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MICROSTRUCTURAL CHANGES ANALYSIS IN ADVANCED HIGH STRENGTH STEELS DUE TO THE SPRINGBACK EFFECT

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Abstract

This work studies the springback effect on four kinds of steels, namely, the dual-phase, low carbon, bake hardening, and interstitial-free steels, currently used as feedstock in vehicle production. In this context, it is inserted the development of a new cutting edge high strength steel in accordance with the ULSAB-AVC project which aims to produce safer and more economical vehicles for the 21st century. The springback effect mechanical characterization was performed by means of sheet metal forming, called as three-point air bending, in which samples were subjected to following internal bending angles: 30º, 60º, 90º, and 120º and then the value of the new internal bending angle was measured, after sheet metal forming. It was also evaluated the mechanical properties of

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the material defined by the tensile test in order to determine its tensile strength, yield strength, and elongation. Furthermore, the cutting edge steel's microstructural characterization was performed by identifying and quantifying the present phases in coexistence by means of digital image processing. The results indicate that the springback effect in the dual-phase steel has the highest springback rate due to its high mechanical strength, and it causes a decrease in the aspect ratio of the grains that suffered mechanical bending with the attempt of returning them to their original form. Low carbon and bake hardening steels have not enough springback effect to cause a change in the grains shape, and the change of the aspect ratio depends on the combination of both elongation and mechanical strength of these steels. In the case of interstitial-free steel, due to its lower mechanical strength, the springback effect has the lowest rate, and the change in aspect ratio depends only on the elongation capacity of the steel. Therefore, it is concluded that the most resistant steel and structural use in automobiles, are the ones who suffer the most springback effect, so it is necessary to find methods for reducing this effect.

1. Introduction

Fossil fuel burning causes imbalances in the ecosystem, so the automobile industry has been having the need of reducing the weight of their products in order to minimize fuel consumption, thereby reducing cost and possible environmental aggressions, which are caused directly or indirectly by the use of such products. Thus, the latest generation cars should be lighter, more economical, safer, and environmentally cleaner [1]. Thus, steel industries, in response to their customers need, developed advanced high strength steels (AHSS) in order to ensure the production of components with the same mechanical strength levels, but with a lower amount of material [2].

However, the widespread use of AHSS in the automotive industry is limited due to challenges in formability, union sheet metal, tool life, and to the springback effect. It is a major problem that compromises the mass production of automotive structural components with AHSS [3]. The resistance of steel sheets is becoming increasingly higher, and the sheet of ultra-high strength steels with tensile strength higher than 1GPa have recently been developed. However, most sheets are currently used in cars with tensile strength of 590MPa or less [4], and the use of ultra-high strength steel sheet is still limited due to their great springback effect.

The springback effect is identified as a change occurring in the shape of the sheet after the removal of the bending tool due to a redistribution of residual elastic tension [5]. Therefore, in order to find solutions to eliminate or reduce this effect, it is essential to predict the occurrence of this effect during the component design, correlated with the microstructural and mechanical properties of the material.

The four types of steels studied in this work are among the major steels used by automobile industries nowadays, in the case the dual-phase steel (DP), the low carbon steel (LC), the bake hardening steel (BH), and the interstitial-free steel (IF). Such materials have mechanical characteristics which are suitable for use in industry, but at the same time having dimensional problems due to the springback effect. Therefore, it is necessary a reproduction of this effect by sheet metal forming, most commonly used in industry for comparing them in order to reduce this effect.

2. Experimental Procedure

2.1. Metallography before the conformation

The following metallographic preparation processes are standardized by ASTM ID: E 3-10 (2007). Test specimens were made from DP, LC, BH, and IF steels, as received at the dimensions of 10mm long, 10mm wide, and 0.8mm thick.

After sectioning the rolling longitudinal direction, the specimens were subjected to a hot embedding with bakelite. In the sanding, the following abrasives were used: 220, 320, 400, 600, 1000, and 1200 mesh. The polishing was performed in an OP-U solution with distilled water, subjecting the specimens to a rotation of 600rpm. The chemical etching was performed with a 2% Nital solution to reveal the grain boundaries of ferrite, as well as its constituents [6].

The micrographs were obtained by using a NIKON optical microscope, model EPIPHOT 200. The image processing was done by using the Image J 1.45 software. All images were standardized in the same lighting conditions and gray shades scale, with the use of enhancing contrast normalizing, and histogram equalization tools.

2.2. Sheet metal forming

Test specimens were made from the same material that was delivered, and sectioned at the following dimensions: 80mm long, 30mm wide, and 0.8mm thick. Such dimensions of the specimens were established according to the parameters defined for the unconstrained cylindrical bending test, presented during the Numisheet conference in 2002 [7].

The specimens were subjected to a test called as the three-point bending in air. This experiment was made by adapting the unconstrained cylindrical bending test method, in which the specimen was subjected to a punch with the cylindrical body. The punch had a 5mm radius, and the distance between the supports of the die was 13mm, according to the ASTM ID: E 290-09 standards for a sample thickness of about 1mm. The three-point bending in air was performed in a universal Shimadzu testing machine, Autograph AG-X model 50kN. The specimens were subjected to sheet metal forming until the bending internal angle reached a predetermined value. The selected values for the internal angle bending were: 30, 60, 90, and 120 degrees for each bend, respectively, using three replicates for each angle in the same material. The punch was removed from the material 20 seconds after reaching the bending angle, and then the measurement was made with a new bending angle to determine whether there was a springback effect or not. For this measurement, the Image J 1.45 software was used for processing images photographed on an Olympus digital camera. Such measurements were made up to a period of 12h, 24h, 48h, and 72h after sheet metal forming. Having the 72h after the sheet metal forming been completed, the angle bending resulting was subtracted from the initial angle which were 30^o, 60^o, 90^o or 120^o, and this subtraction resulted in a total springback effect angle $(\theta_1 + \theta_2)$, as shown in Figure 1.

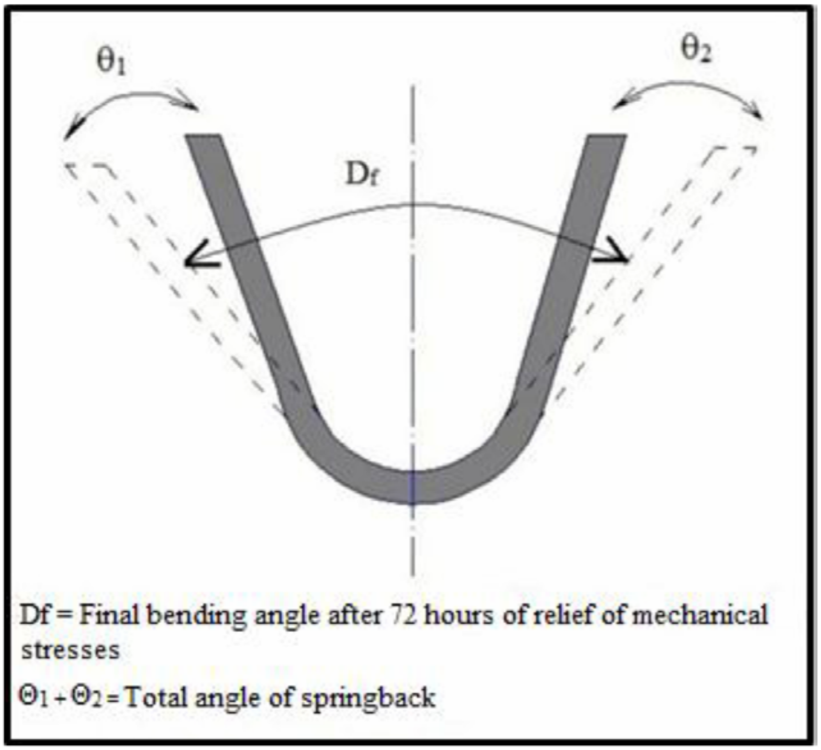

Figure 1. Representation of a specimen steel sheet undergoing to the springback effect.

2.3. Metallography after sheet metal forming

Test specimens were made from materials that were subjected to sheet metal forming after 72 hours of evaluation, with the following dimensions: 10mm length × 10mm wide × 0.8mm thick. The chosen region of the steel plates to obtain the specimens was the one when a curvature was formed due to sheet metal forming. The specimens were cut in a longitudinal direction, i.e., in the direction of steel sheets lamination by dividing them in the middle, and embedding them in order to expose their inner surface, as well as to obtain samples of the region that was deformed during the sheet metal forming.

The metallographic analysis followed in the same manner as in the pre-sheet metal forming, with the use of hot embedding, polishing, and afterwards, the chemical etching was made with a 2% Nital solution. 30 pictures were analysed for each treatment.

The aspect ratio of a geometric shape is the ratio of its sizes in different dimensions. For example, the aspect ratio of a rectangle is the ratio of its longer side to its shorter side – the ratio of width to height, when the rectangle is oriented as a "landscape". The aspect ratio is expressed as two numbers separated by a colon ($x : y$). The values x and y do not represent actual widths and heights but, rather, the relationship between width and height. As an example, 8:5, 16:10, and 1.6:1 are three ways of representing the same aspect ratio.

3. Results and Discussion

With respect to mechanical properties, their values, shown in Table 1, were obtained by tensile tests, extracting the specimens in a transverse direction at 45 degrees to the lamination direction of the material. In Table 1, the tensile strength is designed by RT in MPa, yield strength by LE in MPa, and elongation by Elong in %.

Table 1. Mechanical properties of materials dual-phase steel – DP, low carbon steel – LC, bake hardening steel – BH, and interstitial free steel – IF

Material	RT (MPa)	LE (MPa)	Elong (%)
DP	623.6 ± 2.9	407.3 ± 3.6	23.4 ± 1.4
LC	353.9 ± 0.7	232.4 ± 7.1	30.0 ± 2.2
BH	320.9 ± 5.3	198.7 ± 3.9	33.4 ± 1.7
IF	298.0 ± 2.1	147.9 ± 3.8	40.9 ± 1.9

As shown in Figure 2, the dual-phase steel showed the greatest springback angle (between 7 and 9 degrees), and the interstitial-free steel had lower angles (between 4.5 and 6 degrees). Thus, Figure 2 shows the results that can be compared with Gan's work, whereby it was concluded that materials with higher yield strength tend to have greater springback effect, as compared to other materials with lower yield strength [8].

Also, as shown in Figure 2, the angular variation of the springback effect was increased from 120° to 30° for the tested steels. This means that as the internal angle bending was reduced which were 120°, 90°, 60°, and 30°, respectively, an increase in the springback effect occurred, i.e., to the dual-phase steel, a decrease in the internal angle bending caused a greater springback effect.

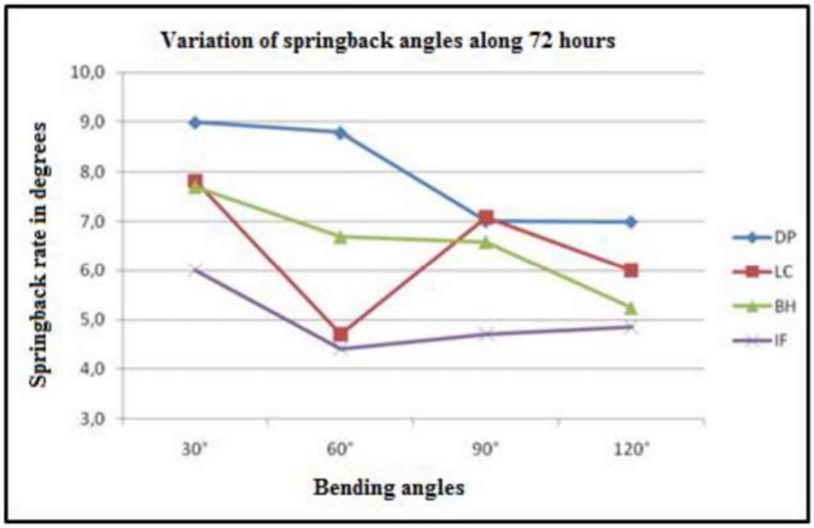

Figure 2. Angle variation of the springback effect for different bending angles after 72 hours.

ANOVA was used as a statistical tool for interpreting the results. It is an analysis of variance and it is an average comparison test of the treatments wherein it was used a two-factor ANOVA type with repetition submitted to an F test at a significance level of 5%. The software used for this function was the Minitab 14.

In the case of the dual-phase steel, Figure 3 shows that the amount of springback effect was lower for the treatment of 120° which presented the highest average aspect ratio values which was different from the other treatments. Therefore, the aspect ratio was higher for a lower springback effect treatment.

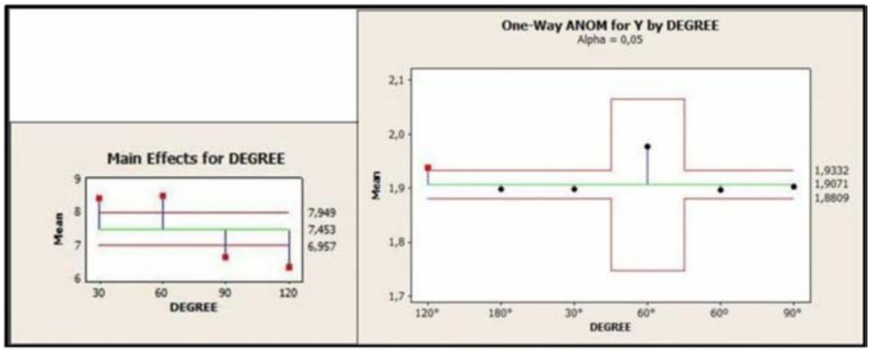

Figure 3. Analysis of variance at 5% level of significance by Minitab software 14 for the effects of the degree in the amount of springback and in the aspect ratio of the grains of dual-phase steel.

Figure 4 from (a) to (f) shows images of the dual-phase steel microstructure obtained by an optical microscopy. It is observed the presence of martensite microstructure (dark portion) in all images, like islands immersed in the ferrite matrix (light portion). Image (a) of Figure 4, for the material as delivered, had no significant visual differences regarding size and shape of ferrite grains in relation to the images (d), (e), and (f). Images (b) and (c) differ from others because it is observed the presence of more elongated ferrite grains in its transverse direction (arrows). Thus, this material, when subjected to the treatment of 120º, presented the highest aspect ratio.

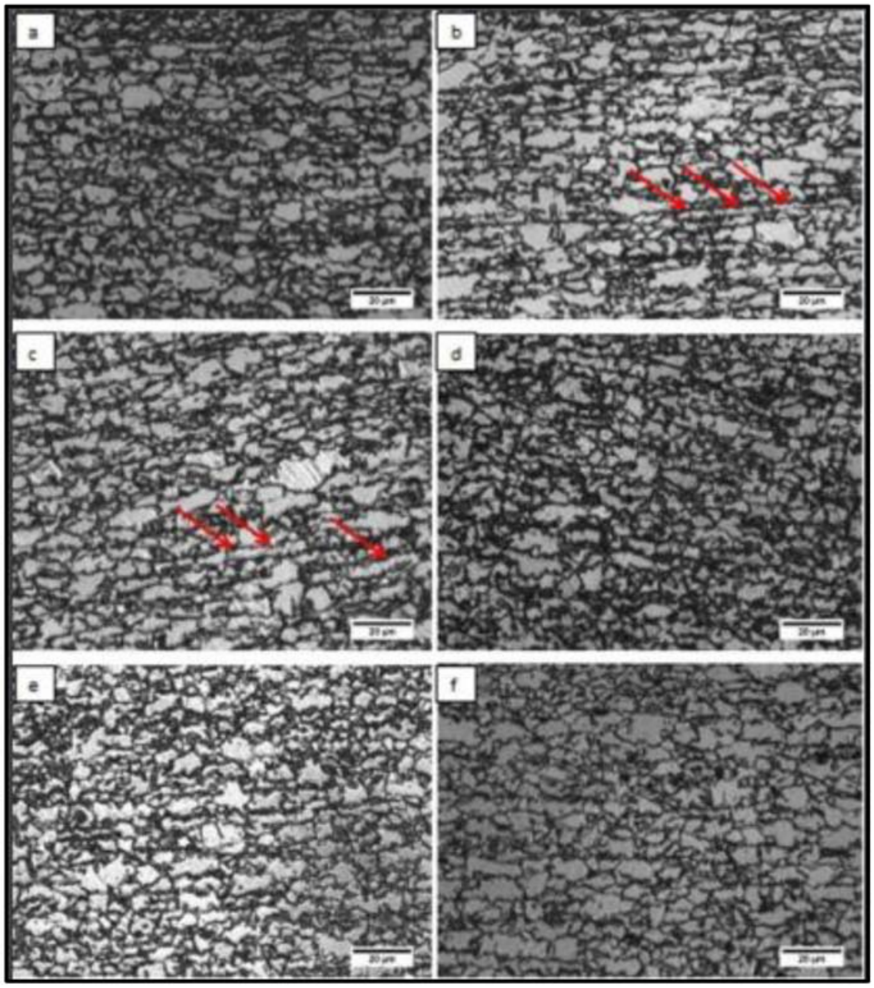

Figure 4. Optical microscopy images dual-phase steel as received and subjected to sheet metal forming, where (a): material as received, (b) and (c): 120º, (d): 90º, (e): 60º, and (f): 30º, increase of 500×, reagent Nital 2%.

Figure 5 refers to the analysis of variance for low carbon steel, demonstrating that the treatment at 30º had the greatest springback effect followed by the treatment at 90º, but the latter was statistically different from the former. These same treatments had the lowest aspect ratio, and were statistically different from the other ones.

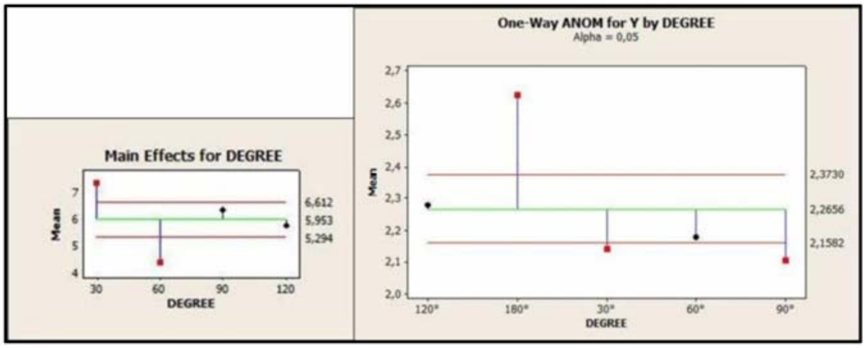

Figure 5. Analysis of variance at 5% level of significance by Minitab software 14 effects of the degree in the amount of springback and in the aspect ratio of the grains of low carbon steel.

In Figure 6 from (a) to (f), there is the presence of a ferrite microstructure. In image (a), it is noted that some ferrite grains have a more elongated aspect in the rolling direction. The material, as delivered, therefore has a higher aspect ratio. In picture (b), there is a decrease in grain size and a lower elongation in the rolling direction. This can be confirmed in Figure 5, where at 120º, the treatment showed a decrease in its aspect ratio when compared to the material as delivered.

The most rounded grains, i.e., in which there are hardly any dimensional differences between the longitudinal and transversal direction whose aspect ratios tend to approach the circularity, are observed in images (c) and (d) represented by treatment samples at 90º which gave the lowest aspect ratio, as shown in Figure 5. Picture (e) presents grains slightly elongated in the rolling direction in comparison to images (c) and (d), confirming the greater aspect ratio of treatment at 60º with respect to treatment at 90º. And picture (f) relating to treatment at 30º has a larger amount of grains that are more rounded than the previous one at 60º, whereas the treatment at 30º had lower aspect ratio compared to the one at 60º, as shown in Figure 5.

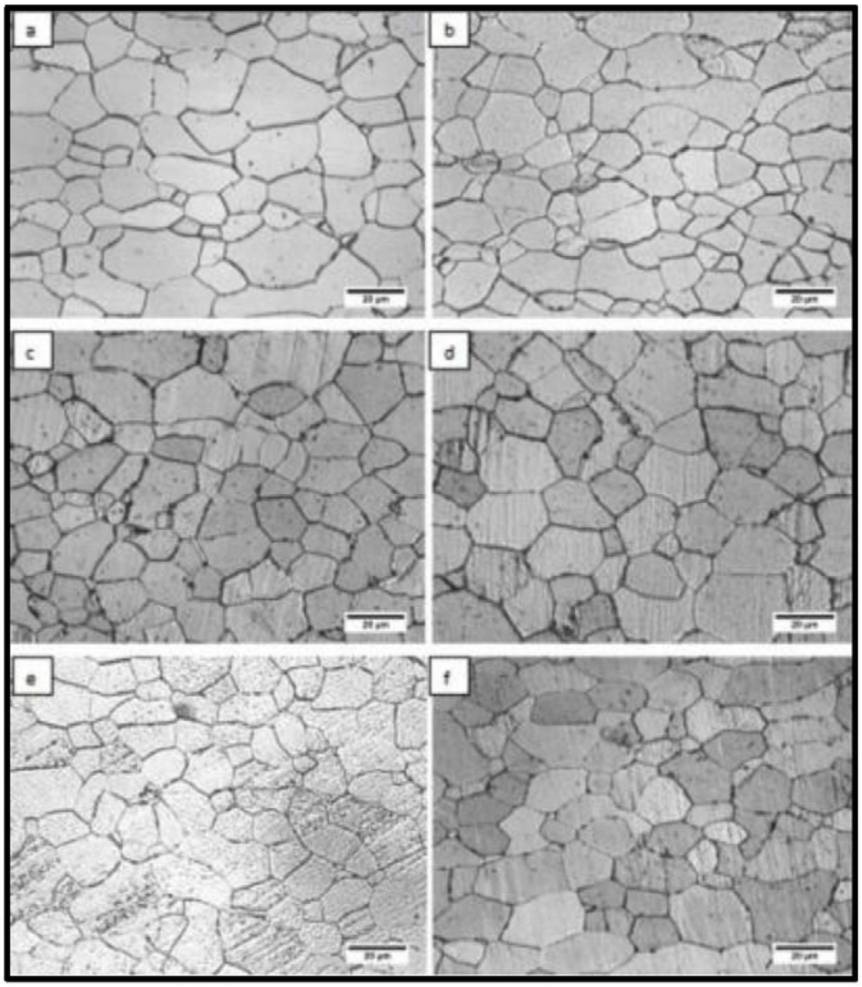

Figure 6. Optical microscopy images low carbon steel as received and subjected to sheet metal forming, where (a): material as received, (b): 120º, (c) and (d): 90º, (e): 60º, and (f): 30º, increase of $500\times$, reagent Nital 2%.

From Figure 7, which shows an analysis of Minitab software 14 for the bake hardening steel, the treatments at 120º and 30º statistically differ from the others. The treatment at 120º had the lowest springback effect and the highest aspect ratio, whereas the one at 30º had the highest springback effect and the lowest aspect ratio.

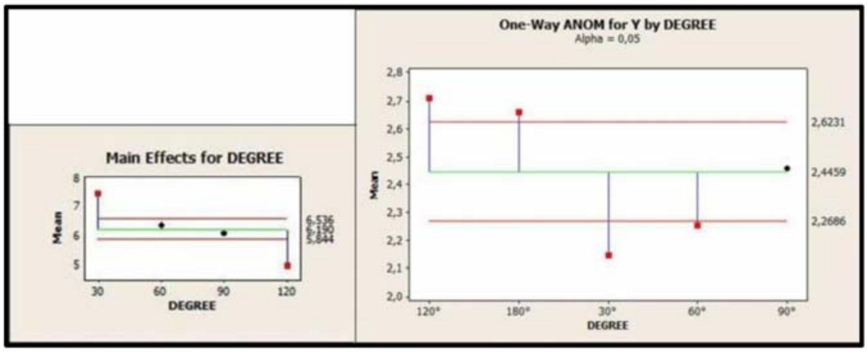

Figure 7. Analysis of variance at 5% level of significance by Minitab software 14 for the effects of the degree in the amount of springback and in the aspect ratio of the grains of bake hardening steel.

Figure 8 from (a) to (f) shows images the bake hardening steel microstructure obtained via optical microscopy, and it was noted the presence of ferrite microstructure in all images. In image (a), it is possible to observe the presence of ferrite grains which are more elongated in the rolling direction, indicating a high aspect ratio as it may be confirmed in the material as delivered to the treatment at 180º, shown in Figure 7. In images (b) and (c), for the treatment at 120º, the arrows indicate the presence of ferrite grains that are more elongated in the rolling direction. Therefore, this treatment has high aspect ratio, as it can be confirmed according to Figure 7.

It is observed in image (d) smaller sizes of ferrite grains, giving lower aspect ratio with respect to the previous treatments. Picture (e) has more elongated grains in the rolling direction since they were bent at 60º, but are less deformed than the ones of the treatment at 120º, and thus with a lower aspect ratio. In picture (f), it is observed that the ferrite grains are aligned in the same direction, since they were bent at 30º, and the bake hardening steel has a higher elongation rate, although this treatment obtained a lower aspect ratio, and their grains presented much smaller and less elongated aspects if compared to previous treatments.

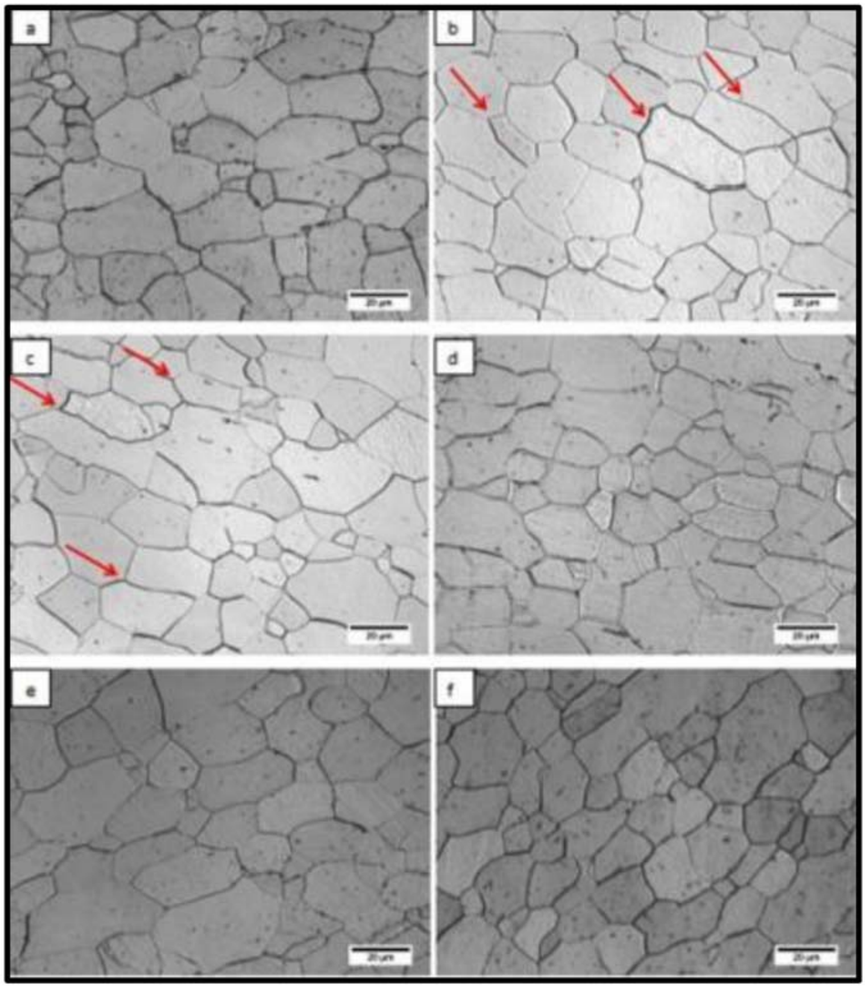

Figure 8. Optical microscopy images bake hardening steel as received and subjected to sheet metal forming, where (a): material as received, (b) and (c): 120º, (d): 90º, (e): 60º, and (f): 30º, increase of 500×, reagent Nital 2%.

From Figure 9, it is possible to better observe the effect of the degree in the aspect ratio, concluding that the treatment at 30º obtained the highest springback effect and the highest aspect ratio, differing significantly from other treatments.

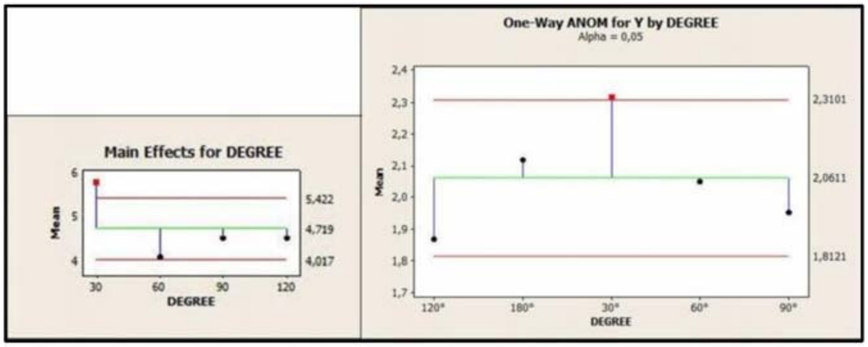

Figure 9. Analysis of variance at 5% level of significance by Minitab software 14 the effects of the degree in the amount of springback and in the aspect ratio of the grains of interstitial-free steel.

In Figure 10 from (a) to (f), which are images of microstructure of the interstitial-free steel, it is noted the presence of ferrite microstructure. The images of (a) to (d) had similar levels of aspect ratio, as shown in Figure 9, as can be seen in the micrographs, the shapes and sizes of the ferrite grains did not suffer significant changes from each other.

Images (e) and (f) show ferrite grains more elongated in one direction, as indicated by the arrows. These grains have also to be flatter when compared to image (d) for the treatment at 60º, so images (e) and (f) obtained from the treatment at 30º should have a higher aspect ratio, as evidenced by Figure 9.

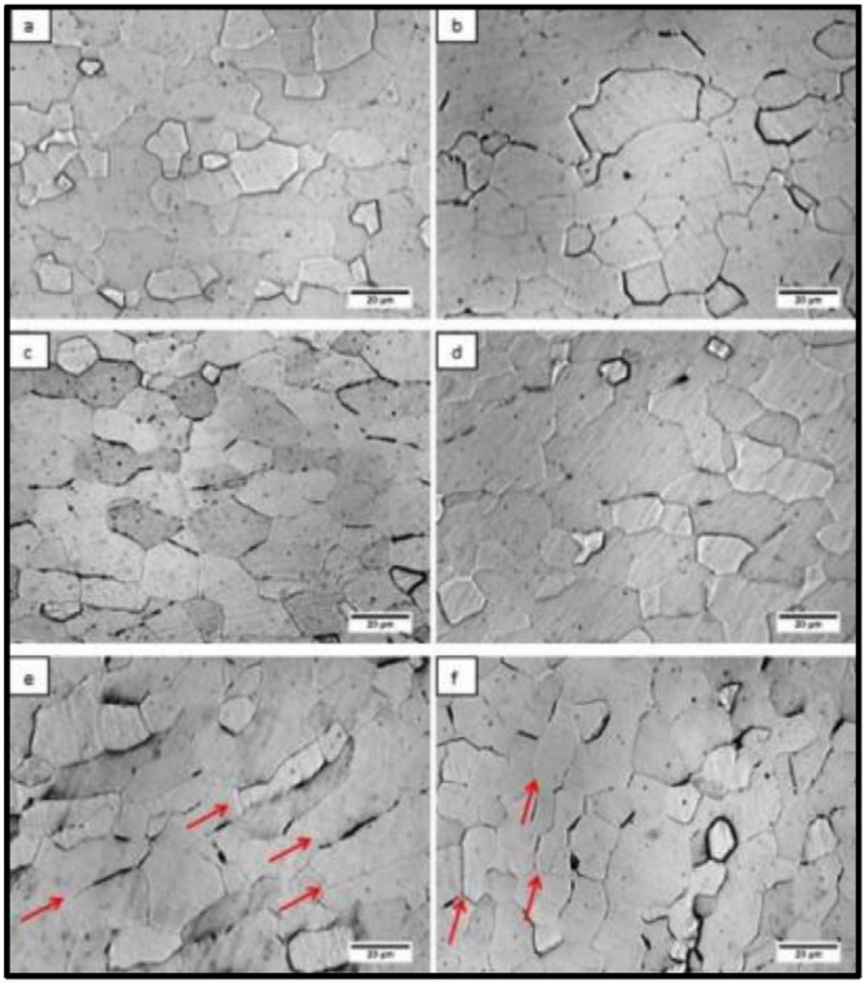

Figure 10. Optical microscopy images interstitial free steel as received and subjected to sheet metal forming, where (a): material as received, (b): 120º, (c): 90º, (d) and (e): 60º, and (f): 30º, increase of 500× , reagent Nital 2%.

The variation in the aspect ratio is also influenced by the springback effect, and not just by the rate of the steel's elongation that can be evidenced by analysing the dual-phase steel which presents the lowest elongation rate among the four materials. Thus, if the aspect ratio were influenced only by the elongation rate, all other sheet metal forming treatments for this steel would have aspect ratios which are statistically identical to the material as delivered. However, for the treatment at 120º, its aspect ratio was statistically higher than that of the material as delivered, since this treatment had the lowest springback effect, which was not sufficient to reduce the sheet metal forming effects. In all sheet metal forming treatments, the dual-phase steel lengthened, but the high springback effect of treatments at 90º, 60º, and 30º were sufficient to return the grains to their original shapes, resulting in similar aspect ratios of the material as delivered.

Therefore, in the dual-phase steel, the aspect ratio variation is independent of its elongation rate of the grains because there was a severe reduction of the internal bending angle which caused a high aspect ratio for sheet metal forming. This aspect ratio decreases after the springback effect, and it increases with the internal bending angle decrease due to its high yield strength.

For the low carbon steel, the treatments at 90º and 30º obtained the greatest springback effects in increasing order, respectively. Then, it is expected that their aspect ratios would increase from 30º to 90º, considering that such treatments are following the same line of results as the dual-phase steel, in which an increase in the springback effect from one treatment to another caused a decrease in the aspect ratio from one treatment to another in the same order.

However, for the low carbon steel, the lower aspect ratios increased from 90º to 30º. There was, therefore, the opposite from what was expected. This may be due to their elongation rate percentage, compared to the dual-phase steel which presents itself 7% higher. This higher percentage of elongation may have been responsible for resulting in an aspect ratio which was slightly higher at 30º, even though this treatment had the greatest springback effect since, according to Callister, the aspect ratio of steel sheets is directly influenced by the elongation rate of the material [9].

Summarizing the main results to the bake hardening steel and correlating the springback effect with the microstructure, it can be said that the greatest effect springback was obtained in the treatment at 30º, which had the lowest aspect ratio. The smallest springback effect occurred in the treatment at 120º, and this treatment had the highest aspect ratio. Thus, still with the bake hardening steel, it is found that in high strength steels, higher springback effect causes a lower aspect ratio and vice-versa, as occurred for the dual-phase and low carbon steels.

In the case of the bake hardening steel, the value of the aspect ratio of treatment was at 120º to a value which was slightly above 180º for the treatment. This means that, during the sheet metal forming, the bake hardening steel had its elongated grains at 120º, and due to the lowest springback effect in this treatment, this effect was not quite sufficient to make such return to their grain original sizes, maintaining a more elongated aspect than in the material as delivered. This result was also influenced by the high elongation rate of the material that is 10% higher when compared to the dual-phase steel.

By establishing a relationship between the microstructure and the springback effect for interstitial-free steel, it is possible to say that the greatest springback effect occurred in the treatment at 30º, and this treatment had the highest average aspect ratio in its individual grains.

Therefore, it is possible observe that in the interstitial-free steel, the springback effect did not cause a decrease in the grain aspect ratio, as with the dual-phase, low carbon, and bake hardening steels.

The interstitial-free steel has lower yield strength and tensile strength limits when compared to the aforementioned steels, and allied to this, has an elongation rate which is 17% higher than the dual-phase steel.

Because of a lower mechanical strength of the interstitial-free steel in comparison to the other steels, a significantly different springback effect amount from the other treatments occurred only by applying the treatment at 30º, which was the most acute internal angle used.

As the interstitial-free steel is less resistant than the other ones, its springback effect is less evident, and it can be said that their grains have a lower need for stress relief after sheet metal forming when compared with more resistant steels, and their grains begin to present greater need to relieve stress only in more severe bending with more acute internal angles, causing a greater springback effect.

4. Conclusion

It is concluded that, for dual-phase steels, low carbon, and bake hardening ones, a higher springback effect causes a lower aspect ratio of grains, and a lower springback effect causes a greater aspect ratio of grains, which demonstrates they are high strength steels. And the opposite occurs for the interstitial-free steel in which a greater springback effect is followed by a greater aspect ratio of grains. The dual-phase, low carbon, and bake hardening steels, which are high strength steels showing a greater springback effect than the least resistant steel such as the interstitial-free steel, mainly due to the refinement of the grains present in more resistant steels, lead to an increase in the contact area absorbing more energy during sheet metal forming, resulting in higher toughness and, therefore, a higher residual elastic stress release during the springback effect is reached.

In the dual-phase steel, the aspect ratio is directly proportional to the internal bending angle, such as by a more acute angle, there is an increase in springback effect which causes a decrease in the aspect ratio. In this steel, the variation in the aspect ratio depends only on the mechanical resistance ability.

The low carbon and bake hardening steels suffered significant rates of springback due to their good resistance rates, but such springback rates are not enough to completely bring the grains to their original sizes before sheet metal forming. This is due to their greater elongation rate, thus the aspect ratio variation is dependent on the combination of the mechanical resistance and elongation ability in these steels.

In the case of the interstitial-free steel, the variation of the aspect ratio of their grains is inversely proportional to the internal angle of bending, such as by a decreasing angle, there is an increase in their aspect ratio. Therefore, for this steel, as opposed to the dual-phase steel, the variation of aspect ratio depends on its elongation ability.

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