# THE INFLUENCE OF NIOBIUM CONTENT ON HOT FLOW STRESS OF HSLA STEELS

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**Abstract**

Microalloyed steel P355NH or EN 10216-3, which is intended for the production of seamless steel tubes for pressure purposes, and S355J2H or EN 10210-1 vary especially by the amount of niobium (0.013 % in case of the steel P355NH and 0.037 % for the S355J2H, respectively). Uniaxial hot compression tests performed on the Hot Deformation Simulator HDS-20 were utilized to compare the influence of the niobium amount on hot flow stresses of these steels. There was investigated in case of the both steels the temperature range from 700 °C to 1200 °C in combination with the nominal strain rate range from 0.1 $s^{-1}$ to 100 $s^{-1}$. The unique computing method was employed to correct the shape of the experimentally obtained hot flow stress curves influenced by the spreading of the test samples at high strains. Then it was possible to calculate with using the peak coordinates the value of the activation energy at hot forming 534.9 $kJ\cdot mol^{-1}$ in case of the steel P355NH and 554.3 $kJ\cdot mol^{-1}$ for the S355J2H. Decrease of the temperature led to an increase of the hot flow stress. The same influence had an increase of the strain rate value. There was found out, the higher amount of the niobium has been led to the increase of the hot flow stress. This means, the hot flow stress of the steel S355J2H is at each temperature higher against of the steel P355NH. Nevertheless, this difference is minimal at higher temperatures.

**Keywords:**

HSLA steel, influence of niobium, uniaxial hot compression test, flow stress curves, peak stress

## 1. INTRODUCTION

Z-Group Steel Holding, a.s., production division Válcovny trub Chomutov, Czech republic [1] is aimed to production of the seamless steel tubes by the Mannesmann way [2, 3]. There was found out, the processing of the steel tubes with thinner wall thickness from the microalloyed steel P355NH and S355J2H is accompanied by the crack creating at the initial part of the rolled tubes. This is probably occurred because of quicker wall cooling at the ending parts of the rolled tubes. This fact then leads to a flow stress increase in these ending parts and thus to an increase of the crack occurring in this area. Despite of the fact that the initial part of the tube is usually cut, as the part of the technological waste, the drawing between the rolls can occur, with respect to the specific technology of the Mannesmann rolling, in case of the tube part widened by the crack. The effect of decreasing temperature on the flow stress increase is obvious. The flow stress increase is also caused by the higher value of the strain rate. In addition, above-mentioned steels vary essentially by the amount of the niobium. This microalloyed element has powerful strengthening effect through the recrystallization deceleration during forming, which leads to the significant flow stress increase [4].The goal of this paper was to determine the influence of the forming temperature and amount of the microalloyed element niobium on the maximum hot flow stress of the above-mentioned HSLA steels at high-rate strains. The values of the maximum flow stress will be then used to evaluate the deformation behavior of the investigated steels. The results of this investigation should be employed to improve the technological process of the seamless steel tubes production in view of the above-mentioned crack occurring. For instance, hot deformation behavior of the steels intended to the production of the seamless steel tubes by the Mannesmann way was also studied in [5, 6].

## 2. EXPERIMENT

The solution of the above-mentioned issue was based on the utilization of the Hot Deformation Simulator HDS-20 at VSB-TU Ostrava whose testing module Hydrawedge II [7] enables at the hot compression test to achieve the nominal strain rate up to 100 $s^{-1}$ [8]. The cylindrical compression-test specimens with the diameter of 10 mm and the height of 15 mm were prepared from the casts of the steel P355NH and the S355J2H. The both casts had a similar carbon equivalent (0.41 in both cases) and chemical composition (**Table 1**). However, they vary essentially by the niobium content (Table 1). From this viewpoint can be said, these casts were for the assessment of the influence of the niobium amount on the hot flow stress of the investigated steels chosen really thoroughly. For the uniaxial compression tests of both steels were chosen the deformation temperatures of 1200 °C; 1100 °C; 1000 °C; 900 °C; 800 °C and 700 °C. These temperatures were combined with the nominal strain rates values of 0.1 $s^{-1}$; 1 $s^{-1}$; 10 $s^{-1}$ and 100 $s^{-1}$. Each sample was after the unified preheating at the temperature of 1280 °C subsequently cooled down on the deformation temperature and deformed at this temperature by the uniaxial compression with the maximum height-true strain of 1.0.

**Table 1** Chemical composition of the casts of the steel P335NH and S355J2H

| | C (%) | Mn (%) | Si (%) | N (%) | V (%) | Nb (%) |
|---|---|---|---|---|---|---|
| P355NH | 0.13 | 1.31 | 0.25 | 0.01 | 0.045 | 0.013 |
| S355J2H | 0.14 | 1.38 | 0.29 | 0.01 | 0.059 | 0.037 |

## 3. RESULTS AND DISCUSSION

### 3.1. The flow stress curve correction

The result of each compression test was obtained in the form of the flow stress curve calculated by the internal algorithm of the used simulator. From the theoretical viewpoint, these obtained experimental curves exhibits the inappropriate increase of the flow stress beyond the strain of 0.4 or 0.6 – see the black lines in **Fig. 1** and **Fig. 2**. This phenomenon then means a serious obstacle in case of the flow stress prediction at high strains. The reason why this is occurring can be explained by varying friction on the contact surfaces between sample and anvils. It is obvious that this fact causes an uneven spreading of the testing samples, which leads to the barrel-like shape. The internal calculating algorithm of the HDS-20 is then probably unable to fully reflect the excessive barreling running at strains above the value of 0.4 or 0.6, respectively. This issue can be overcome by the complicated mathematical methods that are described for example in [9, 10]. In the event of our research, we employed the simple correction method to put right the shape of the experimentally obtained flow stress curves at high strains. This method is using the flow stress curve with the distinct area of steady-state stress. On the basic of this curve is then possible to derive the mathematical function that is able to correct the shape of the flow stress curves in the steady-state area [11]. After that, it is possible to obtain the significantly more accurate results if we apply this concrete function through the set of the experimentally obtained curves. The green lines in Fig. 1 and Fig. 2 represent the examples of this way corrected curves. Figure 2 shows that an addition correction (smoothing) of the shape of the previously corrected flow stress curves is necessary if these curves are obtained at high strain rates values when higher scatter of the recorded data is occurred. This smoothing is suitable for the determination of the basic shape of the flow stress curves and the peak coordinates. Unfortunately, this correction method does not allow to correctly describe the shape of the curves in the ending phase and also does not exhibit the smooth start phase (see the red line in Fig. 2).

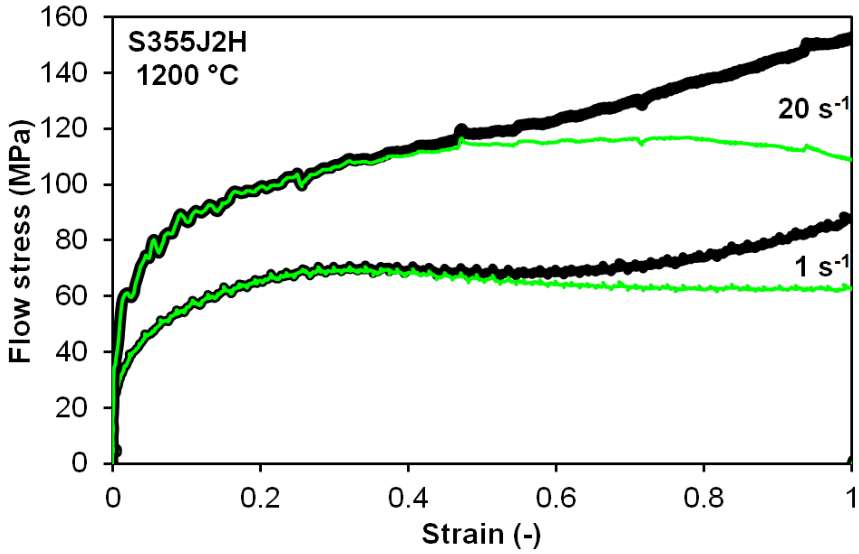


**Fig. 1** Flow stress curve correction

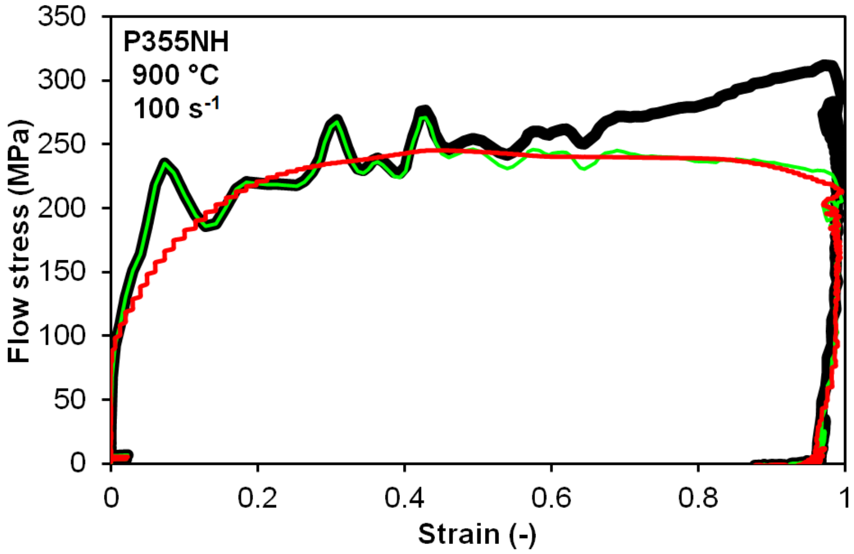


**Fig. 2** Flow stress curve smoothing

### 3.2. Activation energy at hot forming and prediction of the maximum flow stress

Thanks to the above-mentioned corrections was possible to obtain from the corrected flow stress curves the experimental values of the maximum flow stress. Possible prediction of these values can be done through these inverse hyperbolic-sine equations [12]:

$$\sigma_{\max} = \frac{1}{0.0681} \cdot \operatorname{arg\,sinh} \sqrt[1.4354]{\frac{Z}{1.35 \cdot 10^{16}}} \tag{1}$$

$$\sigma_{\max} = \frac{1}{0.0618} \cdot \arg\sinh \sqrt[1.3599]{\frac{Z}{2.36 \cdot 10^{17}}} \tag{2}$$

The equation (1) is valid in case of the steel P355NH and equation (2) is intended as for the steel S355J2H. In both equations, $\sigma_{max}$ (MPa) represents the maximum flow stress and $Z$ ($s^{-1}$) is the Zener-Hollomon parameter [13]:

$$Z = \acute{e} \cdot \exp\left(\frac{Q}{R \cdot T}\right) \tag{3}$$

In the equation (3), $\acute{e}$ ($s^{-1}$) represents the strain rate, $R$ (8.314 $J \cdot K^{-1} \cdot mol^{-1}$) is the universal gas constant, $T$ (K) represents the deformation temperature and $Q$ ($J \cdot mol^{-1}$) is the activation energy at hot forming. The value of the $Q$ takes 534.9 $kJ \cdot mol^{-1}$ in the event of the steel P355NH and 554.3 $kJ \cdot mol^{-1}$ as to the S355J2H, respectively. The value of $Q$ was calculated by the traditional hyperbolic-sine equation [14]. For the all above-mentioned calculations was used the special interactive software ENERGY 4.0, working on the principle of partial linear regressions [15].

### 3.3. Comparison of the maximum flow stress

In order to compare effectively the influence of the deformation temperature and content of the niobium amount on the hot flow stress of the investigated steels, the 3D-graph of the both examined steels was compiled; see **Fig. 3** represents the steel P355NH and **Fig. 4** stated for the S355J2H, respectively. At the first sight, it is clear that flow stress of the both steels increase with the decreasing deformation temperature and the growing strain rate. Nevertheless, the influence of the declining temperature on the flow stress increase is greater in case of the steel S355J2H.

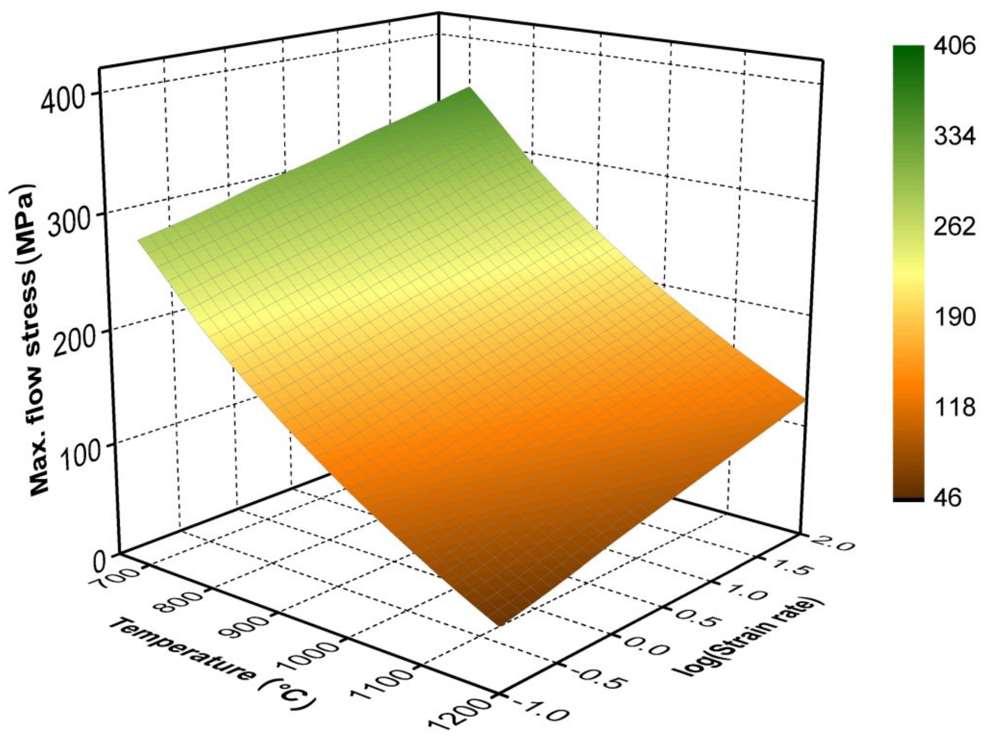


**Fig. 3** 3D-graph of maximum flow stress of the steel P355NH depending on temperature and strain rate

This fact is distinct mainly at the lower strain rates and deformation temperatures (approximately below 900 °C). The reason of this phenomenon can be probably attributed to the stronger precipitation strengthening in case of the steel S355J2H. The maximum flow stresses of the steel S355J2H are in comparison with the P355NH always higher (about 3 % or 5 %) at the temperature above 1000 °C and the nominal strain rate of 20 $s^{-1}$. This difference at the temperature of 700 °C makes even 17 %. The increase of the nominal strain rate up to 100 $s^{-1}$ causes the changes of the maximum flow stress difference. The flow stress of the steel S355J2H is still higher but the difference at 1200 °C makes 11 % and only 3 % at 700 °C. The increase of the maximum flow stress from 12 % up to 17 % was observed at the decrease of the temperature from 1200 to 700 °C in case of the steel P355NH when the value of the nominal strain rate was increased from 20 to 100 $s^{-1}$. In case of the steel S355J2, however, this increase ran from 19 to 3 % at the same temperature decrease. Thus can be said, the inverse trend of the flow stress change occurs under the combined influence of the strain rate and temperature. Certain anomalous flow stress behavior of the steel P355NH at the temperature of 700 °C can be probably linked with the higher content of the ferrite in the structure.

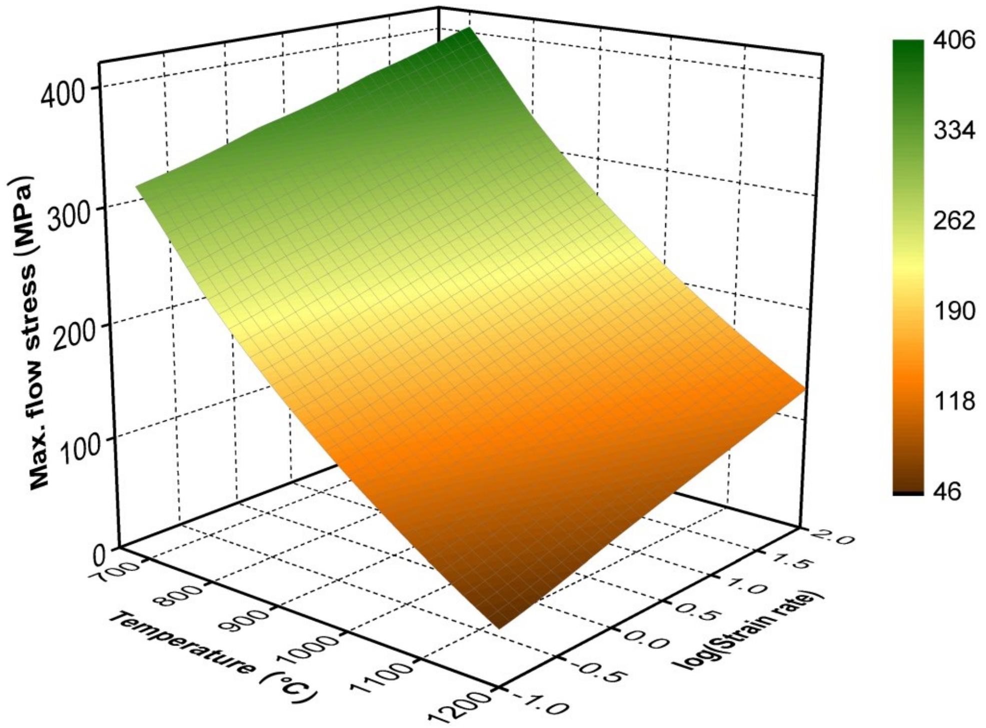


**Fig. 4** 3D-graph of maximum flow stress of the steel S355J2H depending on temperature and strain rate

## 4. CONCLUSIONS

On the basic of the hot compression tests, performed by the Hot Deformation Simulator HDS-20, was possible to obtain the experimental flow stress curves of two microalloyed steels (P355NH and S355J2H) in the temperature range from 700 °C to 1200 °C and the strain rate range from 0.1 $s^{-1}$ to 100 $s^{-1}$. After the necessary shape correction of the recorded flow stress curves were obtained values of the maximum flow stresses and was possible to derive the equations for their prediction in case of both investigated steels. The flow stress of the steel S355J2H was in any cases higher because of higher content of niobium. It was found out, the influence of the decreasing deformation temperature on the flow stress increase have higher sense in case of the steel S355J2H. This can probably occurred because of the stronger precipitation strengthening caused by the higher content of the niobium. The temperature decrease at the strain rate of 20 $s^{-1}$ has been led to the significant increase of the maximum flow stress differences between both steels. Nevertheless, an increase of the strain rate up to 100 $s^{-1}$ has caused that the decreasing temperature led to the significant decrease of the maximum flow stress differences between the examined steels. The increase of the nominal strain rate in case of the steel P355NH caused the significant increase of the maximum flow stress with the decrease of the deformation temperature. In case of the steel S355J2H was, however, increase of the maximum flow stress at the same conditions less apparent. The values of the maximum flow stress can be used to improve the technological process of the seamless steel tubes production by the Mannesmann method to prevent crack occurring in the initial part of the rolled tubes.

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## REFERENCES

[1] Z-Group Steel Holding [online]. [viewed 2015-3-25]. Available from: http://www.steel-holding.cz/

[2] KOLLEROVÁ M., et al. Valcovanie. Alfa: Bratislava,1991.

[3] TUROŇ R., et al. Materiálově-technologický pohled na výrobu a zpracování bezešvých trubek pro zvláštní aplikace. Hutnické listy, Vol. 64, No. 4, 2011, pp. 54-57.

[4] TAMURA I., et al. Thermomechanical Processing of High Strength Low Alloy Steels. Butterworth-Heinemann: London, 2013.

[5] RUSZ S., et al. Fázové přeměny a tvařitelnost vybraných ocelí pro výrobu bezešvých trubek. Hutnické listy, Vol. 67, No. 4, 2014, pp. 26-30.

[6] UNUCKA P., et al. Výzkum technologie výroby bezešvých ocelových trubek pro energetiku. Hutnické listy, Vol. 66, No. 4, 2013, pp. 36-42.

[7] Gleeble Systems [online]. [viewed 2015-3-26]. Available from: http://gleeble.com/products/mcu.html

[8] SCHINDLER I., KAWULOK P. Aplikační možnosti plastometru Gleeble 3800 se simulačním modulem Hydrawedge II na VŠB-TU Ostrava. Hutnické listy, Vol. 66, No. 4, 2013, pp. 85-90.

[9] LI Y. P., et al. Correcting the Stress-Strain Curve in Hot Compression Process to High Strain Level. Metallurgical and Materials Transactions A - Physical Metallurgy and Materials Science Vol. 40A, No. 4, 2009, pp. 982-990.

[10] LI Y. P., et al. Development of Novel Methods for Compensation of Stress-strain Curves. ISIJ INTERNATIONAL, Vol. 51, No. 5, 2011, pp. 782-787.

[11] OPĚLA P., et al. Modely deformačního odporu oceli C45 za tepla. Hutnické listy, Vol. 67, No. 4, 2014, pp. 21-25.

[12] SCHINDLER I., BOŘUTA J. Utilization Potentialities of the Torsion Plastometer. Silesian Technical University: Katowice, 1998.

[13] ZENER C., HOLLOMON J. H. Effect of Strain Rate Upon Plastic Flow of Steel. Journal of Applied Physics, Vol. 15, No. 1, 1944, pp. 22–32.

[14] SCHINDLER I., et al. Vliv výpočetní metody na hodnotu aktivační energie aluminidu železa při tváření za tepla. Hutnické listy. Vol. 65, No. 4, 2012, pp. 55-59.

[15] KUBINA T., et al. A new software calculating the activation energy. In Forming 2005: 12th International Scientific Conference. Ostrava: VŠB-TUO, 2005, pp. 145-150.