FATIGUE BEHAVIOR OF HOT-ROLLED STEEL INTENDED FOR COLD FORMING

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Resume

In the work, there are presented measured tension and fatigue properties of eight low-carbon steels moulded in form of 20 kg ingots that were processed by controlled regime of rolling /cooling and then exposed to simulated effect of two coiling temperatures. The experimental results presented in the work show, that steels with ferrite-martensite or ferrite-bainitic microstructure have in comparison to ferrite-pearlitic or ferrite-carbidic microstructure better strength-plastic properties, but worse resistance to cyclic loading.

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1. Introduction

Lately, there was dramatic increase in use of high or ultrahigh strength steels in automotive industry. The main reason for this increase is the fact that with these steels it is possible to obtain generally required decrease in weight of cars without decrease in comfort or safety of passengers. Dual phase steels (DP steel) are the most used steels, from the group of low-carbon and low-alloyed steels, however, the steels with transformation induced plasticity (TRIP) have the best strength-plastic properties.

By comparison of properties of these steels, we can claim, that TRIP steels have significantly higher ductility only at strength Rm ≥ 700 MPa, i.e. at ultrahigh strength steels [1, 2]. In principle, all steels with Rm ≥ 500 MPa contain some amount of silicium and in case of most widespread TRIP steel silicium with manganese are base alloying components. Positive effect of increase in Si content on parallel increase in strength and ductility was observed at TRIP steels, but also at bainitic steels. On the other hand, increased content of Si in steel strip can negatively affect quality of sheets surface (surface defect type of a tiger-striped scale pattern known as “red scale“), what causes problems at surface adjusting, as well as at cutting of strips with laser [3]. DP steels developed in 80s also contained Si and for above-mentioned reasons did not find broader practical application.

This aspect was taken into consideration at project application, that now is being solved by UMV SAV Košice in cooperation with US Steel Košice s.r.o.. The project is oriented on development of novel low carbon non-silicium ultra high strength steel, primary aimed for automotive industry. In the project, there were proposed steels with different chemical content, processed by different regimes of controlled rolling/cooling, and subsequently exposed to combined effect of cold-rolling with chosen processes of heat treatment. The main aim of the experiments was to find an optimal state of microstructure with balanced ratio of strength-plastic and fatigue properties for particular chemical compositions of steel sheets.

The aim of this contribution is to present the results of experiments, where the effect of chemical composition and coiling temperatures of hot rolled sheets on fatigue resistence of steels were examined.

2. Experimental methods and materials

Experiments were made on eight model steels moulded in form of 20 kg ingots in laboratory. Different chemical conceptions were examined, they were marked as No 1-8 (Table 1).

Table 1

Nominal chemical composition of steels

Steel No.	Composition
1	0.07C-1.5Mn-0.02Si-0.25(Mo+Ti)
2	0.07C-1.90Mn-0.02Si-0.25(Mo+Ti)
3	0.15C-1.2Mn-0.02Si
4	0.15C-1.2Mn-0.02Si-0.15Mo
5	0.15C-1.2Mn-0.02Si-0.25(Mo+Ti)
6	0.15C-1.20Mn-0.02Si-0.3(Mo+Ti)
7	0.15C-1.2Mn-0.02Si-0.50Cr
8	0.15C-1.2Mn-0.02Si-0.25(Mo+Ti)-0.5Cr

The samples, 33mm x 75mm x 100mm, were made from the ingots, that were heated-up to temperature t = 1230°C, holding time 45 min, then were by four passings rolled to thickness $3{,}6^{\pm 0{,}5}$ mm. Finish rolling at temperature t=800°C was followed by laminar water cooling of samples to temperatures $t_{coiling}$ = 680, 580, 480 °C, 20 °C then they were transfered to furnace, the same temperature as $t_{Coiling}$ for 45 min (simulation of coil cooling). In this work, the results of tensile and fatigue tests at samples with $t_{Coiling}$ = 680 °C (set “A“) and 20 °C (set “D“) are presented.

The samples 2,5x10x90 mm with hole in the center having drill diameter d= 1mm (stress concentration factor K_t = 2,73 estimated by [4]) were used for fatigue tests.

Fatigue tests were made in conditions of plane bending at frequency f = 25 Hz and stress ratio $R = \sigma_{min}/\sigma_{max} = -1$.

3. Results and discussion

Microstructure of samples from steels 1-5 (Table 1) was in details analyzed in our two previous works [5, 6] and similar effect of decrease in coiling temperatures $t_{Coiling}$, was observed also at steels 6-8. Total structural heterogenity was decreasing parallel with decrease in $t_{Coiling}$ at all observed steels and at $t_{coiling.} \leq 570$ °C there was observed presence of bainite (B) and in some cases tempered martensite (M). More or less, all steels were characterized by line structure of particular structural components. All steels had fine-grained microstructure, however size of a ferritic grain range widely (e.g. steel 4, grain size lower than 1μm, but also grain size up to 9 μm). Average grain size of Mo+Ti alloyed steels ranges between 4,1 μm to 4,7 μm.

Increased content of Mn has significant effect on morphology, also on different microstructral composition of steels 1 and 2 at all coiling temperatures, mainly $t_{Coiling}$ = 670 °C. Distribution of carbides and carbonitrides Ti and Mo observed in ferrite matrix at steel 2A in comparison to steel 1A had higher dispersity and more equal distribution.

Table 2

Mechanical properties of steels ($t_{coiling}$ = 670 °C)

Steel	R_{eL} [MPa]	R_m [MPa]	$R_{p0.2}/R_m$	A_5 [%]	$R_m x A_5$ [MPa.%]	$\sigma_a/10^5$ [MPa]
1A	498	539	0.92	24.0	12936	392
2A	443	651	0.68	24.0	15624	424
3A	398	456	0.87	32.5	14820	352
4A	412	467	0.89	33.0	15411	365
5A	527	575	0.92	18.0	10350	408
6A	663	679	0.98	20.0	13580	474
7A	415	483	0.86	31.0	14973	354
8A	545	592	0.92	29.0	17168	421

In agreement with microscopical observations, tensile properties of steels were discovered. These are together with measured data of other steels listed in Table 2. As we can see in Table 2, both steels have the same ductility, but steel 2A has in contrast to steel 1A higher strength, by approximately 110 MPa.

Steels 3A, 4A and 7A, which do not contain Ti, have the lowest values of yield stress and strength. In this group, steel alloyed by chrome (7) has the highest strength and the lowest ductility. By comparing values of steels 5 and 6, R_{p02} and R_m to steels 3 and 4, we found out that, by effect of Mo +Ti alloying, steels 5A and 6A have higher values $R_{p0,2}$ by approximately 130 MPa, or by $115^{\pm5}$ MPa higher R_m. How it is usual observed, also data in Table 2 show, that increase in strength characteristics is connected with decrease in ductility. Of the all steels, steel 6A has the highest strength, but steel 5A has the lowest ductility. Steel 8A has the best combination of strength-plastic properties, as the highest product was calculated, $R_m x A_5$ = 17168 MPax% (Table 2).

Absence or limited contribution of precipitance strengthening on the one hand, formation of structural components corresponding to non- or semi-diffusion transformation of austenite (martensite, bainite) on the other hand are characteristical signs of structural changes, that were observed at $t_{Coiling} \le$ 570 °C. As we can see in Table 3, extent of effect of both above-mentioned processes at $t_{Coiling} \le$ 22 °C is significantly affected by relatively small change in chemical composition of steels. Yield stress limit of steel 1D (1,5 % Mn) in comparison to steel 2 (1,9 % Mn) was decreased by 100 MPa and strength was decreased by 60 MPa. At the same time results in Table 3 show that values $R_{p0,2}$ and R_m for steel with higher content of Mn are higher by cca 60 MPa. Values $R_{p0,2}$ of other steels measured at samples after simulated coiling, $t_{Coiling}$ = 22 °C against $t_{Coiling}$ = 670 °C are lower by 22 MPa (steel 8D) to 79 MPa (6D) (Table 2 and Table 3).

In contradiction to that, decrease in $t_{Coiling}$ caused at all steels (except for 1D) increase in values of R_m. In comparison to steels 1-3 this increase was more significant at steels 4-8, in range 182 (5D) to 328 MPa (4D). From calculated values of products R_m x A_5 listed in Table 2 and Table 3 we found out, that they were at the same level (except for steel 8) and values $R_m x A_5$ even increased parallel with increase in hardness of samples caused by decrease of $t_{Coiling}$ at steels 1, 3, 5.

Table 3

Mechanical properties of steels ($t_{coiling}$ = 22 °C)

Steel	$R_{p0.2}$ [MPa]	R_m [MPa]	$R_{p0.2}/R_m$	A_5 [%]	$R_m x A_5$ [MPa.%]	$\sigma_{a,10^5}$ [MPa]
1D	396	598	0.66	25.3	15129	380
2D	457	661	0.69	23.0	15203	395
3D	434	528	0.82	29.5	15576	389
4D	367	795	0.46	18.0	14310	392
5D	483	757	0.64	16.0	12112	468
6D	584	874	0.67	17.5	15295	487
7D	353	694	0.51	20.0	13880	389
8D	523	905	0.58	13.5	12218	425

For comparison, ductility properties of samples after rolling at $t_{Coiling}$ = 20 °C and samples at $t_{Coiling}$ = 670 °C are graphically displayed in Fig. 1.

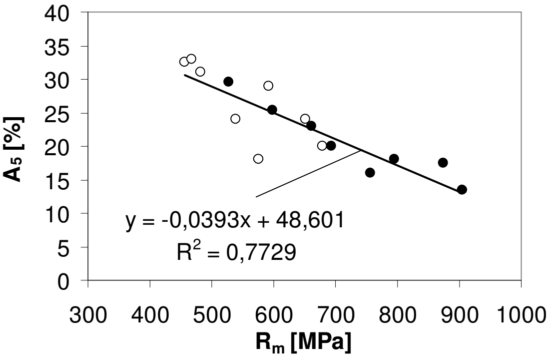

Fig.1 Dependence of ductility on tensile strength of steels (open symbols – samples with $t_{coiling}$ = 670 °C and full symbols – samples with $t_{coiling}$ = 20 °C)

The results presented in this figure clearly show, that samples with lower temperature $t_{Coiling}$ have better strength-plastic properties and also confirm well-known fact that DP steels have in comparison with other steels better plasticity, at the same hardness.

Fatigue properties of DP steels do not usually have such good properties [7] and it was also confirmed by results of this work. Resistance of steels against failure during cyclic loading was evaluated by value of stress amplitude that causes failure of samples after

10^5 cycles. The values of fatigue strength given by this criterion ($\sigma_a/10^5$) of all examined steels are listed in Table 1 and Table 2. In contrast to samples with simulated temperature $t_{Coiling}$ = 22 °C, at samples with $t_{Coiling}$ = 670 °C it was discovered that it is possible to predict fatigue strength with relatively high correlation coefficient (R^2 = 0,93) from values R_m (Fig. 2).

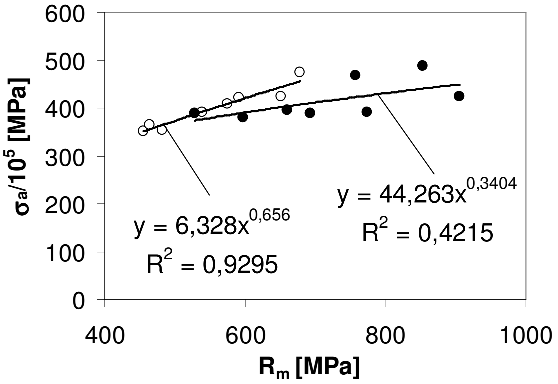

Fig.2 Dependence of fatigue strength on tensile strength of steels (full symbols – samples with $t_{coiling}$ = 20 °C)

If we take into consideration all data listed in Table 2 and in Table, we can observe better correlation between values $\sigma_a/10^5$ and values of hardness than between $\sigma_a/10^5$ and Rm. However, value of correlation coefficient reach here only level R^2 = 0.72 (Fig. 3).

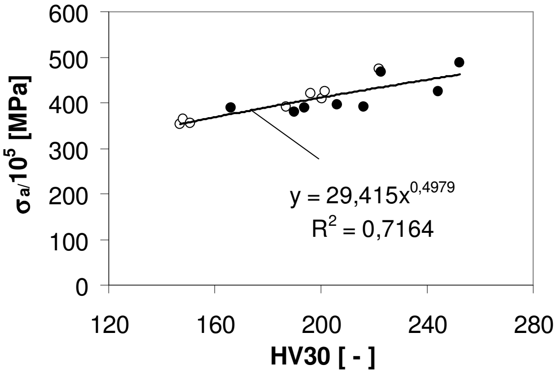

Fig.3 Dependence of fatigue strength on hardness of steels (full symbols – samples with $t_{Coiling}$ = 20 °C)

It was confirmed, that fatigue properties of steels are controlled by structural component with lower resistance against variable loading and are significantly affected by distribution of local stress [7]. Microstructure that contains structural components with significantly different hardness we can consider as very disadvantageous. It is supported by results of steel 8, where previous microstructure that contains ferrite + carbide was changed by decrease in $t_{Coiling}$ to structure ferrite + martensite. As the result, hardness increased from value Rm = 592 to 905 MPa, however, fatigue strength did not change ($\sigma_a/10^5$ = 421 and 425 MPa). Advantage is the structure, where hard martensite coexist with precipitation strengthen ferrite. The highest values of fatigue strength $\sigma_a/10^5$ = 468, or 487 MPa were measured at steels type 5D and 6D (Table 3).

4. Conclusions

Experimental results and presented discussion in the work lead to this conclusion:

- We can expect better strength-plastic properties but relatively worse fatigue resistance at steels with ferrite-martensite microstructure in comparison to steels with other structural conditions.
- In the work, it was shown, that fatigue resistance of dual phase steels can be increased by precipitation strengthening of ferrite matrix.

Acknowledgements

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