INFLUENCE OF THE MICROSTRUCTURE ON THE MECHANICAL PROPERTIES OF ALUMINIUM FOIL

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Abstract

The relations between alloy composition, microstructure, and mechanical properties have been investigated for aluminium foils rolled from a number of strip cast or DC cast alloys. The results show that the yield strength of commercial soft annealed foils is solely determined by the grain size. The Mullen burst strength depends strongly on foil gauge and has a close relation to the tensile strength and ductility of the material. The burst strength can be approximately calculated from gauge, elongation at fracture, and tensile strength with a simple formula. If the grain size is larger than 1/5 of the foil thickness the ultimate tensile strength and particularly the elongation at fracture are strongly reduced and they decrease with increasing grain size. The reason is that when the grain size becomes larger there is a probability that some grains extend through the whole thickness of the foil. Such a grain lacks the constraints of the surrounding grains and when the foil is strained the grain is more susceptible to localized deformation leading to an early fracture. The tensile strength of the foil also depends on the strain hardening capacity of the alloy. It is shown that the strain hardening includes dispersion hardening and probably also grain boundary hardening. The dispersion hardening increases with increasing number of second phase particles of some minimum size i.e. increasing alloy content of iron.

Introduction

Aluminium thin foil is produced in two different ways starting either from a DC cast ingot which is hot rolled to 3 - 6 mm or from a twin roll cast 6 - 7 mm thick sheet. In both cases the sheet is normally cold rolled to the final gauge with an intermediate anneal at 0.5 - 1 mm. A final annealing is performed not only the foil soft and formable but also to remove the rolling oil. The major part of the DC cast foils is produced from the AA1100 or AA1200 alloys which typically contain about 0.6 % Fe and 0.2 % Si and in AA1100 also 0.1 % Cu. To obtain good foil properties from strip cast sheet the silicon concentration must be increased compared to the AA1200 alloy. A silicon content of about 0.5-0,7 % is rather common which means that the alloy designation is AA8011 or AA8111.

One advantage with the strip casting is that the foil usually is stronger compared to most commercially available DC cast foils. The mechanical properties are usually very uniform, both within a coil and between different coils. The reason is that the twin roll strip casting route does not include any high temperature deformation after casting during which non-uniform temperature distributions can occur.

The important mechanical properties of aluminium foil are the Mullen burst strength and the yield strength, $Rp_{0,2}$. A high burst strength is an advantage in all foil applications. The desired yield strength level varies depending on the product. Household foil is expected to be "fold soft" which means that the yield strength, $Rp_{0,2}$, shall be low. A light gauge converter foil shall on the other hand have a sufficient yield strength to avoid band breakage during lamination. The aim of the present paper is to discuss the microstructural features which govern the yield and burst strength of a foil. Various aspects of this matter have been the subject of some interresting papers [1 - 7].

Yield strength

A result of the interannealing is that the amounts of elements in solid solution are reduced to very low levels. An exception is the AA1100 alloy with its copper content which gives a small contribution to the yield strength. In the absence of any appreciable solution hardening the yield strength is expected to be controlled by grain boundary hardening and thus determined solely by the grain size. This is confirmed by the results shown in Figure 1 for different foil alloys. For each material in the diagram different yield strengths have been produced by annealing at different temperatures. The grain size has been determined by scanning electron microscopy when the grain size has been too small for the optical microscope. (All data points seem to lie on the same straight line with the exception of the data for AA8011. This deviation is probably caused by an inhomogeneous grain structure. The grain size at the surface is smaller than in the centre of the foil where it was measured). The figure shows that the yield strength is inversely proportional to the grain size.

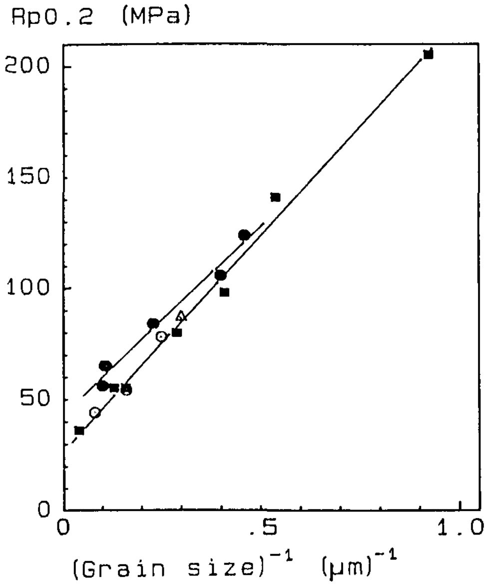
Mullen burst strength

Typical data for the Mullen burst strength as a function of the foil gauge for different commercial foil materials are shown in Figure 2. The burst strength varies strongly not only with foil thickness but also with alloy composition, particularly iron content, and process route.

Amann and Lange [5] have shown that the burst strength, p, should be related to the foil thickness, t, the tensile strength, Rm, and the elongation at fracture, A, in the following way:

$$p \sim t \cdot Rm \cdot A^{1/2} \qquad (1)$$

The influence of the foil gauge, t, on the Mullen burst strength and the relation between the burst strength and the tensile properties transverse to the rolling direction have been examined for a large number of foils of different alloys, gauges and tempers from both hot rolled and strip cast materials. A multiple regression analysis has been performed between the logarithm of the burst strength and the logarithms of t, R_m and A_{50mm}. The correlations were strong and the regression coefficients were 0.91, 0.76 and 0.48 respectively. If the coefficients were changed to 1, 1 and ½ instead in Eq.(1), in accordance with the suggestions of Amann and Lange, the fit was practically as good as with the coefficients found in the regression analysis. This relation is shown in the diagram in Figure 3.



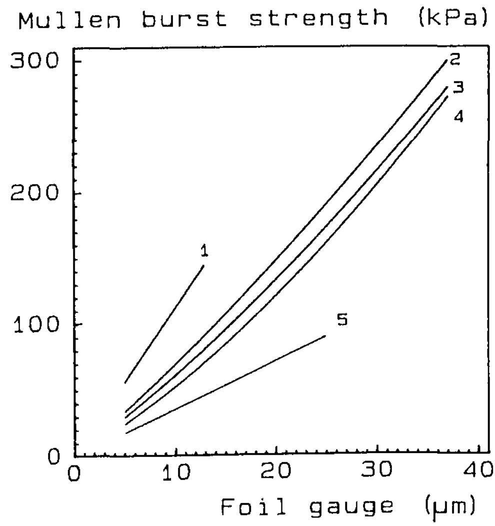


Figure 1. Plot of yield strength versus the inverse of the grain size.
Open circles: Strip cast, interannealed 8,7 μm AA8111 foil.
Open triangle: Strip cast, interannealed 6,4 μm AA8014 foil.
Filled circles: Strip cast, not interannealed 100 μm AA8011 foil.
Filled squares: DC cast, not interannealed 150 μm AA8079 foil.

Figure 2. Typical data for the Mullen burst strength for soft annealed foils of different alloys as a function of foil gauge.
1 Strip cast AA8014 (1,5 % Fe, 0,5 % Mn)
2 DC cast AA1200 (0,8 % Fe, low Si)
3 Strip cast AA8111 (0,5 % Fe, high Si)
4 DC cast AA1200 (0,6 % Fe, low Si)
5 Strip cast AA1050 (0,3 % Fe, low Si)

The results above clearly demonstrate the strong influence of the foil gauge and the fact that in order to obtain a high burst strength the foil must be both strong and ductile. Factors that improve the ultimate tensile strength and the elongation at fracture will also increase the burst strength.

Grain size and elongation at fracture.

Both R_m and A_{50mm} are known to drop with decreasing gauge. It has been shown that if the mean grain size becomes larger than about 1/10 - 1/5 of the sheet thickness both the elongation at fracture and the tensile strength will decrease [4,8]. As a typical grain size of fully soft foil is around 20 μm aluminium foils have low tensile strength and elongation at fracture, both of which decrease with decreasing foil gauge. This fact is well illustrated in Figure 4 in which the elongation at fracture and the tensile strength is plotted as a function of the foil gauge for AA8111 strip cast foils. As the mean grain size is about 15 μm for the fine grained foils and 40-60 μm for the coarse grained independent of gauge, the drop in the tensile properties is

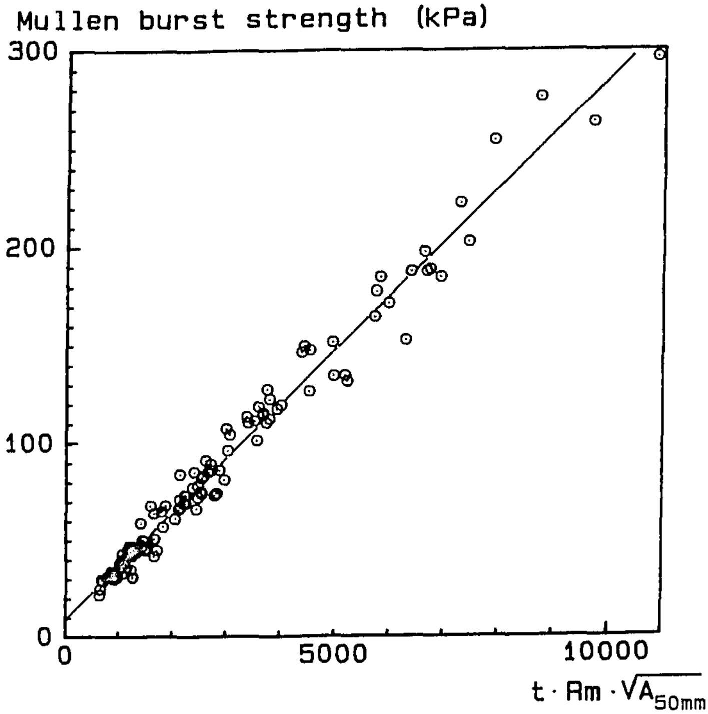


Figure 3. The relation between the Mullen burst strength, p, and the foil gauge, t, tensile strength, R_m, and elongation at fracture, A_{50mm}. The straight line is a representation of $p = 8.8 + 0.0277 \cdot t \cdot R_m \cdot A^{1/2}$, with t in µm, R_m in MPa and A_{50mm} in %.

expected to occur at about 75 µm and 250 µm gauge respectively. The experiments show that the drops in the elongation at fracture occur at about 100 µm and 200µm. The positions of the drops scale rather well with the differences in grain size of the foils.

In Ref. [8] the reason for the effect of the grain size on the tensile strength and elongation is considered to be a reduced strain hardening capacity of the material with increasing grain size to foil gauge ratio. That this is not a correct explanation is shown by the stress-strain diagrams in Figure 5 for two foils of very different gauges from the same mother coil. The strain hardening i.e. the derivative of stress with respect to strain is also plotted in the diagram. Both the stress-strain curves and the strain hardening curves are very similar in all four foils independent of gauge. At a strain corresponding to the uniform elongation the stress, σ, shall be equal to the stress-strain derivate, dσ/dε. This is the case for the thicker foil but for the thin foil the fracture occurs at a lower strain. The cause of the reduced ductility has been discussed by Dover et.al. [4]. When a single grain takes up the full thickness of the sheet the deformation is concentrated to a few slip planes in that grain. The foil is locally thinned at the coarse grain, a crack is formed after a small total elongation, traverses the test specimen and causes an early fracture. In the present case when the mean grain size becomes larger than 1/5 times the foil gauge there is a

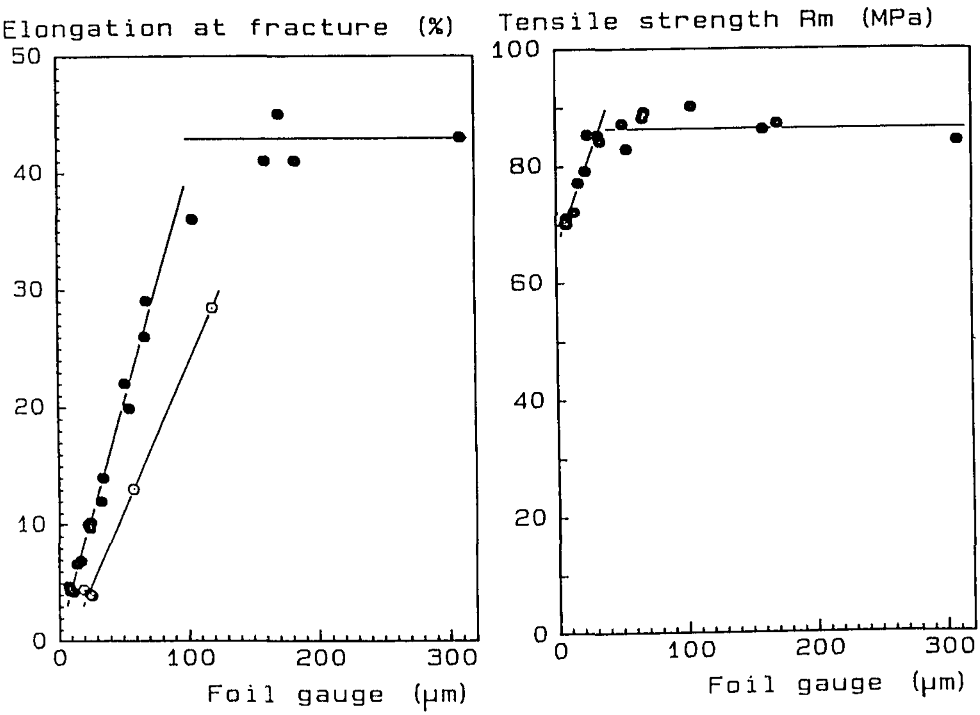


Figure 4. The influence of foil gauge on the tensile properties of strip cast, soft annealed AA8111 foil. Filled circles: grain size 15 μm. Open circles: grain size 40 - 60 μm.

not negligible probability for a few grains to take up the full thickness of the foil leading to a reduced ductility. Figure 6 shows the slip lines on the surface of a coarse grained foil.

Recrystallisation.

It follows from the results above that to improve the elongation at fracture and strength of a thin foil the grain size must be made smaller. It is known that an increased rolling reduction will change the mechanism for recrystallisation during annealing [9]. The first softening mechanism during annealing is a recovery process in which subgrains or grains are formed. If the rolling reduction is sufficient these can grow by a continuous grain growth where grains consume their next neighbours. The more rolling reduction applied before annealing the more extended is this grain growth and a greater part of the softening will take place by that "extended recovery" mechanism [9]. If the continuous grain growth can proceed to full softening the material is said to have softened by *continuous recrystallisation*. Continuous recrystallisation can give a very fine and homogeneous grain size.

When annealing after low to moderate rolling reductions the *final* softening will take place by *discontinuous recrystallisation*. Then a few grains grow faster than the other (sub)grains in the matrix during the recovery period. Discontinuous recrystallisation therefore usually gives a rather coarse grain size compared to the foil thickness.

Besides a high rolling reduction continuous recrystallisation down to soft tempers is favoured by a fine grain size of the material before cold rolling and, most important, the absence of precipitates hindering the growth of the grains. A very coarse grain size can be avoided by creating a large number of large particles by using a high iron alloy content and a high rolling reduction before annealing. In strip cast material the amount of iron in solid solution is very high as a result of the high solidification rate and absence of any high temperature heat treatment. The high silicon concentation used in the AA8111 alloy reduces the tendency to form coarse grains during intermediate annealing partly by increasing the size of the coarse particles formed during casting and partly by having an influence on the mode of precipitation during heating. The mechanism is the subject for a present research project at the Swedish Institute for Metals Research.

Intermetallic particles and the ultimate tensile strength.

The occurrence of grains that are comparable in size to the foil thickness leads to a premature failure of the foil and hence a lowering of the ultimate tensile strength, R_m. In order to study the influence of other microstructural features except coarse grains on the R_m a quantity must be

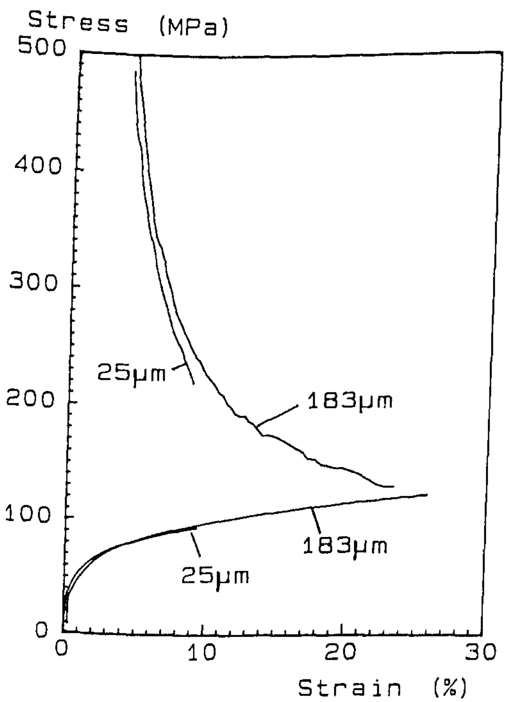


Figure 5. The lower curves show the stress-strain curves for soft annealed AA8111 foil at two different gauges. The upper curves give the derivative of stress upon strain.

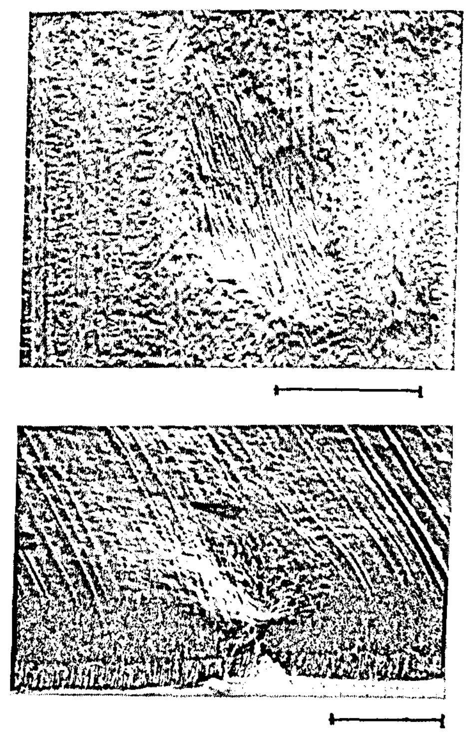


Figure 6. Surface and edge of a tensile test piece of a AA1145 foil with a few coarse grains. (The length of the bars is 100 µm)

found which is not influenced by the prematurel failure. As mentioned earlier the R_m is given by the condition that the derivative of stress upon strain, $d\sigma/d\varepsilon$, is equal to σ. Hence a high strain hardening capacity is necessary to reach a high R_m. The strain hardening of soft annealed aluminium alloys during cold deformation like tensile testing are for strains larger than a few percent often well described by a Ludwik-Hollomon relation:

$$\sigma = K \cdot \varepsilon^n \qquad (2)$$

where K and n are constants. The *true* ultimate tensile strength is then given by

$$\sigma_m = K \cdot n^n \qquad (3)$$

This means that the tensile strength increases proportionally to K but decreases weakly with n considering that actual values of n mostly are in the range 0.2-0.3.

The constant K has been determined for different soft annealed AlFeSi foil alloys by fitting Eq. 2 to the stress-strain curves obtained in tensile testing. The K values found are plotted versus the alloy content of iron in Figure 7. Unfortunately, it has not been possible to create both uniform grain structure and exactly the same grain size in the different groups of alloys as indicated by the different levels of yield strength in each group. Another complication is that different temperatures had to be used for different alloys. However, this inconsistency can be ignored as annealing the interannealed alloys at the same high temperatures as the non-interannealed did not change K significantly. Another feature which must be considered is the effect of crystalline texture but it is difficult to separate it from the influence of grain structure. As both the grain size and the texture are fairly constant within each group it can be concluded that K increases with the iron content of the alloy. The main effect of iron on strain hardening must be a result of dispersion hardening. Probably the smallest dispersoids do not interfere with the dislocations otherwise the strip cast alloys should have much higher tensile strength as they have many more but smaller intermetallic particles than the DC cast strips. The increased iron content gives a small reduction of the constant n in the Ludwik-Hollomon equation but this has only a marginal effect on the strain hardening.

Conclusions.

Burst strength is a complicated material property and a high value requires both a high strength and a good ductility of the material. This is demonstrated by the strong connection to both elongation at fracture and ultimate tensile strength. From the above it is clear that to obtain a high elongation in a foil the grain size shall be uniform and small compared to the foil thickness. A decrease of the grain size has a negative side-effect on ductility as it decreases elongation to diffuse necking. In order to obtain high elongation values the decrease of grain size must be balanced by an increase of strain hardening capacity. An increase of strain hardening capacity has a double effect on burst strength as it also increases tensile strength.

A fine grain size is obtained by process conditions which favour continuous recrystallisation, that is a high rolling reduction, precipitation of iron in coarse precipitates at an early stage and a fine grain size after interannealing [9]. The strain hardening capacity can be increased by increasing the iron content by means of dispersion hardening. The results in Figure 1 show that the very small grain size of a few microns or less necessary to obtain a good elongation at fracture in a thin foil will also give rise to a high yield stress which is not acceptable for certain products.

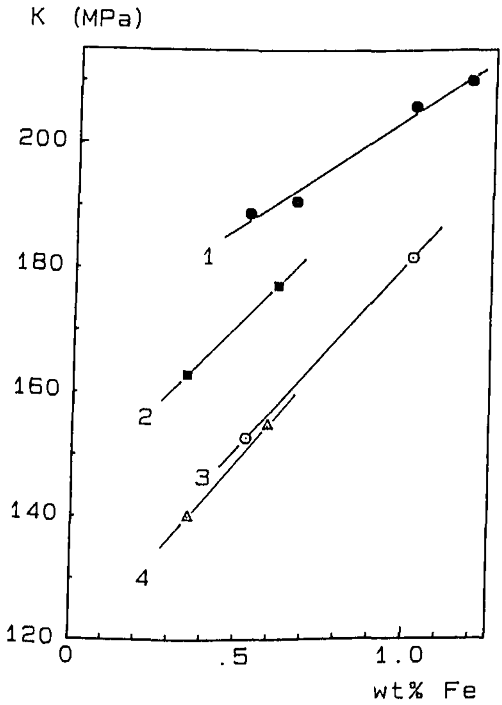


Figure 7. Plot of K in the Ludwik-Hollomon equation versus the alloy content of iron.

1. Strip cast, not interannealed foils with an Fe/Si ratio near 1 and $Rp_{0,2} = 40$ MPa.
2. Strip cast, not interannealed foils with an Fe/Si ratio >>1 and $Rp_{0,2} = 35$ MPa.
3. Strip cast, interannealed foils with an Fe/Si ratio near 1 and $Rp_{0,2} = 30$ MPa.
4. DC cast, interannealed foils with an Fe/Si ratio >> 1 and $Rp_{0,2} = 25$ MPa.

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