Optimization of Thermo-Mechanical Processes of Continuous Casting Products Using High Magnesium Aluminum Alloys in Automotive Industry Applications

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Abstract

5XXX series alloys are preferred in the automotive industry due to its high strength and formability. 5XXX series aluminum alloys, which are difficult to produce under the scope of our work, are sustainable and suitable for high quality expectations of automotive sector; The conditions of continuous casting, which enable efficient production, have been determined and the thermo-mechanical processes required by the final products have been developed. 5754 aluminum alloy sheets, which have many applications in the automotive sector, come to the fore and increase their usage areas every day due to its high strength, weldability and deep formability properties. In the analysis of the study, industrial scale production and laboratory prototype studies were evaluated comparatively for each production stage. In the context of these evaluations, microstructure analysis and thermo-mechanical properties were investigated in detail. In addition, due to the high visual expectation of the automotive sector, surface properties at every stage of production were analyzed by measurable methods.

Keywords

5754 • Magnesium ratio • Continuous casting • Automotive

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Introduction

5XXX aluminum alloys have drawn intensive attention in many engineering applications such as automotive, construction and technology due to their superior properties such as high strength/weight ratio, excellent formability and corrosion resistance in harsh environmental conditions. AA5754, AA5052 and AA5182 are particularly attractive in automotive industry which commit to reduce the carbon emission ratio and cost-effective way to improve the performance of fuel consumption owing to weight reduction [1, 2]. In recent years, the use of 5754 alloys has significantly increased in fuel oil tank, heat shield, engine cover and interior panel applications, which require high strength and good formability [3–5].

During mechanical deformation, dislocation movement is restricted by the replacement of Mg atoms with Al atoms in solid solution. Therefore, work hardening is delayed until high elongation values and the required shape can be easily formed into final product [2]. Mg_2Si phase must be substantially dissolved after the annealing process to avoid tearing and to ensure good formability [6, 7].

In this study, 5754 alloy is cast by using TRC (Twin Roll Casting) technique and subsequently thermo-mechanical processes are conducted to produce 5754-O and H22 tempers. The effect of different magnesium percentages on microstructure and mechanical properties is investigated.

Materials and Methods

In order to analyze the effect of different % Mg ratio, 5754 coils were cast in industrial scale by TRC method in Novelis casting machine in ASAŞ Aluminium. The result of chemical analysis of cast samples measured by OES (Optical Emission Spectrometer) is shown in Table 1.

Process routes are determined by using rolling machine and annealing furnaces in laboratory conditions.

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Table 1 Chemical analysis results of samples

Alloy	Si	Fe	Cu	Mn	Mg	Ti
EN 573 wt%	0.4	0.4	0.1	0.05	2.60–3.60	0.15
3.2% Mg	0.205	0.330	0.060	0.110	3.150	0.010
3% Mg	0.195	0.310	0.045	0.080	3.010	0.015
2.8% Mg	0.170	0.310	0.045	0.075	2.775	0.010

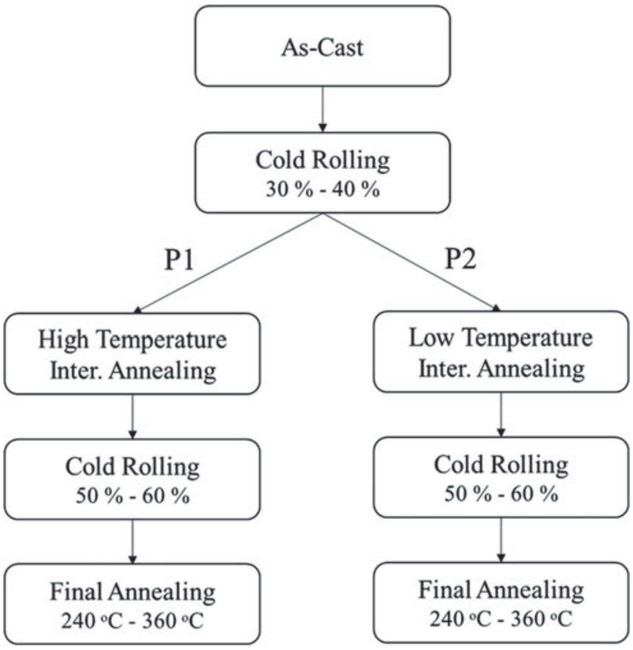

Fig. 1 5754-O and H22 tempers laboratory process studies

Thermo-mechanical processes are indicated in Fig. 1. Intermediate annealing is applied on the samples, which contain different magnesium percentages, rolled by 30–40% deformation from casting thickness. The effect of high and low temperatures in intermediate annealing is investigated. The production of 5754 alloy with O and H22 tempers is carried out at the final thickness (Fig. 1).

Samples that are perpendicular to the rolling direction (90°) and the samples with 3 directions (0°, 45°, 90°) are prepared for O and H22 tempers, respectively, in order to determine mechanical properties. Zwick/Roell Z050 model tensile tester is used to test the samples in accordance with TS EN ISO 6892-1 standard.

Formability of 5754 depends on significant parameters that affect deep drawing behavior. Despite the fact that the properties of isotropic materials do not alter in different directions, aluminum alloys may display different mechanical properties on transverse, longitudinal and diagonal directions. In the literature, this behaviour is called planar anisotropy and it is known that higher values of this anisotropy is detrimental for material's formability [2, 8]. Hence, during deep drawing process planar anisotropy was also analyzed. The corresponding formula is shared below.

$$\Delta R = (R_0 - 2R_{45} + R_{90})/2 \quad (1)$$

Firstly, the metallographic samples were moulded in bakelite resin. Samples' surfaces were ground using SiC grinding paper and subsequently polished by diamond suspension and colloidal silica. In order to obtain grain structure under polarized lights, etching was occurred with Keller solution.

The microstructure of the samples was characterized with polarized and bright light mode by ZEISS Scope A1 model optical microscopy. Panoramic images were created by the correlation of multiple images. The macro structure of 90° bending samples are examined by ZEISS Stemi 2000-c model stereo microscope.

Results and Discussion

The microstructure of the cast samples with different percentages of magnesium is shown in Fig. 2. Based on grain structures, it can be noted that sample with 3.2% Mg content has coarser grain structure than samples having 3% and 2.8% Mg due to the effect of manganese and silicon. The addition of silicon to Al alloys reduces the grain refining potential of TiB_2 [9]. The effect of grain size on mechanical

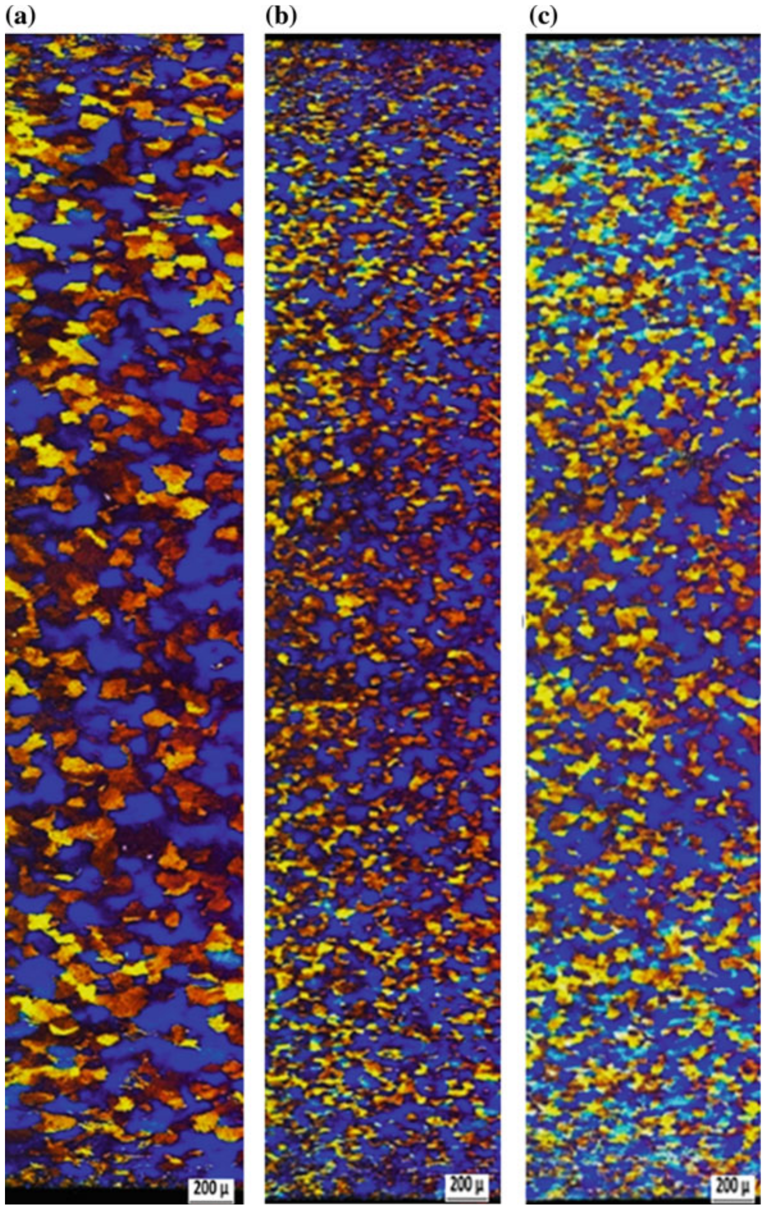

Fig. 2 As cast microstructures under polarized light; **a** 3.2% Mg, **b** 3% Mg, **c** 2.8% Mg

properties can be observed and coarse grains have significant influence on the hardness of the samples [6, 10].

The formation of centerline segregation depends on CC casting solidification conditions. The distribution of centerline segregations in the structure of the samples, which were as-cast and recrystallization annealing at high and low temperatures, are shown in Figs. 3, 4 and 5 respectively. The representative SEM images show that; although centerline segregations precipitate in lamellar shape in as-cast state, recrystallization annealing contribute to change regarding intermetallic formation. After annealing, intermetallic constituent phases transform from lamellar to granular shape.

It was noted that as the magnesium content rises, the amount of centerline segregation in the middle plane increases. Afterward recrystallization annealing at different temperatures, the centerline segregations, which have a negative impact on formability of the final product, were found to be largely dispersed. Furthermore, in high

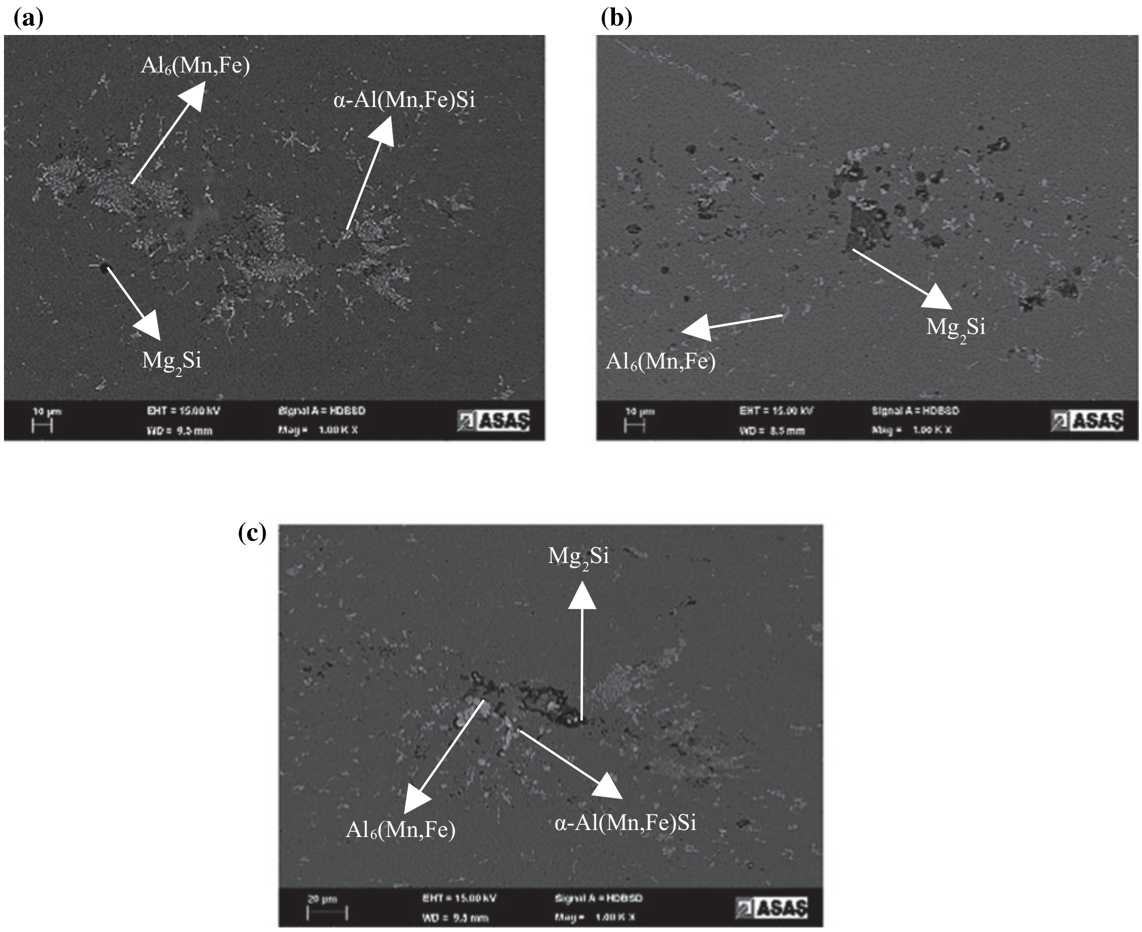

Fig. 3 Representative SEM images of the sample containing 3.2% Mg after recrystallization intermediate annealing; **a** as-cast, **b** high temperature intermediate annealed, **c** low temperature intermediate annealed

temperature annealing centerline segregation was more dissolved to matrix in comparison with low temperature of annealing [7].

Centerline segregation formation on mid-plane region depends entirely on chemical composition and cooling rate. Consequently, the secondary phases such as Al_6Mn, Al_6Fe, Al_3Fe and Mg_2Si form in sequence during the solidification of the alloy [9]. The 5754 alloy was cast with low Si % and therefore the phase α-Al(Mn,Fe)Si was precipitated at low ratio in the structure. In various SEM images, it was characterized that the Al_6(Mn,Fe) phase is the main intermetallic dispersoid.

The grain structures of the samples with different Mg content after high temperature (P1) and low temperature (P2) recrystallization annealing are shown in Figs. 6 and 7. It was noticed that recrystallization took place in all samples after annealing; however, samples annealed at high temperature (P1) have coarser grain size than the samples annealed at low temperature (P2).

P1 and P2 processes were conducted in order to obtain H22 condition, grain structures of the samples containing different Mg content with final thickness are shown below (Figs. 8 and 9). It can be noticed that recrystallization of the samples started and took place partially after annealing. Grain size directly affects mechanical properties in the samples having fine microstructure [10].

It can be seen from Fig. 10, recrystallization was occured in the samples with 2 mm thickness and O temper, and the

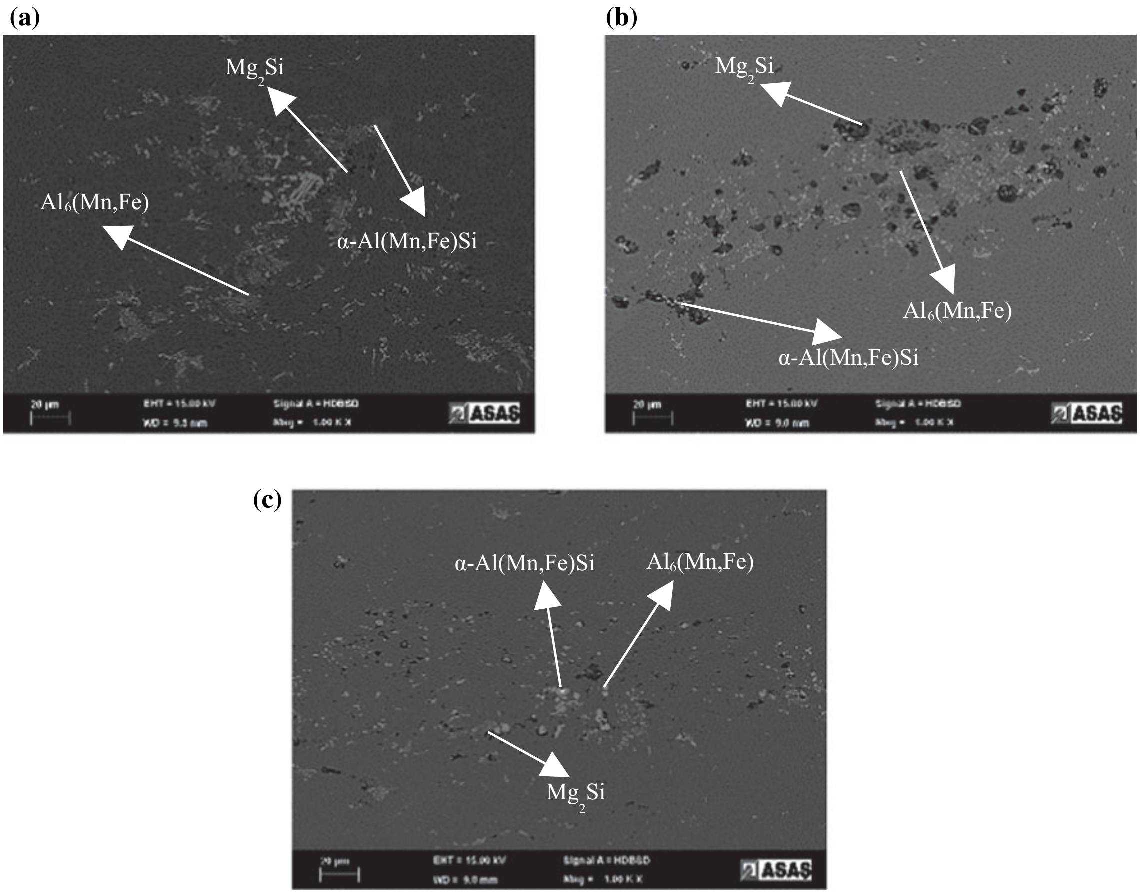

Fig. 4 Representative SEM images of the sample containing 3% Mg after recrystallization intermediate annealing; **a** as-cast, **b** high temperature intermediate annealed, **c** low temperature intermediate annealed

grains in the cross sectional area are uniformly distributed. According to the results including planar anisotropy and deformation hardening (Figs. 15, 16 and 17 respectively), it can be concluded that P1 process is more suitable for deep drawing properties [8, 10].

The desired properties for the final product were achieved by applying a final annealing step. Regarding P1 and P2 processes, the mechanical properties of the specimens with different Mg content at 2.5 mm thickness are indicated in Figs. 11 and 12.

In order to achieve good deep drawing properties in the sample with 2 mm thickness and O temper, the final annealing process was conducted. According to the results, both processes are convenient in terms of EN 485-2 standard (Figs. 13 and 14).

In Fig. 15, the planar anisotropy, which affects the deep-drawing property in 3-direction tensile testing, is measured in the specimen with 2 mm thickness and O temper. As planar anisotropy value approaches zero, formability is affected positively [2, 6].

In Figs. 16 and 17, deformation hardening (n) of 2 mm and 2.5 mm specimens were analyzed and formability was achieved. Formability increases as hardening exponential coefficient increases [11, 12].

Figures 18 and 19 shows the results of 90° bending surfaces of the H22 2.5 mm samples having different Mg

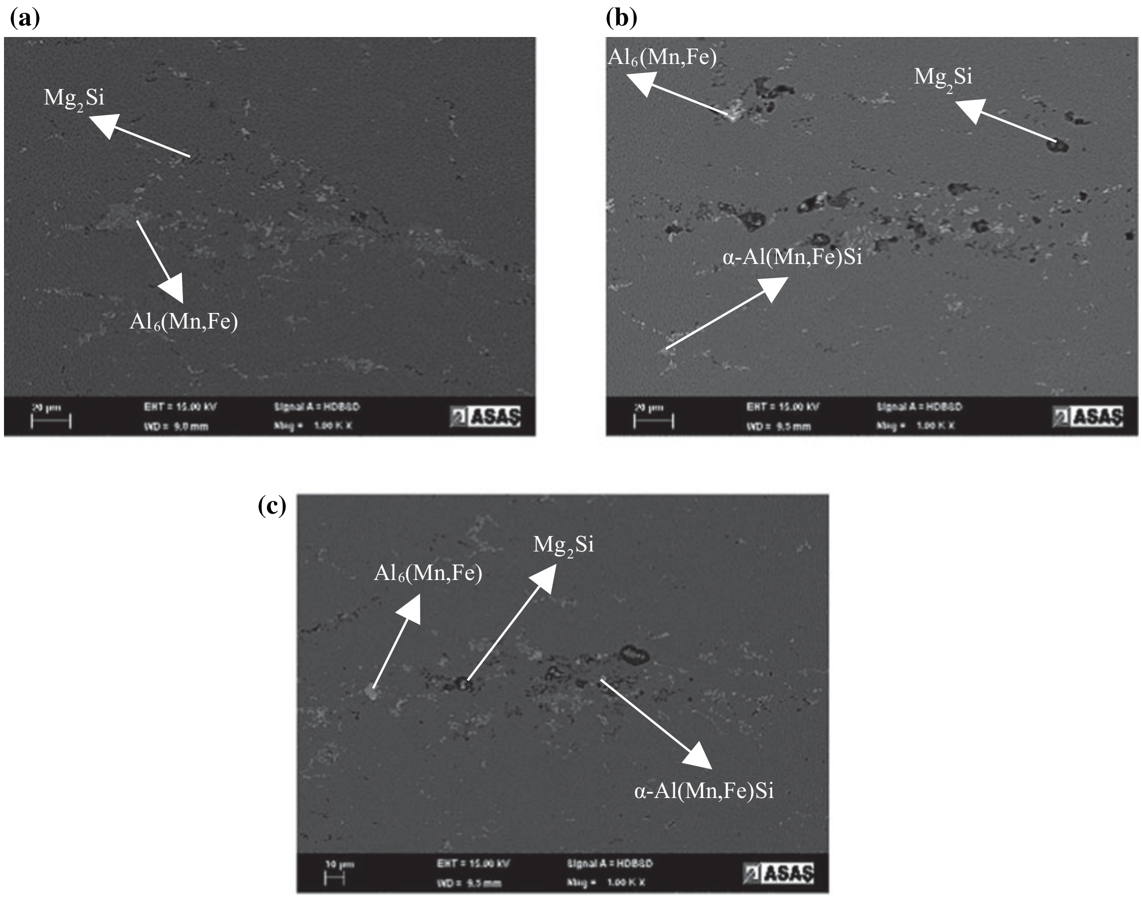

Fig. 5 Representative SEM images of the sample containing 2.8% Mg after recrystallization intermediate annealing; **a** as-cast, **b** high temperature intermediate annealed, **c** low temperature intermediate annealed

contents under the stereo microscope. The surface of samples annealed at high temperature show less fibrous appearance, while samples annealed at low temperature have poor surface quality with cracks depending on the amount of magnesium in the structure. As a result of the tests, it is observed that the samples annealed at high temperatures have superior T-bending behavior.

Conclusion

Microstructure analysis of the cast samples indicated that grain size was fined as the relatively high magnesium content. Contrary to magnesium, manganese content triggered to coarse the grain structure. Regardless of the other elements, it was observed that the grain size was reduced by increasing the percentage of titanium in terms of grain refining.

Increasing the Mg content led to a higher amount of centerline segregation in the cast samples. These segregations, which are formed after casting and adversely affect the formability properties, were eliminated by recrystallization annealing. After the recrystallization annealing at high temperature (P1 process), the centerline segregations were mostly dispersed in the structure.

H22 temper desired for the final product with 2.5 mm thickness, it was found that the mechanical properties of the samples with high temperature intermediate annealing (P1) and the low temperature intermediate annealing (P2) vary as the Mg content increases. H22 temper was achieved for the samples in both P1 and P2 processes.

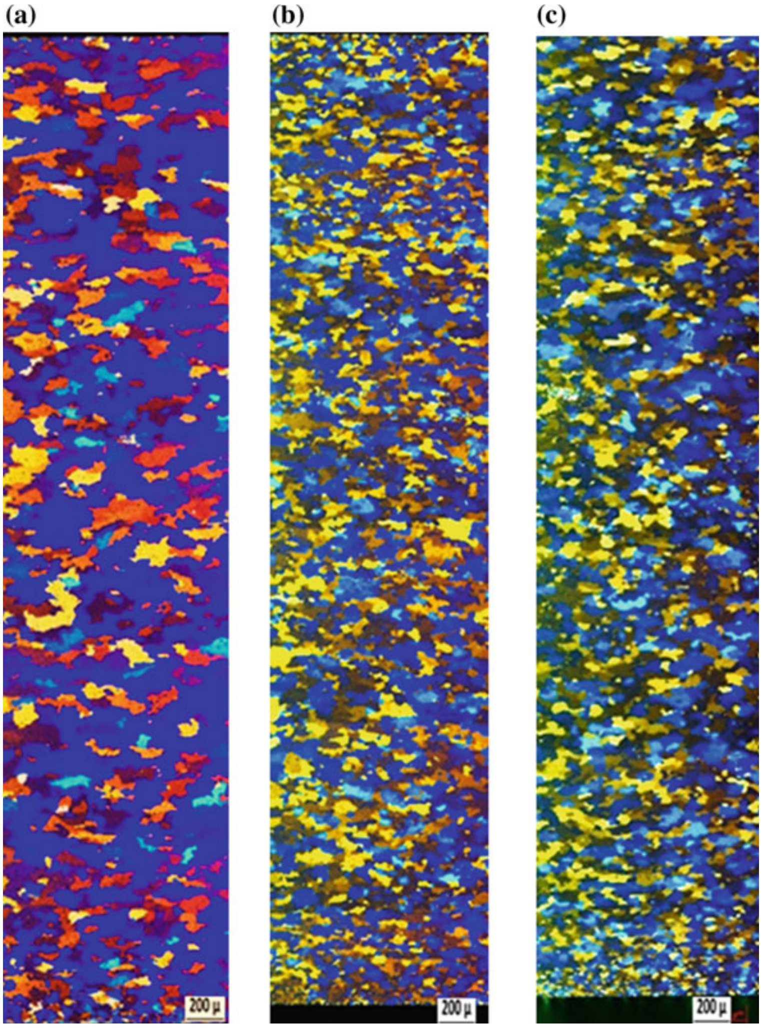

Fig. 6 The microstructure of different Mg-containing samples in the P1 process after high temperature intermediate annealing; **a** 3.2% Mg, **b** 3% Mg, **c** 2.8% Mg

The final product indicated good 90° bending behavior with 2.5 mm thickness and H22 temper by P1 process. Orange peel appearance was at minimum level and no cracks were observed.

Positive outcomes were achieved in the P1 and P2 processes for the 2 mm thickness and O temper deep drawable final product. In order to reduce the effect of segregation distribution on deep drawing, high temperature intermediate annealing process should be preferred for 2 mm O conditioning product.

Planar anisotropy and deformation hardening values, which affect the formability, show improvement after high temperature intermediate annealing. P1 high temperature annealing process should be carried out to obtain final product with O temper.

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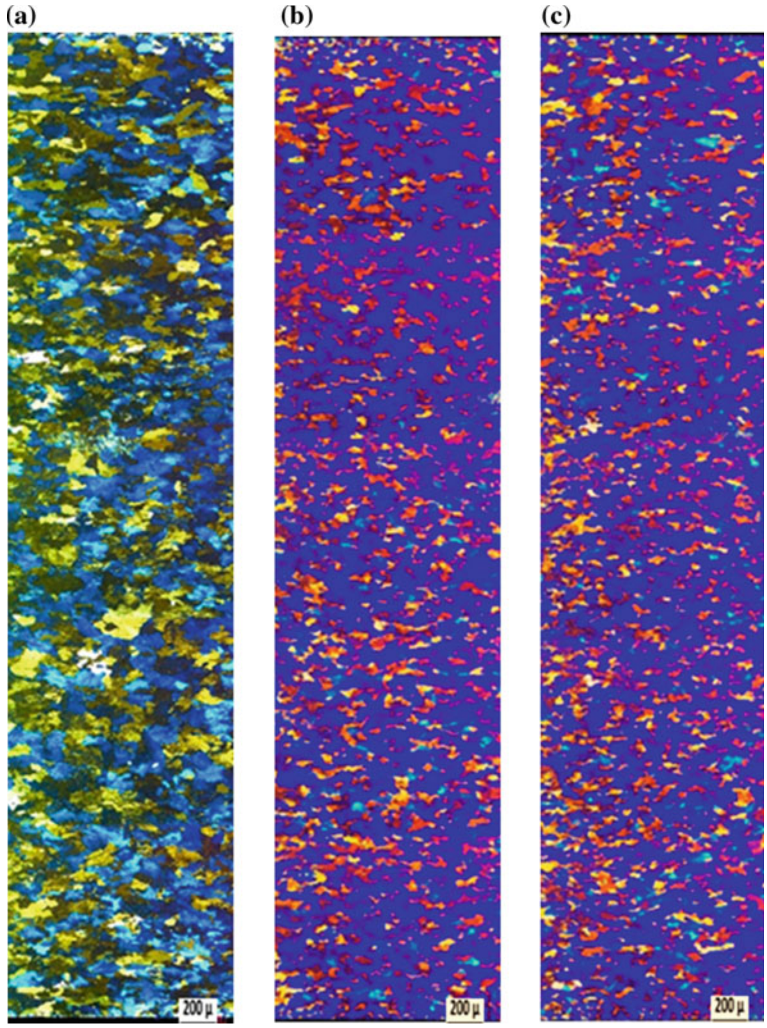

Fig. 7 The microstructure of different Mg-containing samples in the P2 process after low temperature intermediate annealing; **a** 3.2% Mg, **b** 3% Mg, **c** 2.8% Mg

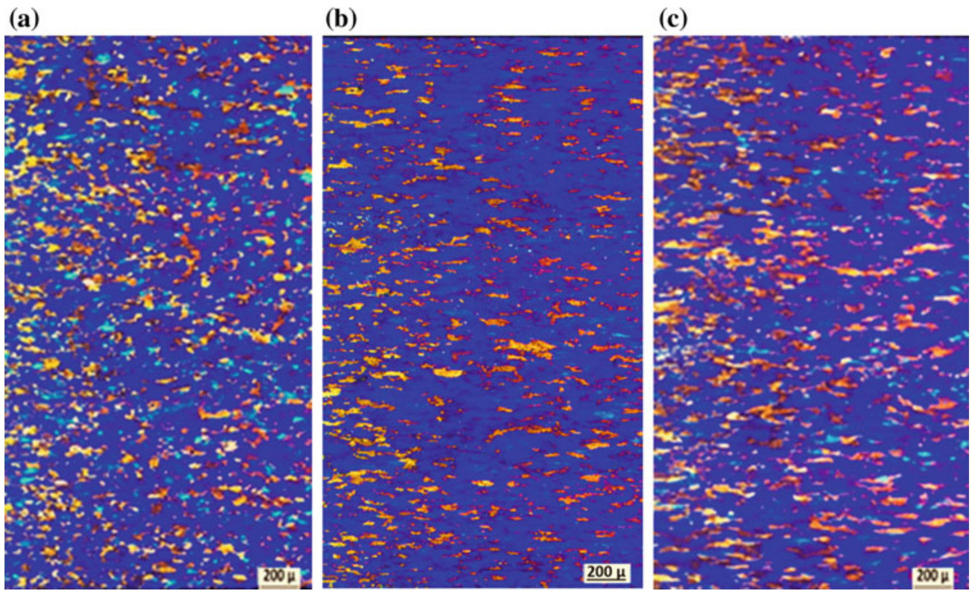

Fig. 8 Microstructures of samples annealed for H22 condition at final thickness of process P1; **a** 3.2% Mg, **b** 3% Mg, **c** 2.8% Mg

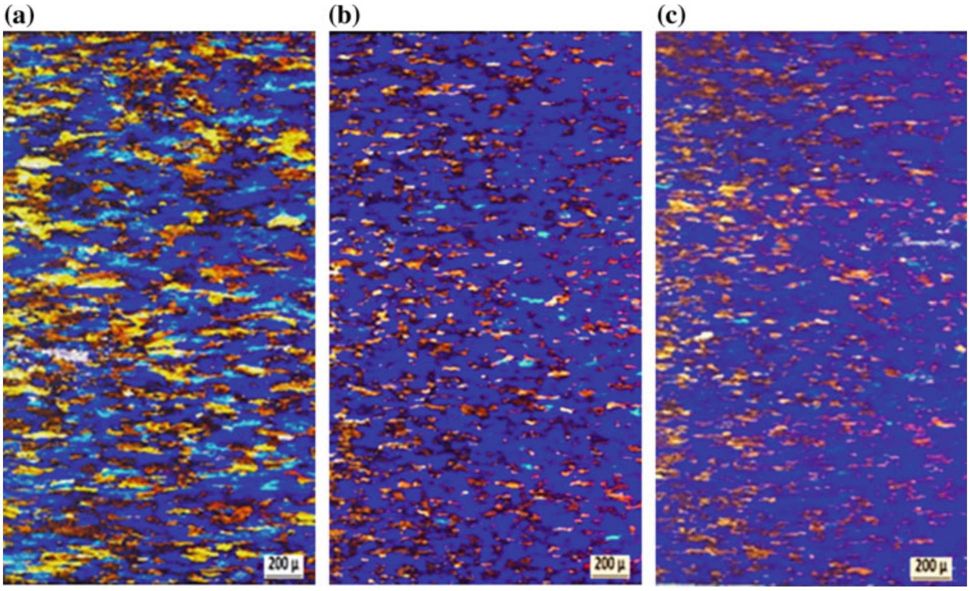

Fig. 9 Microstructures of samples annealed for H22 condition at final thickness of process P2; **a** 3.2% Mg, **b** 3% Mg, **c** 2.8% Mg

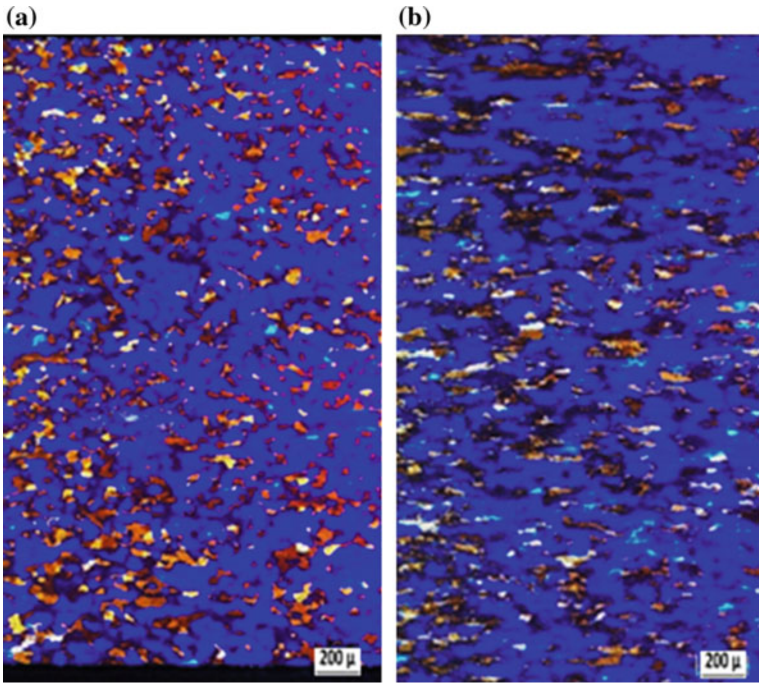

Fig. 10 Microstructures of 2 mm O temper samples; **a** P1 3.2% Mg, **b** P2 3.2% Mg

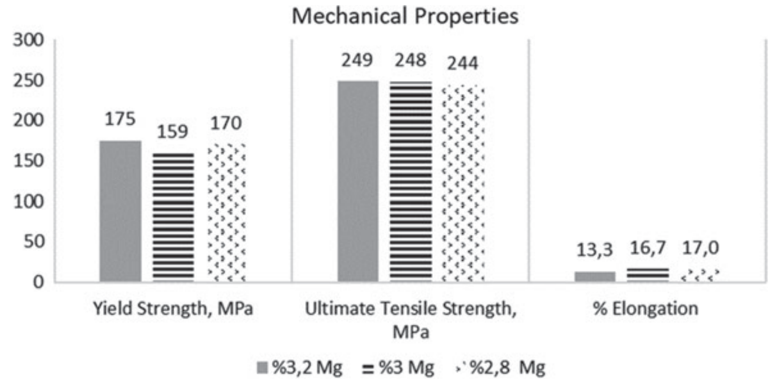

Fig. 11 P1 high temperature intermediate annealed 2.5 mm H22 conditioned for the purpose of % Mg content of mechanical properties results of different specimens

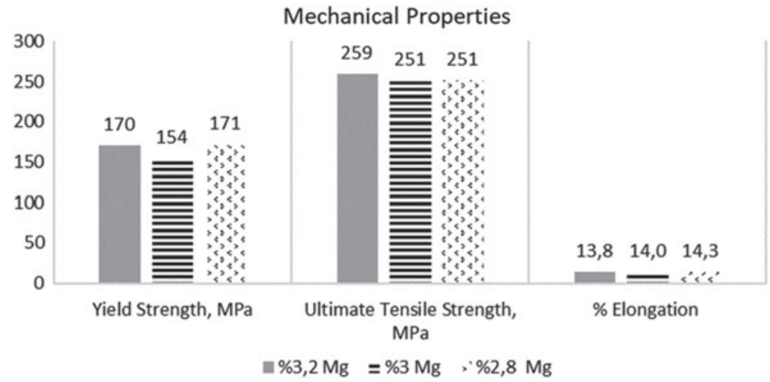

Fig. 12 P2 low temperature intermediate annealed 2.5 mm H22 conditioned for the purpose of % Mg content of mechanical properties results of different specimens

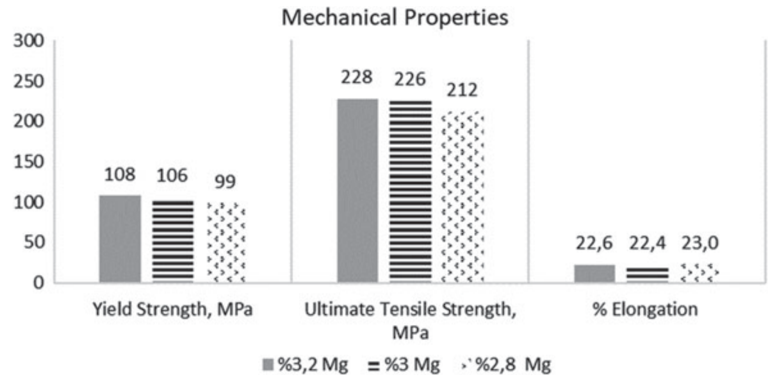

Fig. 13 P1 high temperature intermediate annealed 2 mm O conditioned % Mg ratios for mechanical properties results of different specimens

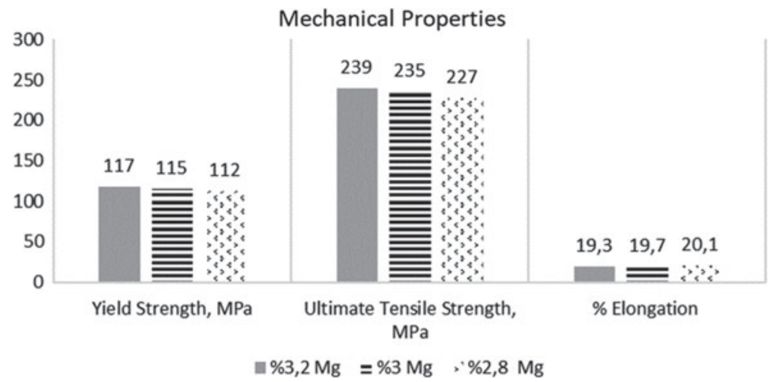

Fig. 14 P2 low temperature intermediate annealed 2 mm O conditioned % Mg ratios for mechanical properties results of different specimens

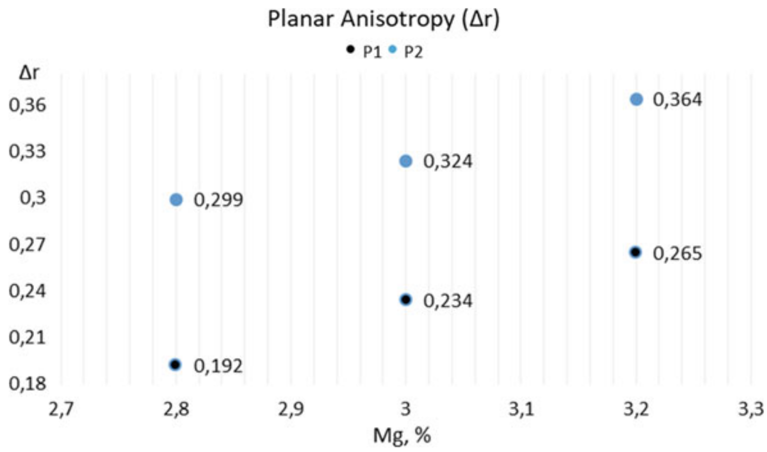

Fig. 15 In final thickness, planar anisotropy values of different specimens with % Mg content at 2 mm O temper in P1 and P2 process

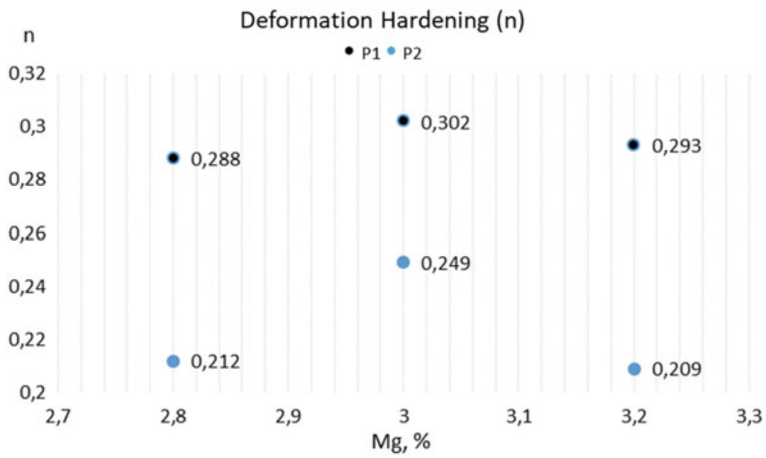

Fig. 16 In final thickness, deformation hardening values of different specimens with % Mg content at 2 mm O temper in P1 and P2 process

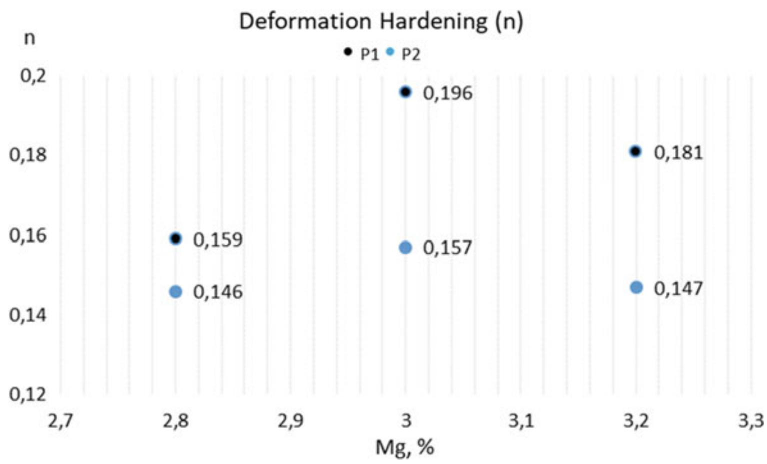

Fig. 17 In final thickness, deformation hardening values of different specimens with % Mg content at 2.5 mm H22 temper in P1 and P2 process

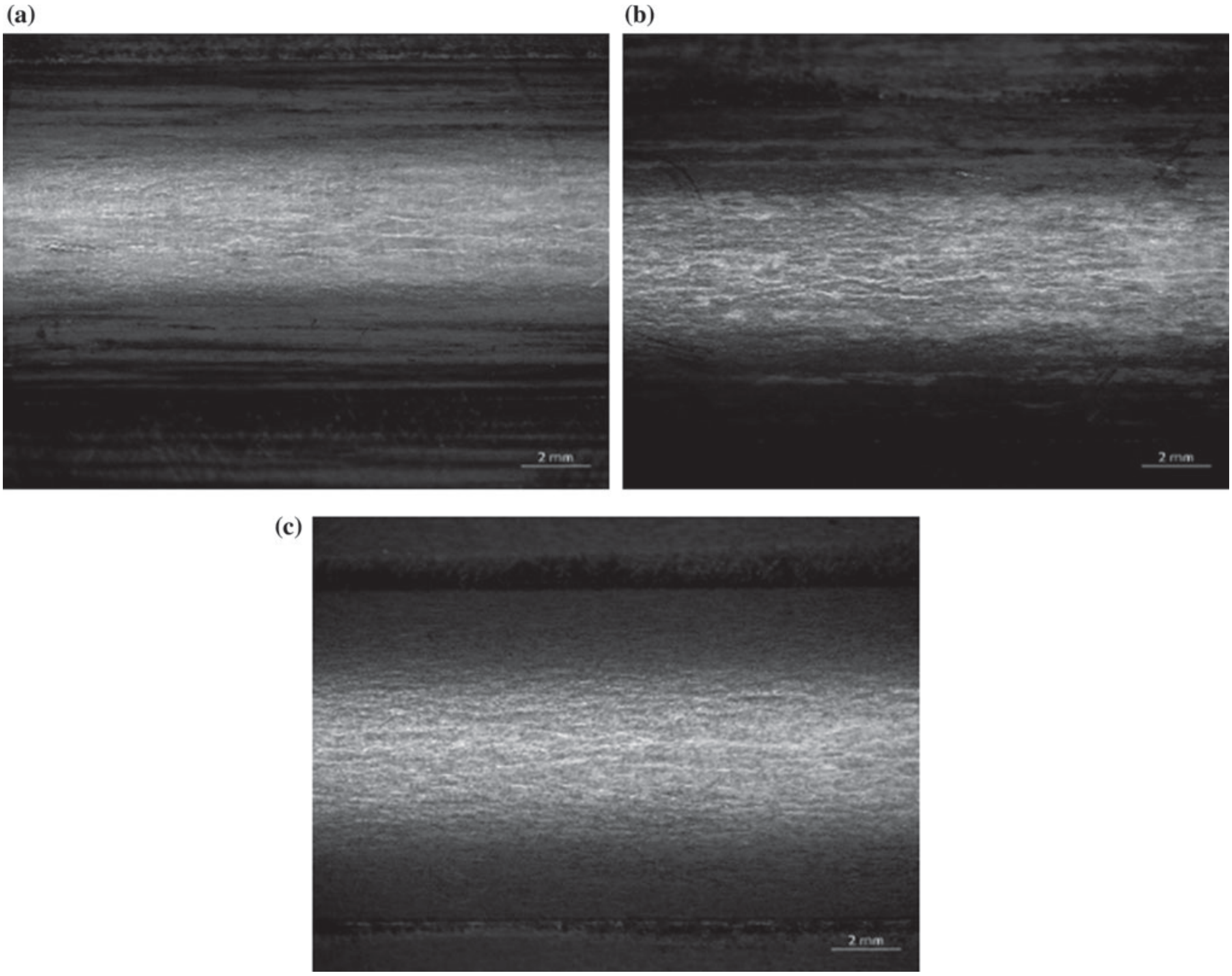

Fig. 18 P1 bending images (0,65x) of the high temperature intermediate annealed samples under a stereo microscope; **a** 3.2% Mg, **b** 3% Mg, **c** 2.8% Mg

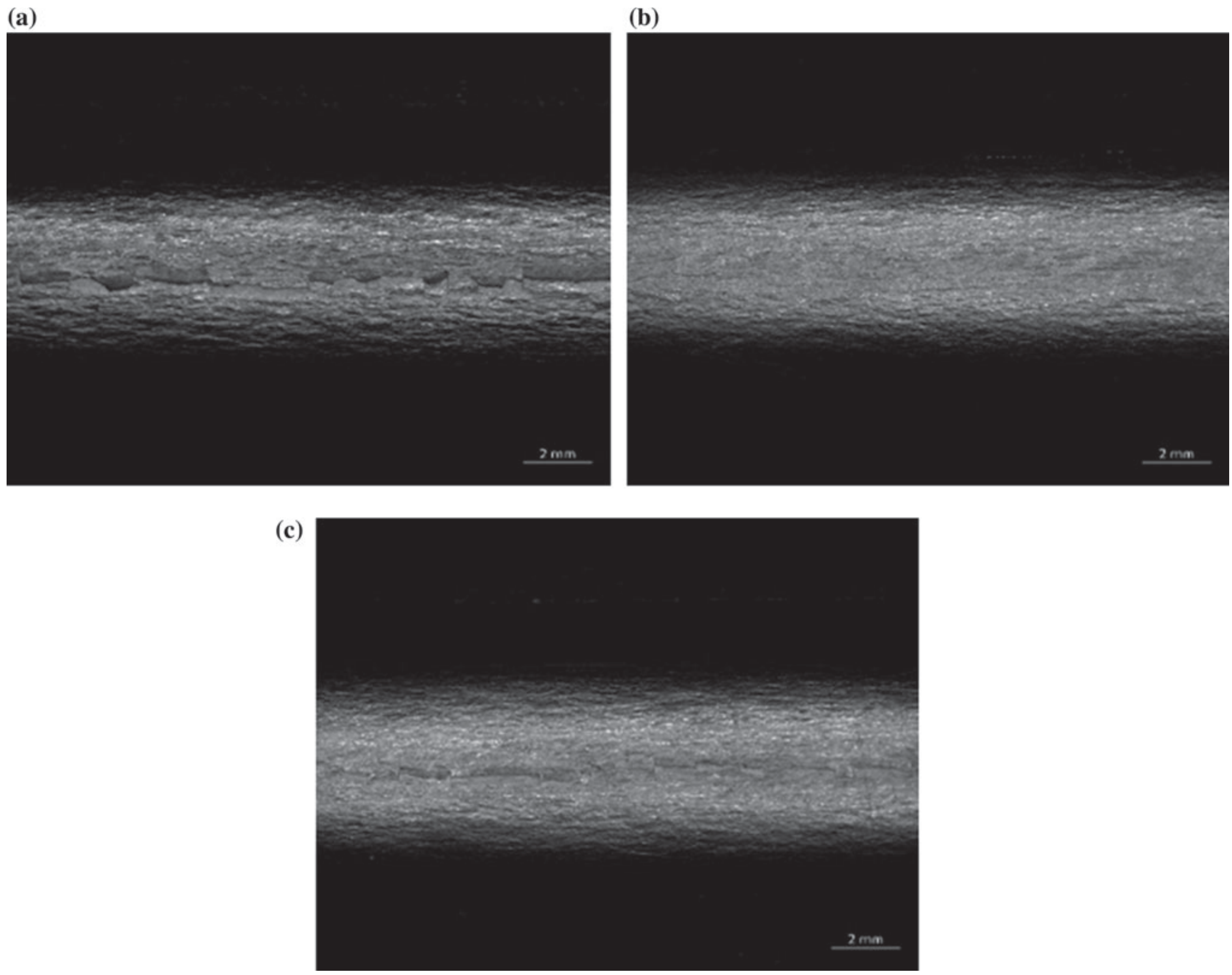

Fig. 19 P2 bending images (0.65x) of low temperature intermediate annealed samples under a stereo microscope; **a** 3.2% Mg, **b** 3% Mg, **c** 2.8% Mg

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