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Influence of Hot Deformation on Mechanical Properties and Microstructure of a Twin-Roll Cast Aluminium Alloy EN AW-6082

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Thin strips of medium- and high-strength age-hardening aluminium alloys are widely used in the automotive industry. Reducing their production costs caused by high energy consumption is an actual challenge. The implementation of the twin-roll casting technology is promising. However, mechanical properties of directly cast high-alloyed thin aluminium strips are oftentimes inadequate to standard specifications. In this work, the influence of a hot deformation following a twin-roll cast strip process on the mechanical properties and microstructure is investigated. For this study strips of age-hardening aluminium alloy EN AW-6082—manufactured at a laboratory scaled twin-roll caster—were single-pass rolled at temperatures of 420 °C and true strains of up to 0.5. The mechanical properties of the as-cast and by different strains hot deformed material in the soft-annealed and age-hardened states were characterized by tensile tests. The results reveal that the twin-roll cast material features the necessary strength properties, though it does not meet the standard requirements for ductility. Furthermore, the required minimum strain during hot rolling that is necessary to ascertain the standard specifications has been determined. Based on micrographs, the uniformity of the mechanical properties and of the microstructure as a result of recrystallization due to hot metal forming and heat treatment were determined. A fine-grain microstructure and satisfactory material ductility after prior rolling with a true strain above 0.41 for the age-hardened state T6 and above 0.1 for the soft-annealed state O have been established.

Keywords aluminum, casting, heat treating, mechanical testing, metallography, rolling

1. Introduction

Light metals and alloys are increasingly used in various fields of construction and engineering. Currently, one of the most important and interesting domains for their application is transport, which is associated with reduced fuel consumption and carbon dioxide emissions in operating vehicles having lower weight. Nowadays, aluminium is still the most common light metal. Alone in 2009 (Ref 1), the use of aluminium alloys in vehicle's structures reduced greenhouse gas (GHG) emissions by at least 1.3 billion metric tonnes of CO_2 equivalent (GtCO2eq). The main advantages of employing aluminium alloys in these structures are their high specific strength and corrosion resistance. Thus from the point of view of lightweight concept implementation, high strength alloys are most interesting for practical applications. The lower limit for tensile strength of such alloys must be at least 300 MPa. Some alloys referred to as wrought aluminium alloys possess these qualities; such as those of Al-Mg systems (5XXX-series), having magnesium contents of approximately 5 %, and of the age-hardening alloys based on Al-Cu (2XXX-series), Al-Zn-Mg (7XXX-series), and high-alloyed Al-Mg-Si system (6XXX-series), e.g. EN AW-6082. Due to the latter's relatively low price and its combination of high strength, good ductility and corrosion resistance, 6xxx-series alloys accounts for 75 % of the products manufactured from wrought alloys (Ref 2). These alloys are most commonly delivered to the machining facilities as semi-finished products—rolled thin sheets or extruded profiles—to be used in the structural elements.

One of the cutting edge and highly effective technologies for the production of sheets from light metal alloys is twin-roll casting of thin strips (see Fig. 1). The distinctive feature of this technology is the combination of metal crystallisation and deformation processes in one unit. This makes it possible to produce strips of 1- to 6-mm thick directly from the melt. This method allows the number of the intermediate metal-heating cycles to be decreased and the number of passes in the rolling mills to be lowered for the thickness reduction during thin sheets production. This method insures the production of high quality sheet products for the lowest energy consumption and production charge (Ref 3).

It was previously established (Ref 4) that the strips of aluminium alloys in the annealed or hardened conditions, which are produced by twin-roll casting without further deformation treatment, do not meet the required standards. These standards which apply to thin strips of high strength alloys relate to the mechanical properties; such as tensile strength and elongation at fracture, the microstructure;

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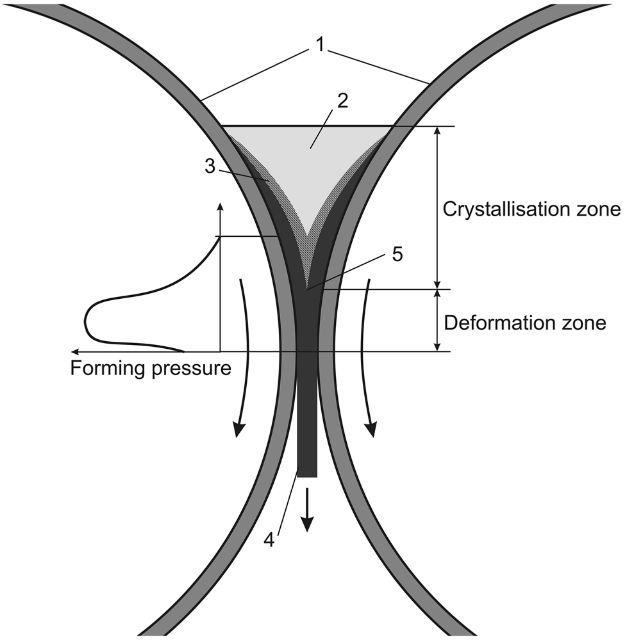

Fig. 1 Principal scheme of the twin-roll casting process: *1* water-cooled rolls, *2* Melt, *3* semi-solid metal, *4* solidified strip, *5* kissing point

particularly the size of the intercrystalline segregation, and the surface quality. This is attributed to the presence of the weakly deformed dendritic sections in the strip structure. These are formed due to the metal in the surface of the strip cooling faster when it passes through the crystallisation zone (see Fig. 1). Also, in the deformation zone the temperature of the surface layers is lower than in the material of the midlayers of the strip. As a result, the hot deformation in the twin-roll caster is localised in the central part of the strip, whereas a cast, non-recrystallised structure is retained on the surface. This results in the deterioration in the mechanical properties, first of all in the ductility and quality, invalidating the benefits of using high-alloyed aluminium in constructions. It also impedes the potential of age hardening for such alloys. Heat treatment and plastic forming are the main methods used to eliminate this specific defect and to improve the semi-finished product's quality. Intercrystalline and axial segregation could be removed through homogenising annealing. Hot or cold rolling in combination with recrystallisation annealing may be used for processing the dendritic structure and improving the ductility of the final product. Studies on the effect of such additional processing of twin-roll cast strips have so far been performed for steel (Ref 5), non-treatable aluminium alloys of the 3XXX and 5XXX series (Ref 6), and the magnesium alloy ZK60 (Ref 7). However, due to the currently limited application of the twin-roll casting technology for sheets produced from high-strength aluminium alloys, no similar studies have yet been carried out for these alloys.

Achieving the desired microstructure and mechanical properties of sheets from age-hardening aluminium alloys involves the complicated processes of a combined thermo-mechanical treatment, which includes alternating rolling and heating cycles. The properties of the finished product depend on the deformation distribution during forming operations and the regime of the precipitation hardening. This was verified particularly by Engler and Hirsch (Ref 8) who demonstrated the impact of thermal and mechanical treatment upon the formation of the flat product microstructures in sheets of 6XXX-series alloys using traditional production technology. This technology included the processing of a material from an ingot of 600-mm thickness to a thin cold-rolled sheet.

The influence of hot deformation on the microstructural evolution of an EN AW-6082 alloy of the Al-Mg-Si system was analysed by Poletti et al. (Ref 9). Furthermore, it was established (Ref 10) that true deformation values of just over 0.1 stimulate the recrystallisation processes in this alloy, whereby a high presence of Mn provides an inhibitory effect on the recrystallisation of aluminium grains. Studies of 6XXX series alloys verified the positive effect of solution annealing on reducing intercrystalline segregation (Ref 11). Cold deformation at low strain combined with natural aging, performed between quenching and artificial aging, may be used as additional operations to increase the strength of the products from alloys of the Al-Mg-Si system (Ref 12, 13). However, the use of the effect in practice is complicated due to the fact that achieving the maximum strength value is limited by the holding time between quenching and artificial aging. The length of the delay should not exceed 1 h (Ref 14).

Earlier, the authors observed a positive effect of hot rolling at a true strain of about 1.1 and of heat treatment on the mechanical properties and the microstructure of the twin-roll cast strips of EN AW-6082 and EN AW-7020 aluminium alloys (Ref 4). However, the dependence of the mechanical properties on the deformation strain during hot rolling and its minimum required value to meet the standards requirements were not analysed. The use of lower hot deformation strains will lead to a reduction of the rolls loading and permit a decrease in the number of hot rolling passes. Besides this, it allows thinner strips to be manufactured in the twin-roll caster while retaining a constant final thickness of the finished product after hot rolling. This may expand the variety of the twin-roll cast products and increase the casting speed (Ref 15).

2. Purpose of the Study

The purpose of this study is firstly to experimentally investigate the influence of the deformation strain in the hot-rolling process combined with precipitation hardening and soft-annealing on the mechanical properties and the microstructure of ENAW-6082 Al-Mg-Si system alloy strips, produced by twin-roll casting. Secondly, to determine the minimum required deformation strain value during the strip's hot deformation to meet the standards requirements for mechanical properties.

3. Experimental Procedure, Equipment, and Materials

The experiments were carried out according to the following procedure: twin-roll casting—hot rolling—heat treatment. For the 6082 alloy strip's production, the laboratory's twin-roll caster, installed in the Institut für Werkstoffkunde, at the Leibniz Universität Hannover, was used. Its basic design and the technological features are detailed by Grydin et al. (Ref 16) Fig. 2 shows a photograph of the twin-roll casting machine prior to one of the experiments.

Chemical composition of the material used for the twin-roll casting experiments is given in Table 1.

The main variable parameters influencing the twin-roll casting process and the quality of the produced strip may be divided into two groups: technological parameters—casting speed and initial melt temperature, and geometrical parameters—the total length of the crystallisation-deformation zone and the roll gap. The experiment was performed based on previously estimated parameters (Ref 4) that were optimised regarding the quality of the strip surface and the loads exerted on the equipment. These parameters ensure steady-state strip formation along the whole width of the crystalliser. The adopted technological and geometrical parameters are given in Table 2. In this case, a transient unsteady state of the twin-roll casting process could be observed some time after the experiment started. It continues until the caster rolls reach a constant temperature. The thermal part of the process subsequently becomes stable, allowing the strips to be produced with uniform properties along the length and the width and having a good surface quality without casting defects, such as hot cracking.

As mentioned above, the strips frequently do not meet the standards requirements with regards to strength and ductility after twin-roll casting without an additional treatment. Therefore, in order to rework the cast structure to a deformed state as a result of recrystallisation, and to increase the mechanical properties and the quality of the surface, the approximately 3-mm-thick cast strip (see Fig. 3) was subjected both to hot rolling using a laboratory rolling mill and to subsequent heat treatment.

For the experiments, six samples were cut-out of the strip's parts which were obtained under steady state thermal conditions of the twin-roll casting. To investigate the dependence of the change in mechanical properties from the hot-forming strain, the 3-mm strip samples were rolled at various roll gap settings. As reference specimens, those parts of the strips were sampled, which were subsequently not subjected to the hot rolling, but were heat treated together with the rolled parts. The rolling was performed in one pass at a temperature of 420 °C and a speed of 0.37 m s^{-1} using 140-mm diameter smooth rolls. Thus, the values of thickness deformation strain comprised approximately 10, 16, 25, and 34 %. Furthermore, based on previous results, the procedure was supplemented with a sample rolled at a strain of 5 % for the subsequent annealing. The properties of the twin-roll cast strip in the "O" condition are slightly inferior to the standard requirements, whereas even a relative low strain deformation can improve the quality of the alloy. On the other hand, rolling at a high strain is of more interest for the strips in the quenched condition ("T6"). Thus, the experiment was supplemented with a hot rolling pass at approximately 40 % strain. Further increase of the strain was not possible due to the load restrictions for the laboratory equipment. Main results of the strips' measurements and strain calculations are given in Table 3.

Fig. 2 Twin-roll caster used for the experimental program

Heat treatment is demanded to enable a comparison to be drawn between the strip's mechanical properties and the requirements for flat rolled high-strength alloys according to DIN EN 485-2:2009-1(Ref 17). The hardening treatment under "T6" conditions, consisting of either solution annealing with subsequent quenching and artificial aging, which provides the maximum obtainable strength properties, or annealing treatment under "O" conditions to attain maximum ductility, were selected from the possible options for heat treatment of the Al-Mg-Si system alloys. The heating of the deformed strips and the reference specimens was carried out in a convection furnace to ensure rapid heating of the metal to the heat treatment temperature.

Thermal treatment according to "T6" conditions included solution annealing for 20 min at 540 °C, quenching in water and artificial aging at 160 °C for 8 h, whereas the "O" conditions include additional softening and full annealing for 1 h at 420 °C with subsequent cooling at 25 °C per hour to below 100 °C.

Table 2 Optimised parameters for the twin-roll casting process of strips from ENAW-6082 alloy based on the experimental results

Parameter	Value
Roll diameter/mm	370
Strip width/mm	200
Strip thickness/mm	≈ 3
Casting rate/m min^{-1}	3.5
Melt temperature/°C	700
Total height of crystallisation-deformation zone/mm	45
Coolant flow rate/l min^{-1}	112

Table 1 Chemical composition of the studied EN AW-6082 alloy in wt.%

Alloying components		Si/%	Fe/%	Cu/%	Mn/%	Mg/%	Cr/%	Zn/%	Other/%	Al/%
6082	Standard	0.7-1.3	Max 0.5	Max 0.1	0.4-1.0	0.6 -1.2	Max 0.25	Max 0.2	…	Balance
	Analysis	1.12	0.391	0.084	0.51	0.77	0.03	0.068	0.073	96.954

Following heat treatment, the specimens for mechanical tensile testing were taken in accordance with ISO 6892-1:2009 (Ref 18) and metallographic studies of the strip's microstructure were performed. For the purpose of tensile testing, 3 samples were prepared for each mode of thermal treatment and hot rolling.

4. Results of Experimental Studies

The results of the mechanical tests for the age-hardened and for the annealed strips are given; as averages of the obtained data, in Table 4 and 5, respectively.

Analysis of the mechanical tests data, given in Table 4 and 5, demonstrate that, following the heat treatment, the twin-roll cast strip meets the standard requirements for strength properties, whereas the ductility properties are below the required elongation at fracture value. On the basis of these test results, it is shown that the hot rolling of the cast strip, even using a low deformation strain of 5 %, combined with annealing, results in an increase in the average value of elongation at fracture above the required 16 %. However, part of the elongation test samples did not reach the required level of ductility properties; this is demonstrated in Fig. 4. Hot rolling with 10 % strain combined with annealing ensures compliance with the DIN EN 485-2:2009-1 standard requirements for both ductility and strength properties. The effect of hot deformation on the ductility properties develops more prominently in the strips which are subjected to "T6" conditions after heat treatment (see Fig. 5). Thus, hot rolling using a true strain of 0.29 results in doubling the elongation at fracture compared with the twin-roll cast heat treated metal. However, even this is not sufficient to exceed the minimum level of ductility properties required by the Standard. Only hot rolling using reductions of over 34 % provides for the increase in elongation at fracture above the required 7 % for the material subjected to the "T6" condition.

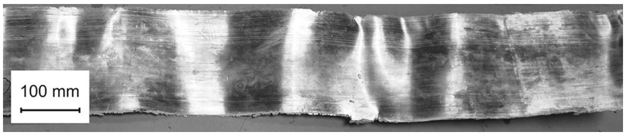

Fig. 3 End part of the strip from EN AW-6082 alloy, produced by means of twin-roll casting

According to the graphs shown in Fig. 4 and 5, hot rolling at over 0.29 true strain values prior to heat treatment under "O" and "T6" conditions only results in an insignificant 10 % reduction in material-yield strength, whereas the tensile strength remains practically unchanged. The effect of hot forming on the ductility of the metal after annealing develops a prominent increase in elongation at fracture. This development increases with the true strain growing from 0 to 0.1. Further increases in the reduction do not result in the improvement of the material ductility under "O" conditions. For the hardened metal, the elongation at fracture value increases with the growth in the preliminary hot deformation strain. This was observed over the whole range of the true strains investigated.

To explain this behavior of the aluminium alloy, we shall examine the micrographs of prepared micro-sections in the rolling direction under polarised light; the sections were electrolytically etched according to Barker (Ref 19) (see Fig. 6). The low ductility of twin-roll cast strips following the relevant heat treatments, represented by micro-sections in Fig. 6a and e, may be explained by the presence of the residual cast microstructure in the material. Here, recrystallisation had not been completed during the deformation in the twin-roll caster. As mentioned above, this is due to the presence of manganese in the 6082 alloy. Manganese, being a transitional metal, increases the temperature of aluminium recrystallisation and slows down the formation and the growth of new grains (Ref 20-22). To initiate the process of metal recrystallisation, the true strain of hot deformation must exceed the critical value, which is 0.1 for this alloy (Ref 23, 24). However, this strain

Table 3 Strip thickness and strain values obtained as a result of hot rolling of twin-roll cast strips

No.	Initial thickness of a sample/mm	Final thickness of a sample/mm	Strain on the thickness ε/%	True strain on the thickness	Elongation ratio	Subsequent heat treatment
1	3.10	2.95	4.9	0.05	1.03	O
2	3.15	2.85	9.5	0.10	1.07	O or T6
3	3.15	2.65	15.9	0.17	1.15	O or T6
4	3.16	2.40	25	0.29	1.34	O or T6
5	3.17	2.10	33.75	0.41	1.43	O or T6
6	3.25[a]	1.96	39.5	0.51	1.48	T6

[a] To test the repeatability, sample No. 6 was selected from a strip obtained from another twin-roll casting trial to that for samples Nos. 1-5

Table 4 Mechanical properties of EN AW-6082 aluminium alloy strip after twin-roll casting, hot rolling, and heat treatment under "T6" conditions

Strain at hot rolling/%	0	10	16	25	34	40	DIN EN 485-2:2009-1 requirements
Mechanical properties values							
Yield strength/MPa	305	293	295	267	266	265	≥ 260
Ultimate tensile strength/MPa	334	339	324	322	333	328	≥ 310
Elongation at fracture/%	1.51	2.73	1.12	3.12	7.47	8.34	≥ 7

Table 5 Mechanical properties of EN AW-6082 aluminium alloy strip after twin-roll casting, hot rolling, and heat treatment under "O" conditions

Strain at hot rolling/%	0	5	10	15	25	34	DIN EN 485-2:2009-1 requirements
Mechanical properties values							
Yield strength/MPa	67	75	77	74	56	58	≤ 85
Ultimate tensile strength/MPa	122	125	139	133	127	137	≤ 150
Elongation at fracture/%	14.38	16.05	19.74	19.78	19.86	19.33	≥ 16

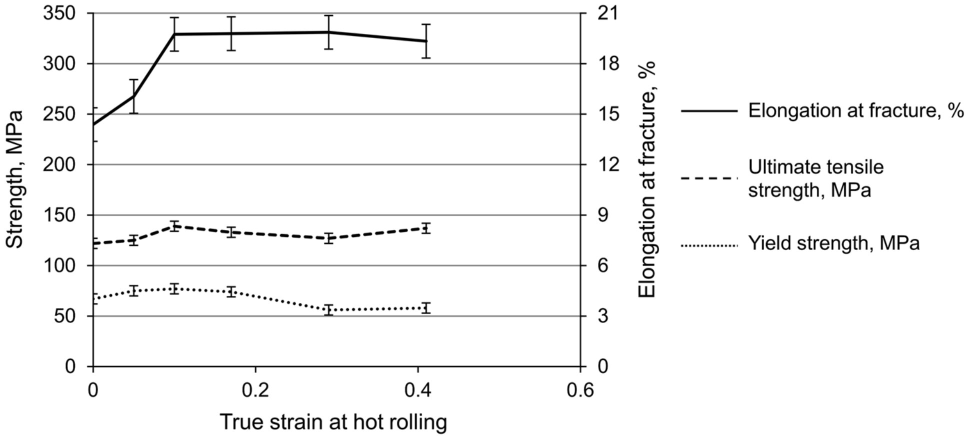

Fig. 4 Dependence of the strip mechanical properties after annealing ("O" condition) on the true strain at the hot rolling

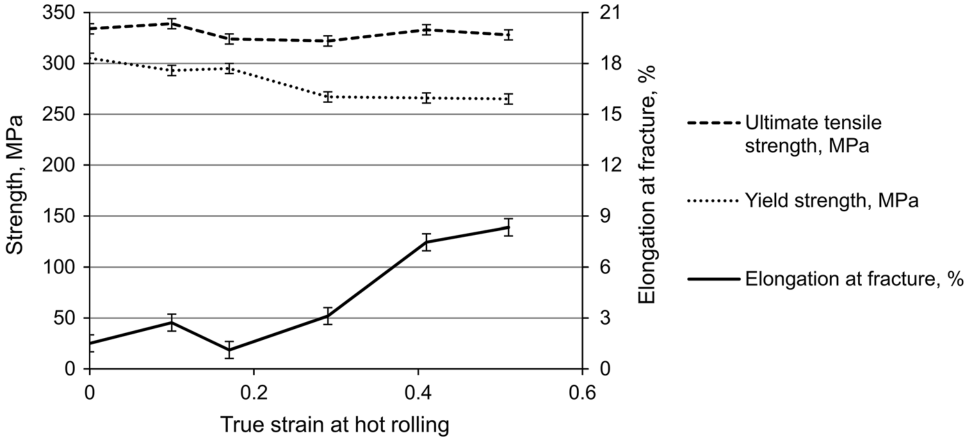

Fig. 5 Dependence of the strip mechanical properties after age-hardening ("T6" condition) on the true strain at the hot rolling

value at the selected rolling temperature is not sufficient for the complete transformation of the cast microstructure. This is also validated by the micrographs in Fig. 6b and f. Furthermore, traces of the distinctive cast microstructure in the near-surface regions of the strips could also be found after hot rolling with higher deformation strains. On increasing the strain to 25 % or higher, in the material, the partially recrystallised microstructure prevails, the grains acquire an elongated shape, oriented in the rolling direction, which is typical for rolled thin strips (Ref 8, 9, 25). It is noticeable that a coarse-grained structure forms, which is observed after hot rolling using a 25 % reduction and subsequent heat treatment using either treatment modes (see Fig. 6c, g). This observation correlates with the results of those studies (Ref 26), in which authors observed the formation of large recrystallised grains in 6082 alloy within the strain range from 0.2 to 0.3 at a 450 °C deformation temperature. In the indicated range of the strain, the reduction in the recrystallised grain sizes may be achieved by increasing the temperature of hot deformation of 6082 alloy to over 500 °C. As shown in Fig. 6d and h, hot rolling using reductions of 34 % and more, results in the formation of predominantly recrystallised fine-grain microstructures. The mechanical properties of such

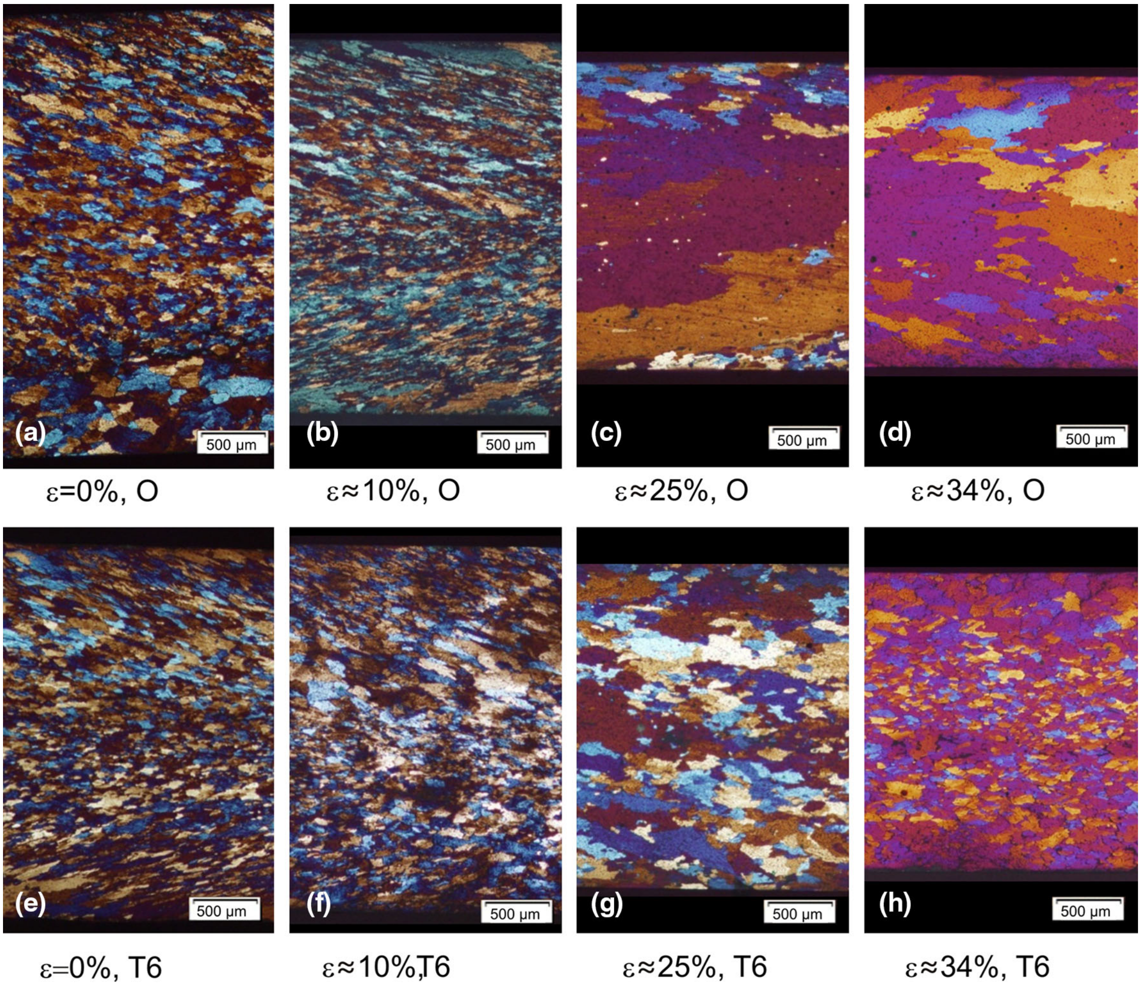

Fig. 6 Microstructures of the samples, prepared from the strips after hot rolling with various strains and heat treatment ("O" and "T6" conditions) (a) $\varepsilon = 0$ %, O; (b) $\varepsilon \approx 10$ %, O; (c) $\varepsilon \approx 25$ %, O; (d) $\varepsilon \approx 34$ %, O; (e) $\varepsilon = 0$ %, T6; (f) $\varepsilon \approx 10$ %, T6; (g) $\varepsilon \approx 25$ %, T6; (h) $\varepsilon \approx 34$ %, T6

materials achieve the required high level following the relevant heat treatments.

5. Conclusions

The effect on the mechanical properties and the microstructure of the deformation strain during hot rolling and the subsequent heat treatment conditions was experimentally analysed for the twin-roll cast strips of the EN AW-6082 alloy. It was established that the properties of the strips after twin-roll casting do not meet the DIN EN 485-2:2009-1 standard requirements for the value of elongation at fracture. It was demonstrated that hot rolling of twin-roll cast strips improves the ductility of the metal and results in the formation of the predominantly recrystallised microstructure. The minimum required true strain values for hot rolling were determined which provide compliance with the standard requirements for the value of elongation at fracture. The minimum required true strain value for the annealed strips is 0.1. The sheet in the age-hardened condition (T6 mode) requires intermediate hot rolling at 420 °C with minimum true strain of 0.41.

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