

Effect of Aluminium and Manganese Contents on the Microstructure Development of Forged and Annealed TRIP Steel

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Three low carbon steels with 1.5 and 3%Mn and either 1.5%Al or 2%Al were forged from cast ingots into bars using various heating temperatures and deformation conditions. Bars were heat treated by annealing at 950 °C to gain homogenized input materials for subsequent experiments. The effect of various austenitization temperatures and holds in the region of 800 -1200 °C was tested with regard to the final microstructure and hardness development. Hardness in the region of 320-550 HV 10 was obtained. The highest hardness was for all austenitizing temperatures achieved for 1.5Al3Mn steel and it decreased with decreasing manganese to aluminium content ration. This concentration ratio determined transformation behaviour and subsequently also formability of these three steels. Increase of this ratio to 2 for 1.5Al3Mn steel resulted in high tendency to cracking during forging at 1150°C and generally to the shift of phase transformations to lower temperatures and longer times.

Keywords: Manganese, Aluminium, TRIP steel, Forging, Annealing

1 Introduction

Demands for continuous improvement of mechanical properties of steels determined for application in automotive industry resulted in the last two decades in development of several new grades of advanced high strength steel (AHSS) which are using beneficial effect of controlled amount of retained austenite in the final microstructure. Typical example of the AHSS of the first generation were low carbon low alloyed TRIP (transformation induced plasticity) steels with a multiphase microstructure consisting of ferrite, bainite and retained austenite. They reached strengths around 800 MPa with total elongations of 30-40%. Low amounts of manganese (1-2 weight %) are used in TRIP steels to support stabilization of retained austenite, which can gradually transform to martensite during cold plastic deformation [1-4]. Tensile strength was significantly improved by steels with a martensitic matrix with thin films of retained austenite formed along martensitic laths. These medium carbon low-alloyed steels were produced by quenching and partitioning (QP) method. Their high strengths were close to the as-quenched steel of the same chemical composition, reaching 2000 MPa, however total elongation was increased to circa 15% [5-7]. The search for new steel grades with yet better combination of high strength and elongation resulted in development of high manganese AHSS steels of the second generation. Manganese contents around 20 % are used to ensure stabilization of high fractions of retained austenite, which improves mechanical properties by exhibiting TWIP (twinning induced plasticity) effect [8, 9]. Interesting mechanical properties of these steels are however achieved at a cost of rather expensive alloying and therefore the third generation of AHSS aims to develop new steel grades, which will enable similar mechanical properties with leaner alloying concepts. One of the promising ways to achieve this goal seems to be the development of AHSS with increased manganese contents, which will be kept below 10% [10].

A second trend in development of AHSS is decreasing the weight of the final parts not only by increased strength

of the steel, but also by purposeful alloying by light substitutional elements, such as aluminium. This type of low-density steels is combining various amounts of medium to high manganese contents with aluminium contents around 5-7% [11,12]. The formability of these steels is mainly troublesome due to the formation of brittle intermetallic at grain boundaries and depends strongly on chemical composition, mainly on the ration of carbon, manganese and aluminium. Aluminium alloying started to be used few years ago also in low alloyed TRIP steels as a replacement of silicon [13, 14]. Aluminium can ensure solid solution strengthening and suppression of carbide formation nearly as well as silicon, but does not share its deterioration effect on the surface quality. Presence of silicon oxides on the surface of TRIP steel parts caused problems with subsequent hot dip galvanizing, which aluminium alloying prevents [4, 14].

This work deals with two low carbon steels with 3% of manganese and two different amounts of aluminium, either 1.5% or 2%. Both of these alloying elements are therefore slightly above the values typically used for TRIP steels, yet bellow the amount used in high manganese or low-density steels. As a reference material, a third low carbon steel with 1.5% of manganese and 1.5% of aluminium is used as a typical example of advanced TRIP steel with partial substitution of silicon by aluminium.

2 Experimental program

Two low carbon experimental steels varying only in the aluminium contents were used for the experimental program. The steels are further alloyed by 3% of manganese to support retained austenite stabilization. The third low carbon low alloyed steel with 1.5% of manganese and 1.5% of aluminium was used as a reference material with chemical composition typical for TRIP steels. Lower amount of silicon was kept to increase solid solution strengthening, as the effect of aluminium is slightly weaker. It was documented in low alloyed TRIP steels that complete replacement of silicon by aluminium resulted in significant drop of tensile properties. The steels

were further micro-alloyed by niobium which proved to have a positive effect on postponing pearlite [15] trans-

formation during the cooling thus enabling the application of slow cooling rates without the risk of undesirable pearlite formation.

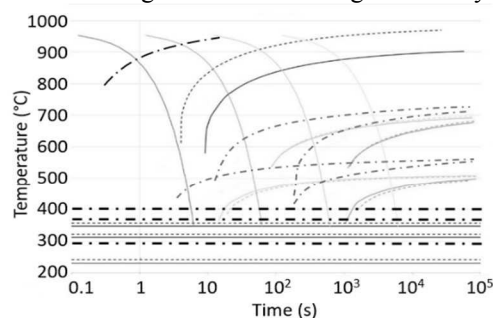
Tab. 1 chemical composition of experimental steels in weight %

	C	Si	Mn	P	S	Cr	Al	Nb	Mn/Al ratio
1.5Al - 3Mn	0.2	0.6	3.0	0.008	0.003	0.19	1.5	0.06	2
2 Al - 3Mn	0.2	0.6	3.0	0.008	0.003	0.17	2.0	0.06	1.5
1.5Al -1.5Mn	0.2	0.6	1.5	0.008	0.003	0.19	1.5	0.06	1

CCT (continuous cooling transformation) diagrams of all three steels were calculated in JMatPro software (Fig.1). Increase in aluminium content by only 0.5% resulted in a shift of ferrite transformation areas to shorter times and also to an increase in Ac3 temperature by 70 °C in 2Al3Mn in comparison to 1.5Al3Mn steel. Reference low manganese 1.5Al1.5Mn steel possessed by far the highest transformation temperatures of all three steels and the transformation curves are also shifted even further to shorter times. Differences in transformation behaviour of these steels cannot apparently be explained simply by variation of manganese or aluminium contents alone, but rather by various ratios of manganese and aluminium in individual steels. It can be stated that with increasing manganese to aluminium ratio, phase transformation curves are shifting to longer times and generally to lower transformation temperatures.

50 kg ingots were vacuum cast, cut into four equal parts and forged into bars using laboratory hydraulic

press. In the first step, the forging of both steels was carried out with one hour soaking at the temperature of 1150 °C and gradual reduction of the cross section from 38 mm to 20mm. The steels were repeatedly re-heated for 20 minutes between the reductions. After the forging, the bars were air cooled to the room temperature. Forged bars were further annealed for two hours at 950 °C in laboratory furnace and again air cooled to the room temperature. The steels 2Al3Mn and 1.5Al1.5Mn were successfully forged into bars using this method (Fig. 1b), however the bars of 1.5Al3Mn steel started to crack after the very first reduction and only some of the bars managed to undergo the second reduction prior to cracking (Fig 1c). This steel was therefore forged again with lower soaking temperature of 1050 °C and in this case, the complete process with gradual reduction of the cross section from 38 mm to 20mm was carried out without cracking. The steel was again repeatedly re-heated for 20 minutes between the reductions.



a) Calculated CCT diagrams



b) successfully forged bars



c) cracked bars of 1.5Al3Mn steel

Fig. 1 (a) CCT diagram of both steels: 1.5Al1.5Mn - dot and dashed lines, 1.5Al3Mn - full lines, 2Al3Mn -dashed lines (b) and (c) forged bars

In the next step, forged and annealed bars were further used for determination of the effect of soaking temperature on the final microstructure and hardness. Samples were cut from the annealed bars, soaked in laboratory furnace for 30 min at various temperatures in the range of 800 – 1200 °C and finally water quenched to the room temperature. The lowest soaking temperatures used for each steel differed slightly depending on the Ac3 temperature calculated by JMatPro. The soaking started at 800°C for 1.5Al-1.5Mn steel, 850°C for 1.5%Al-3%Mn steel and at 900 °C for 2%Al-3%Mn steel with the highest Ac3 temperature.

Microstructure analysis was carried out at metallographic cross-sections prepared by standard technique and etched in 3% Nital for microstructure observation and in picric acid heated at 65 °C for prior austenite grain size evaluation using an Olympus BX 61 light microscope and an EVO 25 scanning electron microscope. Mechanical

properties were determined by measurement of hardness HV 10. Prior austenite grain sizes were determined by image analysis of micrographs taken at 200 magnification.

3 Results and discussions

3.1 Forging and annealing

The forge-ability of the steel at the temperature of 1150 °C was good for 3Mn2Al steel, as well as for 1.5Mn1.5Al steel, however it was troublesome for 3Mn1.5Al. As the amount of other alloying elements was the same for all three steels, the problems were apparently created by various manganese to aluminium ratios. When manganese to aluminium ratio was equal to 1 and 1.5, the formability was good. With the increase to 2, the steel started to crack along prior austenite grain boundaries (PAG) and fall into pieces (Fig. 1c).

The microstructure after the forging of 3Mn2Al steel

consisted of the mixture of upper and lower bainite. Martensite occurred between bainitic ferrite laths of upper bainite and the average hardness of this microstructure was 340 HV 10 (Fig. 2a). The prior austenite grain (PAG) size at the soaking temperature of 1150 °C was 52 micrometres (Fig 3). Subsequent annealing at 950 °C resulted in an average prior austenite grain increase to 68 micrometres. It is interesting to note however, that the PAG

boundaries are mainly serrated with traces of chains of very fine grains clearly visible not only in areas of proeutectoid ferrite formation (Fig 3, bottom left image). The microstructure of an annealed state was again predominantly bainitic mixture of upper and lower bainite (Fig 2 b, c) with small areas of martensite and individual grains of proeutectoid ferrite formed at PAG boundaries and practically the same hardness of 338 HV 10.

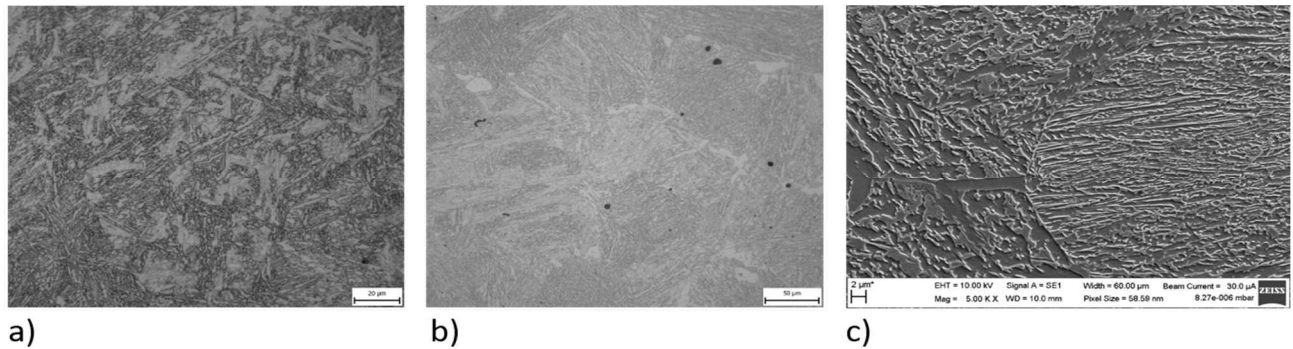


Fig. 2 Bainitic microstructure of 2Al3Mn steel a) after forging, b) and c) after forging and annealing. Larger grains of proeutectoid ferrite are visible after annealing

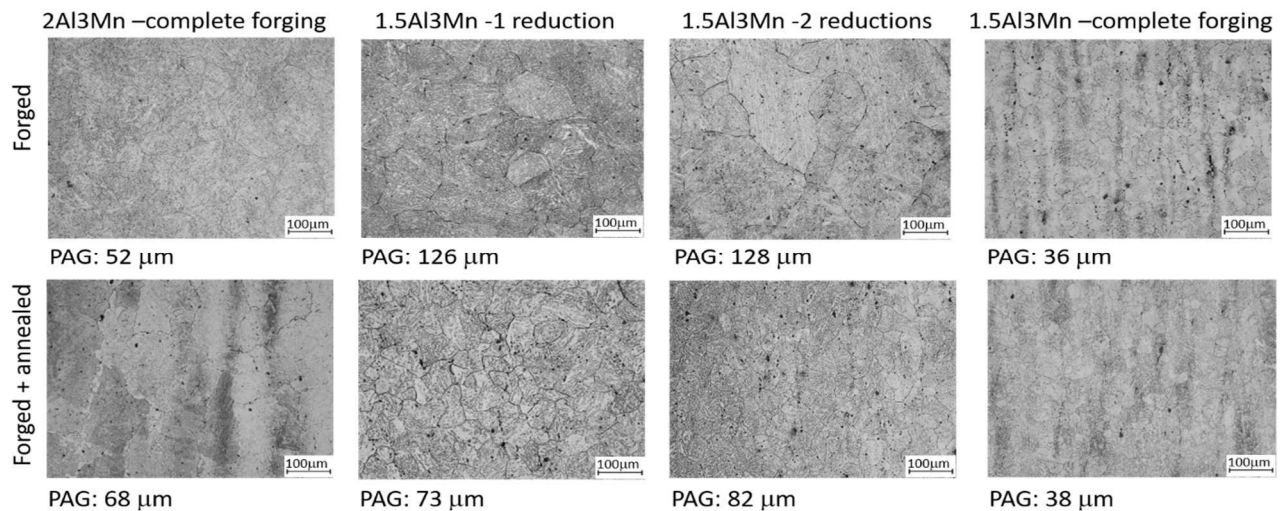


Fig. 3 Development of prior austenite grain (PAG) size. Note serrated grain boundaries in the microstructure of 2Al3Mn after forging and subsequent annealing (bottom left image).

The microstructures obtained by forging of 1.5Al3Mn steel with soaking temperature of 1150 °C were similar for the samples with one and two reductions, consisting in both cases of the mixtures of upper and lower bainite (Fig. 4). More distinctive packets of laths were observed in the sample with two reductions and also the laths of bainitic ferrite were thicker (Fig. 4 d,e). The average PAG size was 126 micrometres, which is more than double the PAG size of the 2Al3Mn steel (Fig. 3). The scales removed from the surface of the steel after forging with higher soaking temperature of 1150°C show the presence of oxides at PAG and martensitic matrix of quicker cooled surface (Fig. 4 f). The oxidized areas are further enriched by silicon and locally also by aluminium, suggesting some segregation issues at PAG.

The microstructure achieved by forging with soaking at a lower temperature of 1050 °C consisted of considerable amount of martensite blocks spread in the bainitic

matrix and was thus different from all previously described microstructures (Fig. 5 a,b). Higher amount of lower bainite, smaller thicknesses of bainitic ferrite laths and generally more pronounced lath morphology of bainite were observed. Average prior austenite grain size at 1050°C was only 36 micrometres and the PAG did not grow significantly during subsequent annealing. Annealed microstructure also retained most of the features of the forged microstructure.

Forging of reference 1.5Al1.5Mn low alloyed steel proved that both ferrite and pearlite formation are in this steel indeed quicker than in previous two steels with 3% manganese. Continuous chains of proeutectoid ferrite grains formed at prior austenite boundaries, while the matrix was still mainly bainitic with smaller amount of pearlite scattered inside bainitic blocks (Fig. 6). This mixed microstructure had the lowest hardness of 243 HV 10. Similar microstructure with very little pearlite and slightly higher hardness of 253 HV 10 resulted from subsequent annealing at 1050°C.

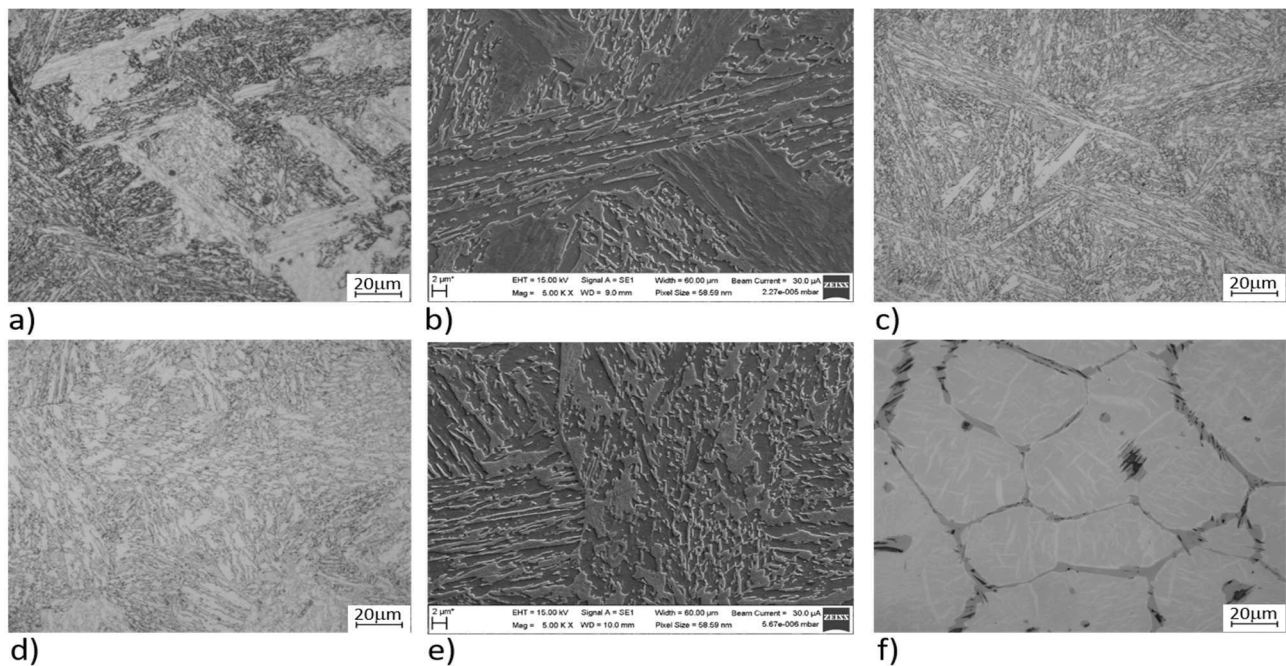


Fig. 4 Predominantly bainitic microstructures of 1.5Al3Mn steel after one reduction (a), (b), after one reduction and annealing (c), (d), after two reductions and annealing (c), (d). Microstructure of a scale with oxides at PAG (e).

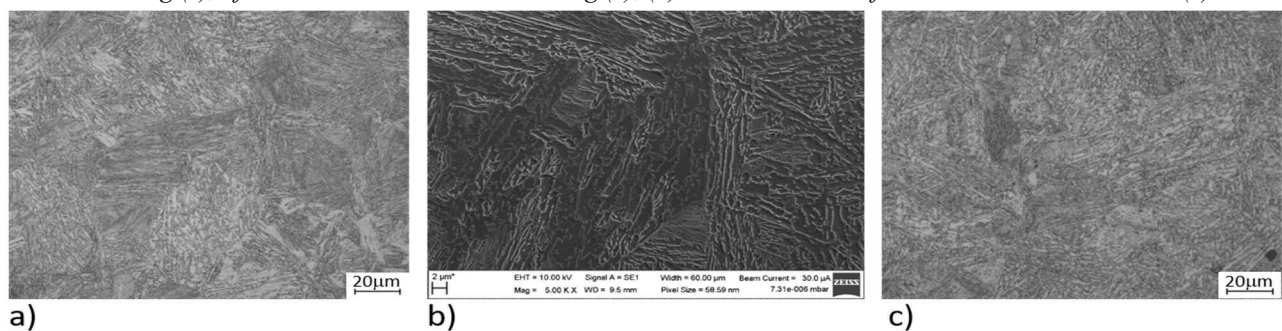


Fig. 5 Bainitic-martensitic microstructure of 1.5Al3Mn steel after forging with lower soaking temperature of 1050 °C (a), (b) and after forging and annealing (c).

Special type of bainite typical for TRIP-aided steels was found in the microstructures of all three experimental steels. This carbide-free bainite consists of bainitic ferrite and retained austenite and besides morphologies of commonly known upper and lower bainite, it is often present as granular bainite or the mixture of acicular ferrite and retained austenite islands [1,3,5]. In the case of this work, some of the remaining austenite in steels with 3% of manganese was not stable enough and even at low cooling rates provided by air cooling transformed to martensite in the very end of the cooling. This resulted in areas, which

have bainite-like morphology when observed in light microscope. However, detail analysis by scanning electron microscope proved that the areas, which would conventionally be retained austenite (or cementite in plain carbon steels), are in fact martensitic. This martensite can be traced back as the light brown areas in light micrographs (Fig. 4c, d). Partial transformation of remaining austenite to martensite is often observed in low alloyed TRIP steel, leading to formation of M-A constituent. However, in the case of 3%Mn steels, the transformation was more prominent and creates areas of mixed bainitic ferrite and purely martensitic laths or islands (Fig.2c, Fig. 4 b,e).

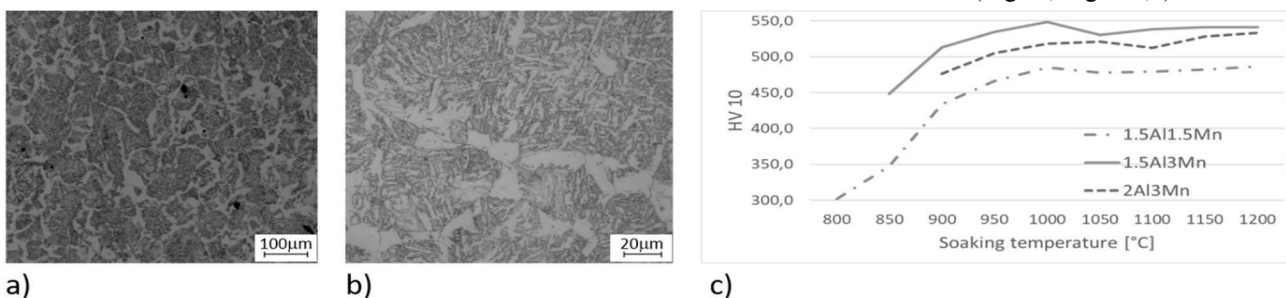


Fig. 6 Microstructure of reference steel after forging (a), forging and annealing (b). Development of hardness according to the soaking temperature (c).

3.2 Effect of soaking temperature on microstructure and hardness

Soaking temperatures of 900-1200°C were used for 2Al3Mn steel. The microstructure obtained by the soak-

ing at 900 °C was bainitic (Fig. 7a). With increasing soaking temperature the microstructure turned fully martensitic (Fig. 7b-c) and the hardness increased from 476 HV 10 for 900 °C soaking to 533 HV 10 for soaking temperature of 1200 °C.

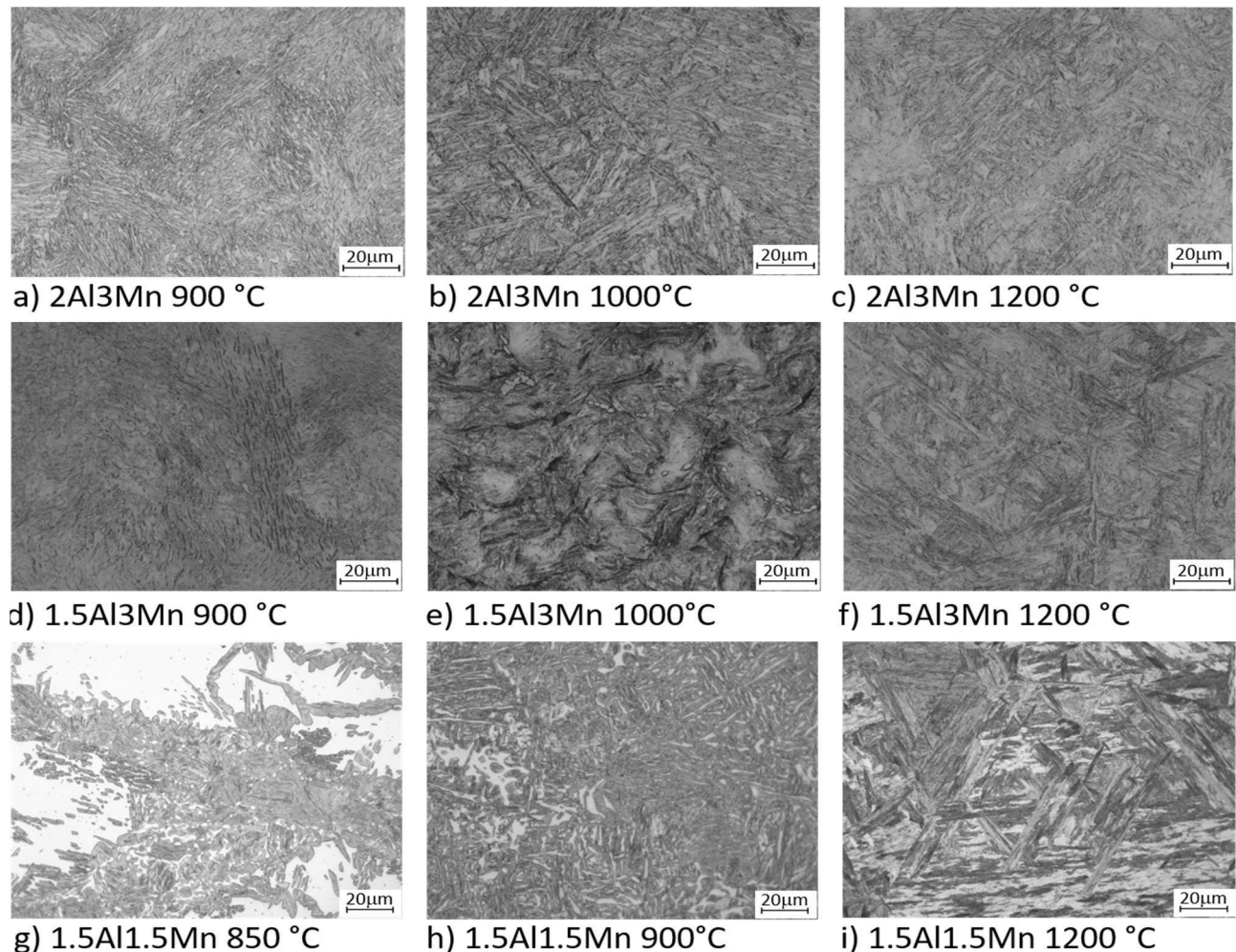


Fig. 7 Microstructure development for experimental steels after quenching from various soaking temperatures. Bainitic microstructures were obtained by soaking at 900 °C for all steels.

Bainitic microstructure was also obtained by soaking of 1.52Al3Mn steel at 900°C (Fig. 7 d). Achieved hardness of 512 HV10 was significantly higher than for 2Al3Mn steel soaked at the same temperature. The microstructure became fully martensitic from the soaking temperature of 950 °C. Hardness gradually increased with increasing soaking temperature to 541 HV 10. Relatively frequent coarse particles were observed in the microstructures of 1.52Al3Mn steel for all soaking temperature, only the frequency was slightly lower in the microstructure produced by soaking at 1200 °C (Fig. 7e-f). The particles were of various morphologies and complex chemical compositions, containing different combinations of aluminium, sulphur, titanium, manganese and niobium.

Reference steel 1.5Al1.5Mn showed different behaviour (Fig. 7 g-i). It should be noted that after soaking at 850 °C, the microstructure was composed of bands of polygonal ferrite and bainite (Fig. 7g). The banding disappeared with increasing soaking temperature to 900 °C (Fig. 7h), probably due to higher diffusivity of alloying

elements, which resulted in better homogenization of local chemical composition within the sample. The microstructure provided by soaking at the temperature of 900 °C was mainly bainitic, possessing thicker laths of bainitic ferrite than the steels with 3% of manganese and there were also many larger ferritic areas of irregular shapes. Small grains of ferrite were still found in the martensitic matrix after soaking at 950°C and the microstructure became fully martensitic from the soaking temperature of 1000 °C. The hardness of this steel was generally lower than the hardness of 3% Mn steels soaked at the same temperature, starting with 360 HV 10 for soaking at 850 °C and reaching 485 HV 10 for 1200 °C soaking temperature.

4 Conclusions

For low carbon high strength steels with low to middle contents of manganese and aluminium, the ratio of the contents of these two alloying elements plays a crucial

role for transformation behaviour of the steels. Suitable temperatures of forging or heat treatment can be therefore strongly influenced by relatively small changes in chemical composition of these steels. Problems with forging at the temperature of 1150°C were encountered for 1.5Al3Mn steel, while two steels 1.5Al1.5Mn and 2Al3Mn with lower manganese to aluminium ratio did not present any problems. Both steels with 3% of manganese provided bainitic-martensitic microstructures after forging and annealing even after air cooling from forging and annealing temperature. Reference steel with 1.5% of manganese possess more complex microstructures consisting of bainite, proeutectoid ferrite and occasional pearlite.

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