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Microstructure and selected properties of Mn-Al duplex steels

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ABSTRACT

Purpose: Automotive industry constantly demands high-strength steels which are characterized by the energy absorption possibilities during a collision. Such materials may, in the future, replace the currently used conventional steels. The groups of steels which meet these criteria are the austenitic steels and austenitic-ferritic steels with high manganese content (15-30%) and high aluminium content (1-6%).

Design/methodology/approach: The influence of the chemical composition on the mechanical properties of steel with high carbon, manganese and aluminium concentration was analysed in this paper. Moreover, the susceptibility of those steels to hot deformation was assessed in plastometric tests.

Findings: The conducted research enabled the optimisation of the chemical composition of duplex steels and manufacture of steel with favourable relation of strength to ductility.

Practical implications: The obtained steel is characterised by beneficial properties which outbalance the austenitic steels type TWIP and may be applied in vehicle construction on elements connected with safety.

Originality/value: The achieved results will be used to develop a technology of thermomechanical treatment of duplex steels.

Keywords: Metallic alloys; Microstructure; Mechanical properties

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MATERIALS

1. Introduction

Application of new, high-strength steels with high formability in automotive industry leads to substantial decrease of vehicle weight. At the same time we can observe improvement of safety during crash, thanks to high absorption of energy which the elements made of such steel feature. High-manganese austenitic steel, in which research centres are currently interested, is characterised by extremely high formability and substantial strength. Capability of energy absorption is also much bigger in this case in comparison with conventional steels. Such a set of features can be explained by the presence of alternative deformation mechanisms, such as: creation of twins (TWIP effect), phase transitions produced by strain (TRIP) and plasticity induced by shear bands [1-9].

TWIP steels contain 20-35% manganese, 3-9% aluminium and/or up to 6% silicon (in mass %) Carbon content in total does not exceed 0.003-0.6%.

Wide application of TWIP steels is hindered by difficulties connected with their production and processing. Development of this group of steels, implementation to large-scale production and application as structural material is conditioned by improvement of their plasticity in room temperature and hot processing. By proper selection of chemical composition, modification of initial microstructure, grain refinement and application of suitable thermal and plastic working, it is possible to obtain optimum connection of mechanical and plastic properties. Moreover, the procedure of materials selection for automotive industry requires tests of mechanical properties as a function of strain rate, because at high strain rates, typical for car crash, mechanical strength is substantially changed [10-14].

Currently at the Silesian Technical University tests of new steel with high content of manganese and aluminium or silicon designed for constructional elements for automotive industry, are carried out .

This article presents the results of tests of microstructure and mechanical properties of steel Mn-Al with duplex austenitic-ferritic microstructure. It was proved that the tested steels are characterized by good sustainability to hot deformation in temperature range 1100-900°C. It was stated here that there exists a beneficial relationship between the strength properties to plastic properties in case of duplex steels type X60MnAl30-9 and X50MnAl25-9 in comparison to steels of single-phase structure.

2. Materials for research and methodology

In the first stage of research, 5 laboratory melts were made with different relation of C-Mn-Al. The chemical composition was selected on the basis of Schaeffler diagram with the assumption of duplex austenitic-ferritic microstructure. Ingots size 20x30 mm and the length of 120 mm were smelted in a vacuum furnace. The chemical analyses were conducted with the use of emission spectrometer. The chemical compositions of the laboratory melts of the tested steels were presented in Table 1.

Table 1.
Chemical composition of laboratory melts of tested steels, [%] of mass

Number of melt	C	Mn	Al	Si
1.	0.15	28.8	9.1	0.15
2.	0.30	23.2	7.2	0.22
3.	0.50	24.0	9.1	0.29
4.	0.46	28.2	8.7	0.16
5.	0.60	29.5	8.9	0.35

The process of hot forging was conducted on a forging hammer in temperature range of 1150-900°C with the use of draft of 10-15%.

In order to assess the formability of steel a SICO (Strain Induced Crack Opening) test on Gleeble simulator was conducted. The SICO test is based on heating the middle area of the sample of a circular section and size ϕ10×86.4 mm to a given assumed temperature and next on deformation by compression. During the compression the middle area is very intensively influenced by plastic flow. When a limit of deformation is reached the cracks may be initiated. The test was conducted in the temperature of 800-1100°C, with the use of maximum displacement of the tool of 15mm with the speed of 50 mm/s. For samples after forging, a static tension test and impact resistance test were conducted with the use of samples with notch ISO V.

The samples from analysed steels were deformed on Gleeble simulator in temperatures of 900 and 1100°C with the strain rate of 1 s^{-1} in conditions of uniaxial compression. Samples after casting and hot forging were tested in order to check their microstructure, the relation of each of the phases was determined with the use of quantity metallography.

In the second stage of the research a manufacturing technology of high-manganese steel with required chemical composition was developed for the process of smelting and casting in vacuum inductive furnace VSG-50 by Balzers. In order to homogenize the chemical composition an additional joint penetration was used. During smelting boron was added in quantity of 0.001% and mischmetal in the amount of 1g/kg of metal. This metal was casted to sand casting mould with draft of 4° in order to eliminate maximally the casting defects. The following ingots were achieved: sizes bottom ϕ30 mm, top ϕ45 mm, height 400 mm.

The ingots were hot rolled to achieve rods with diameter of ϕ15 mm on hot rolling mill duo in TU Bergakademie in Freiberg. Before the deformation, the ingots were annealing in 1150°C for 2 hours. Next, rolling was conducted in eight operations. The finishing temperature of rolling was 950-900°C.

Following the casting and hot working a microstructural analysis was conducted on the axis-parallel section of the sample, using bright field optical microscopy. The microstructure was detected by chemical etching in a 10% nital solution. Observation of the structures was conducted on an Olympus GX51. A quantitative evaluation of the structure was conducted using the METILO programme. The surface fraction A_A [%] of ferrite or austenite was detected.

3. Results

The primary microstructures of the samples of alloys after casting are shown in Figs. 1-5. The tested material has dendritic microstructure of ferritic-austenitic type (Fig. 1). The tested steels No. 2-5 with a various amount of dendritic austenitic-ferritic microstructure are shown in Figs. 2-5.

Samples marked with number 3 and 5 in a condition after casting were tested with SICO test according to the described methodology. The diagram of dependencies of the recorded force as a function of strain for steel marked with number 5 (Table 1) is shown in Fig. 6. An intensive decrease of working force was observed when the temperature of the trial rose. For given temperatures, the force initially rises, and at strain ε of about 2 stabilises on a constant level which signifies a stable flow of metal. Visual examination of samples after SICO test show that the steel has good deformability in temperature range of 900-1100°C (Figs. 7 a, b). Insignificant cracks on the side surface were noticed after deformation in temperature of 800°C.

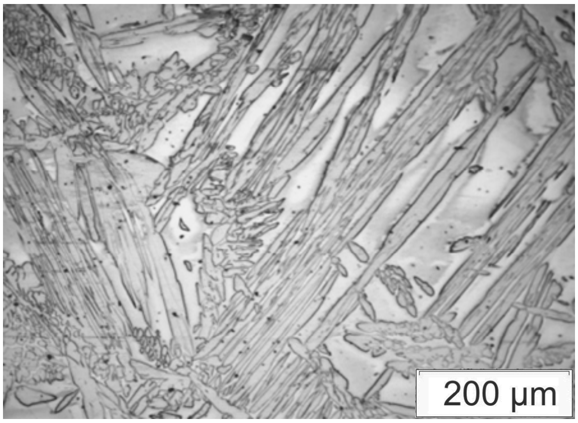


Fig. 1. Primary microstructure of ferritic-austenitic type of a sample after casting from melt 1 (Table 1)

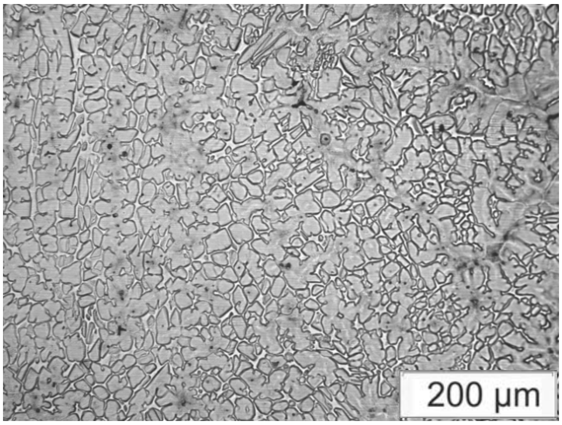


Fig. 2. Primary microstructure of austenitic-ferritic type of a sample after casting from melt 2 (Table 1)

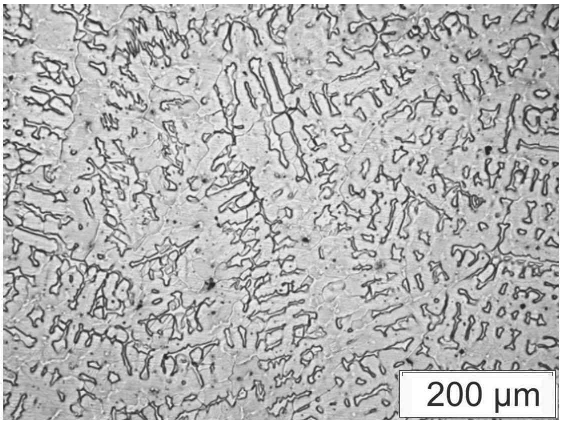


Fig. 3. Primary microstructure of austenitic-ferritic type of a sample after casting from melt 3 (Table 1)

The conducted tests of forging confirmed the results achieved in the SICO tests. A good susceptibility to formability was stated for tested steels in temperatures 1150-900°C.

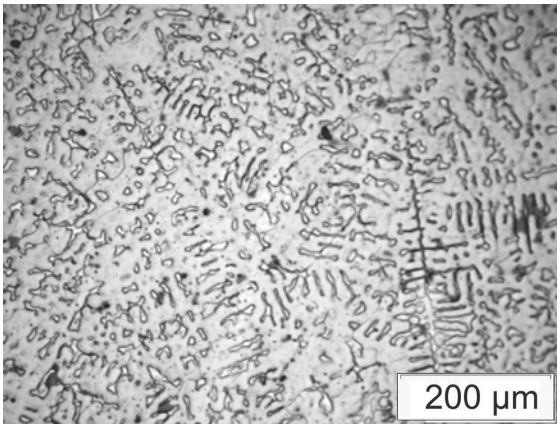


Fig. 4. Primary microstructure of austenitic-ferritic type of a sample after casting from melt 4 (Table 1)

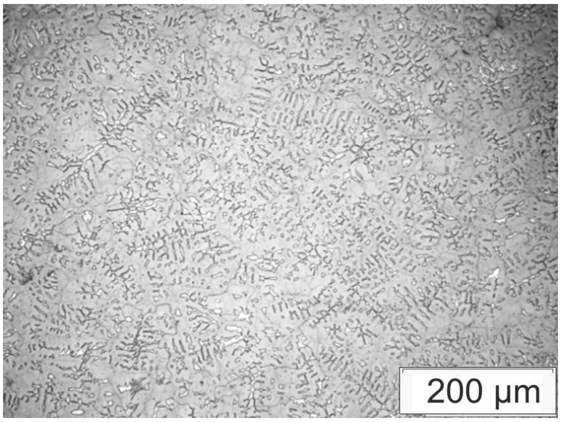


Fig. 5. Primary microstructure of austenitic-ferritic type of a sample after casting from melt 5 (Table 1)

Lowering the temperature below 850°C caused the initiation of cracks on the surface of forgings.

Mechanical properties of the tested steels marked in static tensile test, impact resistance and hardness measurements results were shown in Table 2. Steel from melt No. 3 - UTS = 995MPa - has the highest strength properties. Steel No. 5 has strength less strength to tension (UTS = 920MPa), but has the lowest elongation to rupture (A_5 = 35%). Tested steels No. 1, 2, 4 had lower strength properties UTS = 650-850MPa with elongation A_5 from 15 to 20%.

Table 2.
Mechanical properties of tested steels after hot rolling

Steel	$YS_{0.2}$ [MPa]	UTS [MPa]	A_5 [%]	KCV [J/cm^2]
X50MnAl24-9 (No. 3)	880	1050	22	260
X60MnAl30-9 (No. 5)	790	950	35	290
X50MnAl25-5	370	720	45	300

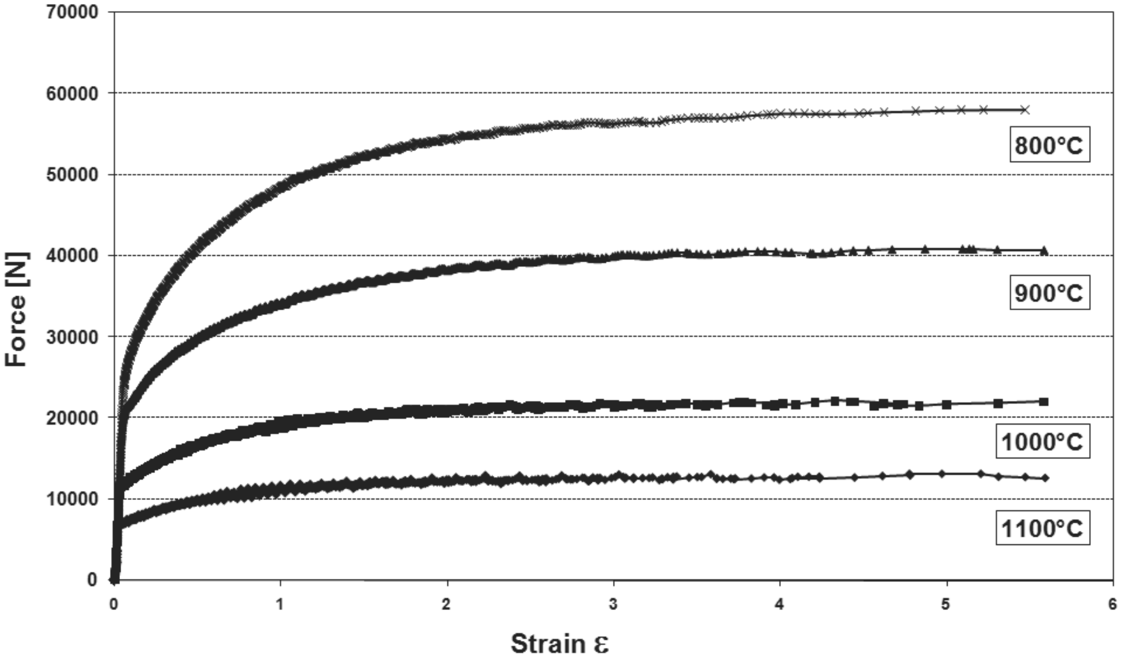


Fig. 6. The force registered in temperature function and strain for samples after SICO test from melt No. 5

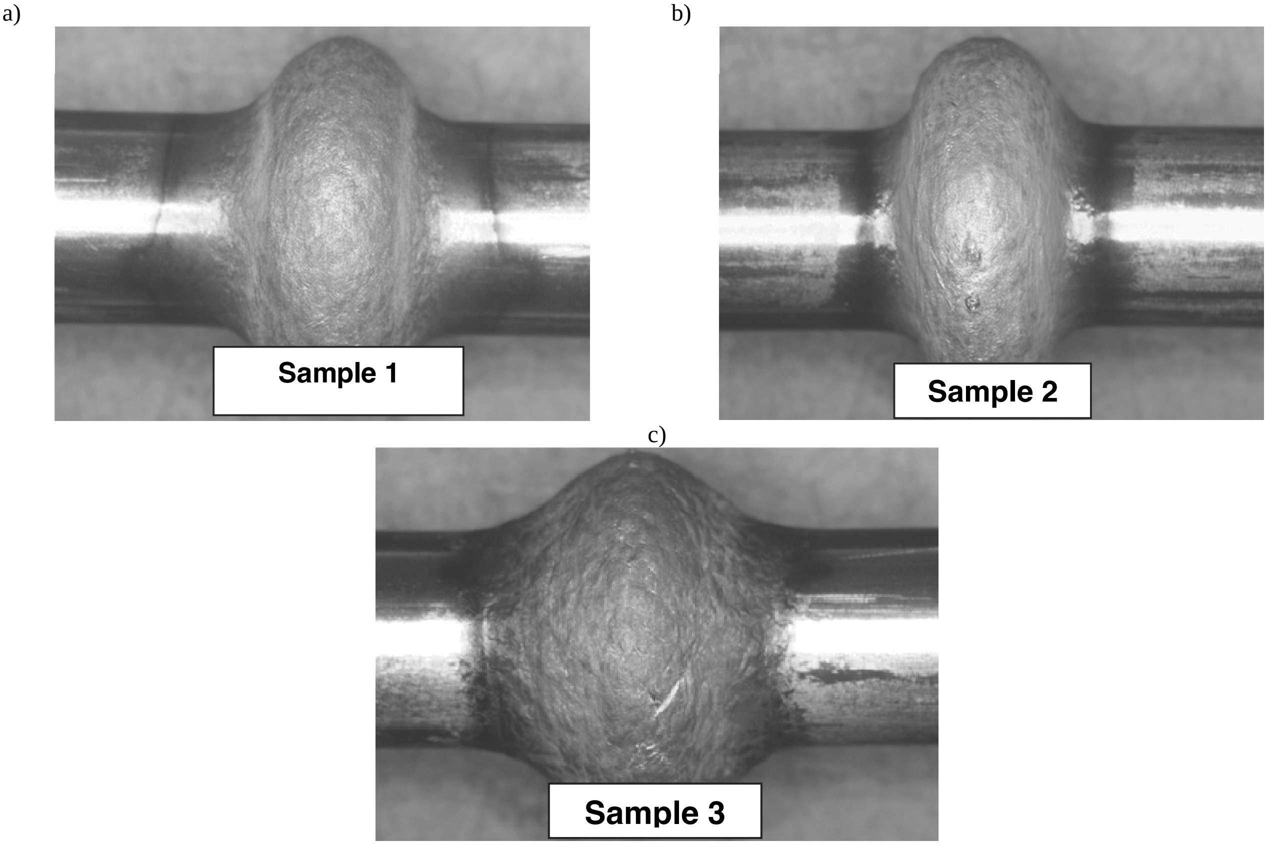


Fig. 7. View of samples after strain in SICO test; a) deformation at 1000°C, b) deformation at 900°C, c) deformation at 800°C

Microstructures of tested steels after forging are shown in Figs. 8-12. The measured part of ferrite phase in microstructure is presented in Table 3. Samples of tested steels had a austenitic-ferritic microstructure with varied content of those phases. It was proved, that the processes undergoing during forging have removed the primary dendritic structure. A regular layout of the ferrite islands in austenite matrix or the opposite on case of melt No. 1 was observed (Table 3).

Table 3.
Phase composition and mechanical properties of tested steels after hot forging

Number of melt	A_A [%ferritic]	$YS_{0.2}$ [MPa]	UTS [MPa]	A_5 [%]	KCV [J/cm^2]
1.	80	540	650	20	260
2.	22	690	850	15	230
3.	40	790	995	19	220
4.	26	650	850	26	240
5.	15	750	920	35	280

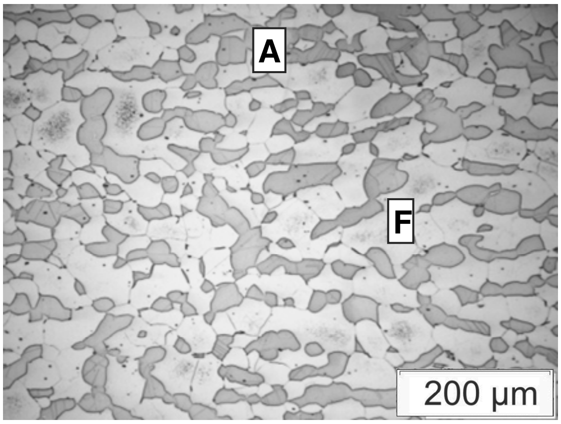


Fig. 8. Microstructure of steel no. 1 after forging and annealing in temperature of 900°C for 60 minutes

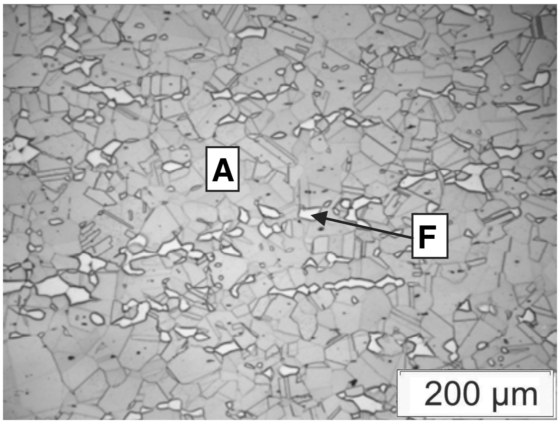


Fig. 9. Microstructure of steel no. 2 after forging and annealing in temperature of 900°C for 60 minutes

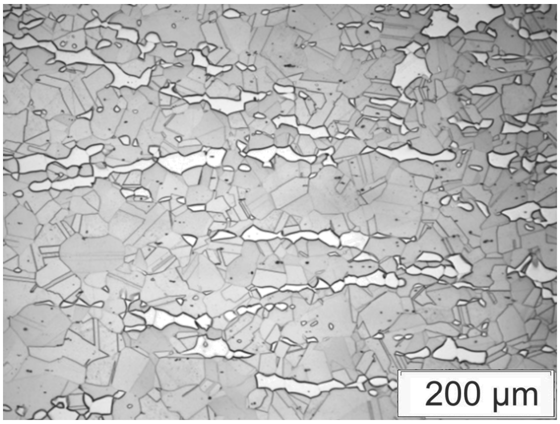


Fig. 10. Microstructure of steel no. 3 after forging and annealing in temperature of 900°C for 60 minutes

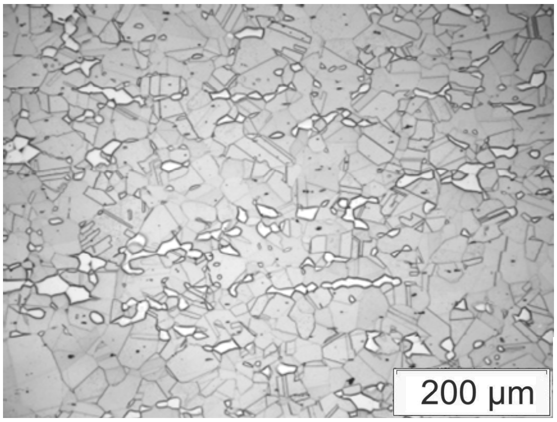


Fig. 11. Microstructure of steel no. 4 after forging and annealing in temperature of 900°C for 60 minutes

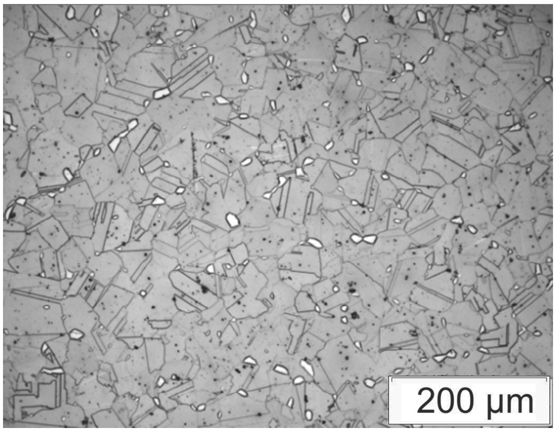


Fig. 12. Microstructure of steel no. 5 after forging and annealing in temperature of 900°C for 60 minutes

Characteristics of plasticity of tested steels in conditions of uni-axial compression in temperatures of 900 and 1100°C are shown in Figs. 13a, b. The achieved characteristics have shown the increase of drag of flow with the decrease of ferrite content in the microstructure. The lowest level of stress was observed in the microstructure of steel No. 1 of the highest content of ferrite. A characteristic decrease in stress was visible in connection with dynamic recrystallization of austenite for samples from tested steels after exceeding the maximum on the flow curve. Such effect decreases with the increase of the amount of ferrite in microstructure which means the higher workability to dynamic recovery.

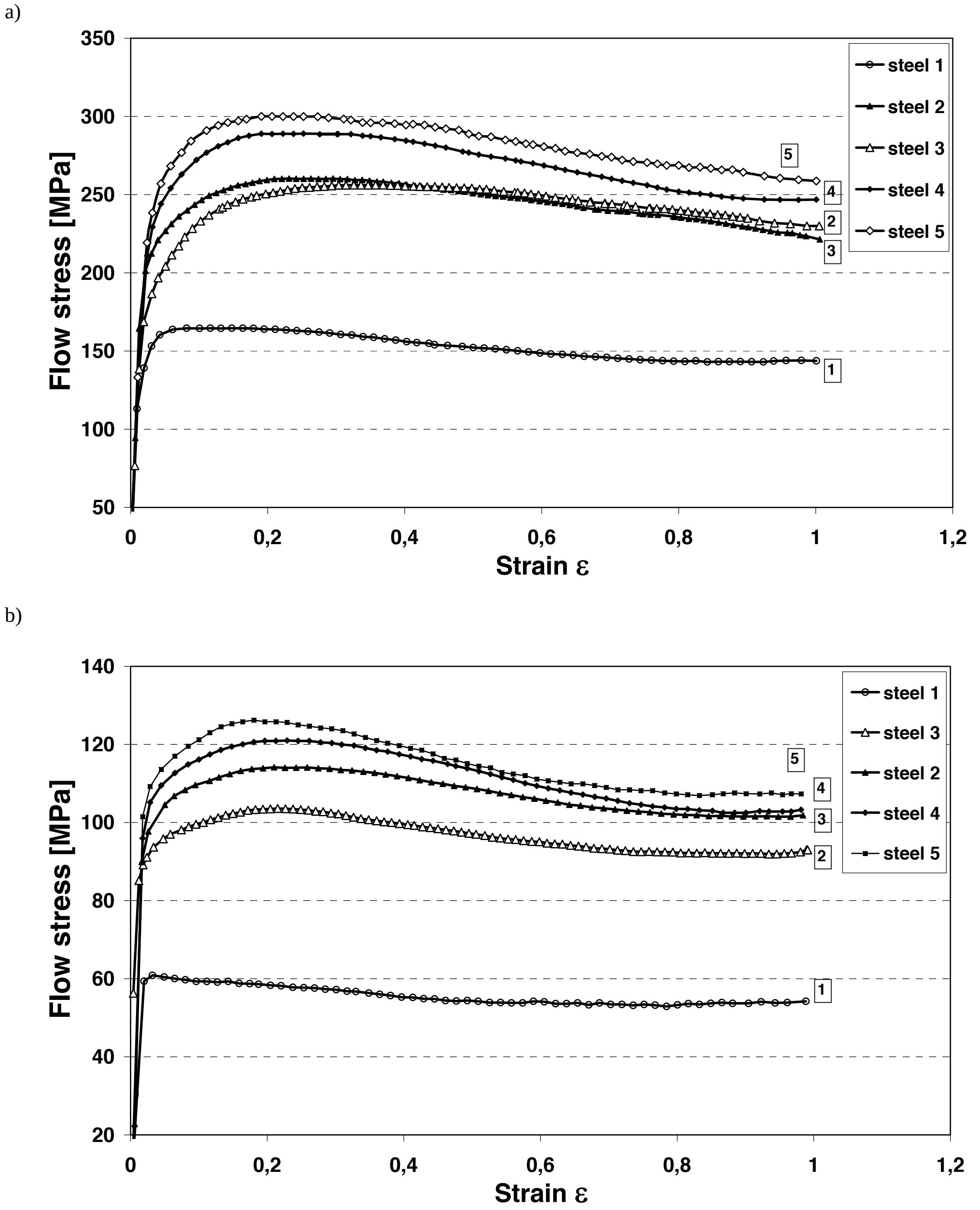
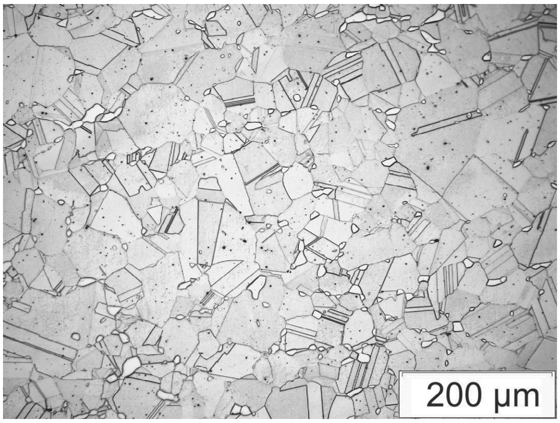


Fig. 13. Characteristic of plasticity of investigated steels after deformation at 900°C and 1100°C with a rate of 1 s^{-1}

On the basis of the achieved research results from laboratory melts, steels No. 3 and 5 were chosen for further tests. Mechanical properties defined for samples from rolled rods created in the second stage of test show the further improvement of mechanical properties (Table 2). Steel X60MnAl30-9 (No. 5) had a similar chemical composition to the steel presented in the work [15]. Microstructure of X60MnAl30-9 steel after hot rolling was presented in Figures 14 a (transverse section), and b (longitudinal section).

a)



b)

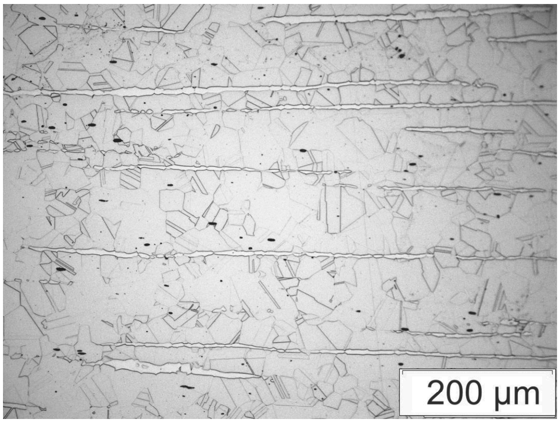


Fig. 14. Microstructure of X60MnAl30-9 steel after rolling and annealing at 1100°C was presented in Figure 14 a (transverse section) and b (longitudinal section)

Steel X50MnAl24-9 (No. 3) has the highest strength (UTS=1050 MPa), but with smaller elongation A_5=22%. In order to compare it, the table also presents test results of mechanical properties for austenitic steel type X50MnAl25-5, conducted in the same way, the details of which may be found in paper [16].

4. Discussion

The increase of concentration of carbon and aluminium influences the strength of high-manganese steel, as a result of solid solution consolidation. The quantity ratio of the existing phases is also very important. It is visible particularly in the analysis of the properties of steels from melts 3 and 4. Steel containing about 40% of ferrite has the highest strength. In steel from melt 5 the highest plasticity was achieved.

The presence of ferrite in the amount of 10-20% seems to be the most appropriate in strength – ductility relation for this group of steels. Data, presented in Table 3, show that strength properties of austenitic-ferritic steels surpass the steels with austenitic microstructure. In case of steel X60MnAl30-9 a slightly smaller elongation (about 10%) in comparison to steel X55MnAl25-5 was observed.

SICO tests of deformability conducted on a simulator and forging tests show good workability of tested steels to hot plastic working in temperature range of 1150-900°C.

5. Conclusions

This article presents a part of the results of conducted works connected with research on high-manganese steels and their potential possibilities of use in automotive industry. Such steels are expected to possess a beneficial relation of resistance properties to plastic properties. The article [16] shows that the product of resistance and elongation should equal 50 000 MPa × %. Such assumption is met particularly for steel type X60MnAl30-9. A technology of steel making, refining and casting for this steel group was worked out. A good liability to hot plastic working was indicated. It gives the possibility to create construction elements of a vehicle connected with safety. In further papers on the topic it is planned to conduct experiments connected with the assessment of the steel properties during deformation realised with a high speed, which shows the conditions during a crash.

Acknowledgements

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