V.I. Shcherbinin, K. Schuenemann, M.K. Thumme, *IEEE Transactions on Plasma Science*, **34**(3), 512 – 517 (2006) https://doi.org/10.1109/TPS.2006.875760
3. P. Andrenko, A. Rogovyi, I. Hrechka, S. Khovanskyi, M. Svynarenko, *Journal of Physics: Conference Series*, **1741**(1) (2021) https://doi.org/10.1088/1742-6596/1741/1/012024
4. Y. Gutarevych, V. Mateichyk, J. Matijošius, A. Rimkus, I. Gritsuk, O. Syrota, Y. Shuba, *Energies*, **13**(5), 1076 (2020) https://doi.org/10.3390/en13051076
5. D.B. Hlushkova, O.D. Hrinchenko, L.L. Kostina, A.P. Cholodov, *Problems of Atomic Science and Technology*, **1**(113), 181-188 (2018).
6. Sergiyenko O.,Hernández Balbuena, D., Tyrsa V., Rosas Méndez, Patricia Luz A. Lopez M. R, Hernandez W, Podrygalo M., Gurko A. Journal of the International Measurement Confederation, 44, 1229 – 1242, (2011) https://www.sciencedirect.com/science/article/abs/pii/S0263224111001254?via%3Dihub
7. Vafaeva, K.M., Dhyani, M., Acharya, P., Parik, K., Ledalla, S., *Bio Web of Conferences*, **86**, 01111 (2024) https://doi.org/10.1051/bioconf/20248601111
8. M. Krbata, M. Kohutiar, J. Escherova et. al. *Applied Mechanics*, **6**(1), 16. (2025). https://doi.org/10.3390/applmech6010016
9. M. Yuan, L. Zhang, J. Wan et. al. *Structures*, **75**, 108677 (2025). https://doi.org/10.1016/j.istruc.2025.108677
10. K.M. Vafaeva, N.I. Vatin, D.F. Karpov, V. Romanovski, *Materials Research Express*. **12,** 075307 (2025) https://doi.org/10.1088/2053-1591/adf161
11. D. Leontiev, O.I. Voronkov, V. Korohodskyi, D. Hlushkova, I. Nikitchenko, E. Teslenko, O. Lykhodii, *SAE Technical Paper*, 2020-01-2222 (2020) https://doi.org/10.4271/2020-01-2222
12. Kalinina, N.E., Glushkova, D.B., Voronkov, A.I., Kalinin, V.T.**,** *Functional Materials*, 2**6**(3), 514–518 (2019) https://doi.org/10.15407/fm26.03.514
13. M. Rajendran, M. Arumugam, L. Sourirajan et. al., *Results in Engineering,* 26, 104614 (2025) https://doi.org/10.1016/j.rineng.2025.104614
14. D.B. Hlushkova, V.M. Volchuk, *Functional Materials*, 30(3), 453 (2023) https://doi.org/10.15407/fm30.03.453
15. C. Ding, L. Jiang, J. Xu, S. Guo, J. Zhang, P. Xiong, Z. Piao, *International Journal of Bifurcation and Chaos*, **35**(08), 2550098 (2025) https://doi.org/10.1142/S0218127425500981
16. P. Zhang, J. Ding, J. Guo, F. Wang, *Fractal and Fractional*, **8**(6), 304 (2024) https://doi.org/10.3390/fractalfract8060304
17. Andrenko P., Rogovyi A., Hrechka I., Khovanskyi S., Svynarenko M. Journal of Physics: Conference Series, 1741, (2021) https://iopscience.iop.org/article/10.1088/1742-6596/1741/1/012024
18. Kalinina, N.E., Glushkova, D.B., Voronkov, A.I., Kalinin, V.T., Functional Materials, 26(3), 514–518 (2019) https://doi.org/10.15407/fm26.03.514
19. V.K. Maksudovna, G.Z. Anatolyevna, S. Dixit et. al. *E3S Web of Conferences,* **430**, 01191 (2023) https://doi.org/10.1051/e3sconf/202343001191
20. D.B. Hlushkova, V.M. Volchuk, P.M. Polyansky, V.A. Saenko, A.A. Efimenko, *Functional Materials*, **30**(2) 275 (2023) https://doi.org/10.15407/fm30.02.275
21. D.B. Hlushkova, A.V. Kalinin, N.E. Kalinina, V.M. Volchuk, V.A. Saenko, A.A. Efimenko, *Problems of Atomic Science and Technology*, **2**(144), 126-129 (2023). https://doi.org/10.46813/2023-144-126
22. V.I. Bolshakov, V.M. Volchuk, Yu.I. Dubrov, *Metallofizika i Noveishie Tekhnologii*, **40**(9), 1165-1171 (2018) https://doi.org/10.15407/mfint.40.09.1165