Mechanisms of Sagging during Brazing of Aluminium Heat Exchangers

Bevis Hutchinson[1], Olivier Rod[1], Margareta Nylén[1],

Annika Carlsson[2] and Anders Oskarsson[2]

[1] Swerea-KIMAB, Box 55970, SE-10216 Stockholm, Sweden

[2] Sapa Technology, SE-61281 Finspång, Sweden

Sagging is a creep deformation that tends to occur in high temperature brazing of aluminium heat exchangers. A method is described whereby sagging of test specimens is monitored continuously during simulated brazing cycles and this is applied to alloy sheets in various conditions. Sagging does not increase steadily with increasing temperature but occurs mostly during periods of recovery and recrystallisation, consistent with recent theories of grain boundary migration. Creep sagging involving grain boundary sliding is seen during a dwell time at the peak temperature. The tendency for sagging is shown to be very dependent on the prior microstructure of the sheet alloy and on its development during the brazing treatment.

1. Introduction

During the manufacture of brazed heat exchangers the assembled units are heated either in vacuum or in nitrogen gas such that the braze metal melts to create strong, tight and conductive joints between the different components [1]. Melting of the braze necessitates temperatures in the vicinity of 600°C where the strength of the components is quite low and there is a danger of the units sagging due to creep processes. Since the units are exposed to load during brazing in the furnace, the stresses in them may be significant and shape stability of the products is vital. It is therefore essential that the thin fins which provide the principal stiffening are able to resist creep sagging throughout the period of exposure to high temperatures. The progressive decrease in thickness of fin-stock alloys to reduce weight in vehicles means that sagging continues to present a challenge during brazing operations.

A generally accepted test is available to evaluate the tendency for sagging in these thin sheet materials [2] but there is no single standard for the thermal cycle and this may significantly influence the measured sagging. Typically, a cantilever strip of the sheet is heated in a furnace through a thermal cycle that simulates the brazing process. The distance that the end of the strip drops after the test gives a measure of the metal's sagging tendency, Fig.1(a). Although these tests give a useful indication of material quality, they cannot provide much information about the mechanisms that are responsible for it. We have therefore developed a modified test where the strip specimens are monitored continuously during the heating cycle so that the rate of sagging at various times/temperatures can be related to the microstructural changes taking place inside the metal.

2. Experimental procedure

The new test rig uses a programmable radiant furnace to heat the specimen according to the desired thermal cycle while its position is recorded continuously with a digital camera, Fig.1(b). The free length of the beam was 50mm in all cases reported here. Temperature is recorded and controlled using a fine wire thermocouple that is spot welded on to an identical dummy specimen. Considerable effort was expended in optimising the set-up such that temperature gradients are minimised and excellent reproducibility is achieved. A typical thermal cycle involves heating at a pre-determined rate between 0.1 and 3°C/s to a peak temperature of about 600°C, followed by a dwell time of some minutes at the peak temperature. Different commercial brazing furnaces can be simulated in this way. This equipment has been used to study both bare and braze-clad sheets, including experiments where

the braze metal is melted at high temperature. However, the present paper is concerned with sagging effects in the solid state only so the investigated materials were all bare, un-clad sheets.
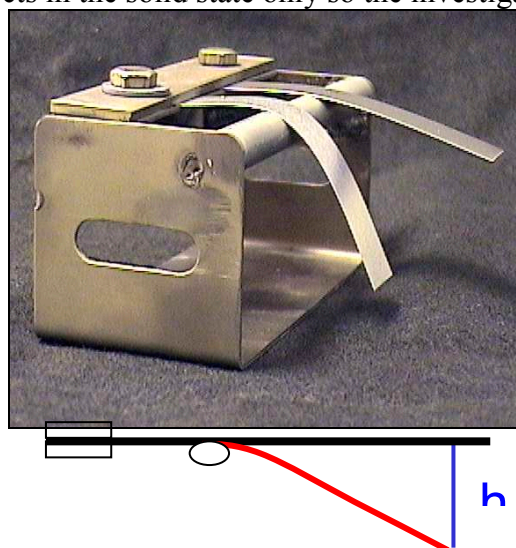

Fig.1(a) Conventional testing of sagging height 'h' after a heating cycle

Fig.1(b) Equipment for continuous monitoring of sagging during a heating cycle

The sheet materials were all the same variant of a modified AA3103 alloy, which were processed in different ways to modify their initial microstructures. Thickness was 0.1mm in all cases; other details are as in Table 1. Results presented here all relate to a heating rate of 1 ºC/s up to 600°C followed by holding for a dwell period of 3 minutes at that peak temperature. In addition, specimens were heated in the same manner up to various temperatures and then quenched for metallographic examination of the structural changes taking place.

Table 1. Test materials used in the present investigation

Alloy code	Initial microstructure
O (S)	Recrystallised microstructure, small grain size
O (M)	Recrystallised microstructure, medium grain size
O (L)	Recrystallised microstructure, large grain size
H18	Deformed, fibrous grain structure
H24	Deformed + recovered, fibrous grain structure
H14-1	Coarse grains, lightly deformed
H14-2	Coarse grains, lightly deformed

3. Results and discussion

Sagging curves for the seven different material conditions are compared in a single diagram in Fig.2. Note that the left hand side of this figure relates to the period of continuous heating (1ºC/s) while the right hand side shows changes during the 3 minute dwell period. The amount of sagging should naturally be as small as possible.

It is immediately apparent that sagging in these materials is not a simple thermally activated phenomenon that depends only upon temperature. Different temperature ranges can be identified where more or less sagging takes place and the magnitude of the changes varies considerably within these ranges depending on the material's initial condition. The first stage (I) is approximately from 200°C to 300°C where there is no change in the O-temper materials and the greatest effect is seen for the heavily cold rolled H18-temper. Rather rapid creep occurs between about 300°C and 350°C (stage II) for the various unrecrystallised conditions but not for the recrystallised O-tempers. In most cases there is a plateau between 350°C and about 550°C (stage III) where little change takes place.

Above about 550°C and during the dwell period at 600°C there is a major sagging contribution in some cases but very little in others (stage IV). The total effect is very variable, being the sum of the various contributions in all the temperature ranges.
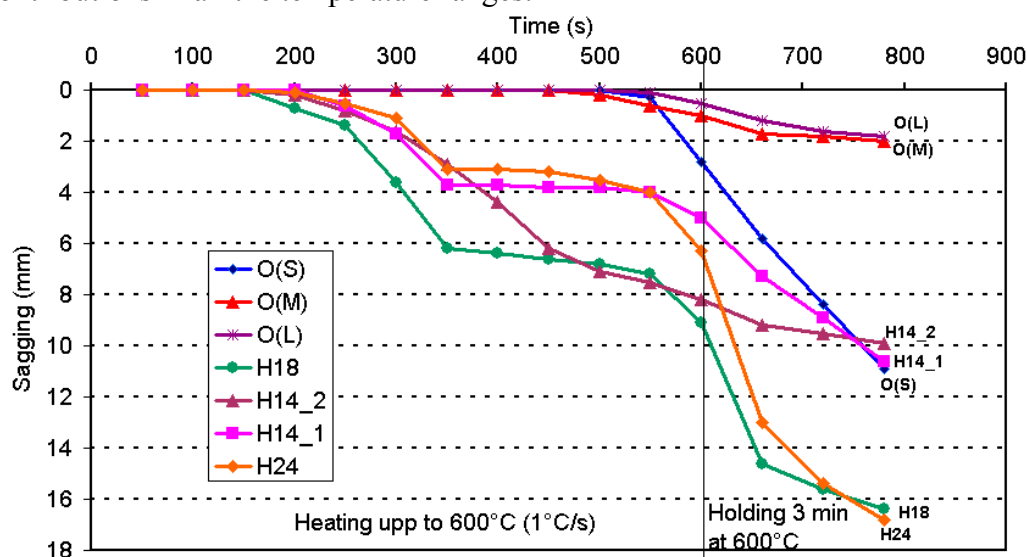

Fig.2 Degree of sagging at various stages through the simulated brazing thermal cycle. The scale for time (s) corresponds also to temperature (°C) up to 600s (600°C)

In order to understand these complex behaviours it is necessary to consider how the microstructures evolve during the heating and holding cycle. Results of metallographic examinations on samples quenched from different temperatures are summarised in Table 2. Associating the extent of sagging with the respective microstructural changes it is possible to draw some conclusions about the mechanisms that are responsible.

Table 2. Microstructures of the alloys at different stages of the brazing thermal cycle

Alloy code	Initial	300°C	400°C	550°C	600°C	600°C/3min
O (S)	TR small grain size	-	-	-	-	TR (40 μm)
O (M)	TR medium grain size	-	-	-	-	TR (106 μm)
O (L)	TR large grain size	-	-	-	-	TR (274 μm)
H18	Deformed	Def	TR	TR	TR (55 μm)	TR (57 μm)
H24	Deformed	Def	TR	TR	TR (65 μm)	TR (53 μm)
H14SR	Deformed	Def	TR	TR	TR (74 μm)	TR (78 μm)
H14	Deformed	Def	PR	TR	TR (121 μm)	TR (122 μm)
Def – deformed structure, PR – partly recrystallised, TR – totally recrystallised, (x μm) – grain size						

Stage I – between about 200ºC and 300ºC is absent in recrystallised material and becomes more pronounced as the degree of cold deformation in the sheet increases, being greatest for the H18 temper. There is no observable change in the microstructure as seen in the optical microscope but this is the temperature range where recovery of dislocations and migration of subboundaries occurs in these alloys [3]. The movement of subboundaries under stress has previously been identified as making a significant contribution to creep deformation [4] so we denote this behaviour as '*recovery sagging*'. It cannot occur in recrystallised structures for the evident reason that they do not contain any significant content of subboundaries.

Stage II – between about 300ºC and 350ºC, although extending to above 500ºC in one case, corresponds to the temperature range where recrystallisation is taking place. The prior processing of material H14-2 results in a slow, drawn-out, recrystallisation process so that stage II persists to higher

temperatures in this case. It is only recently that a relationship between recrystallisation and shape change has been recognized. The present experiments are perhaps the first to demonstrate this effect unambiguously in polycrystalline material. Migration of grain boundaries can be driven by applied stresses in bi-crystal experiments [5] and a coupling between boundary migration and shearing has been shown both theoretically [6] and experimentally [7]. As pointed out elsewhere [8], any grain boundary migration during recrystallisation or grain growth that is driven by stress must result in a deformation. For these reasons we denote stage II as '*recrystallisation sagging*'.

Stage III – represents a range where little or no change takes place despite the further increase in temperature. The grain structure is essentially static since recrystallisation is now complete and grain growth is very effectively prevented by the high density of dispersoid particles present in these alloys. At these temperatures and for these rather small stresses, creep by dislocation glide/climb or grain boundary sliding have very little effect and we use the name '*plateau*' for stage III.

Stage IV – takes place above about 550ºC and below the solidus temperature so it is certainly a solid state phenomenon. The extent of sagging in this stage varies greatly between the different material conditions as can be seen in Fig.2. The 0(M), 0(L) and H14 tempers are largely immune to deformation at this stage while H18 and H24 are very susceptible, showing about twice the amount of sagging during stage IV as in the previous three stages. Since no significant microstructural evolution takes place here it can be deduced that a form of conventional creep process is involved. Examples of the grain structures at this stage of the heat treatment are shown in longitudinal sections in Fig.3.
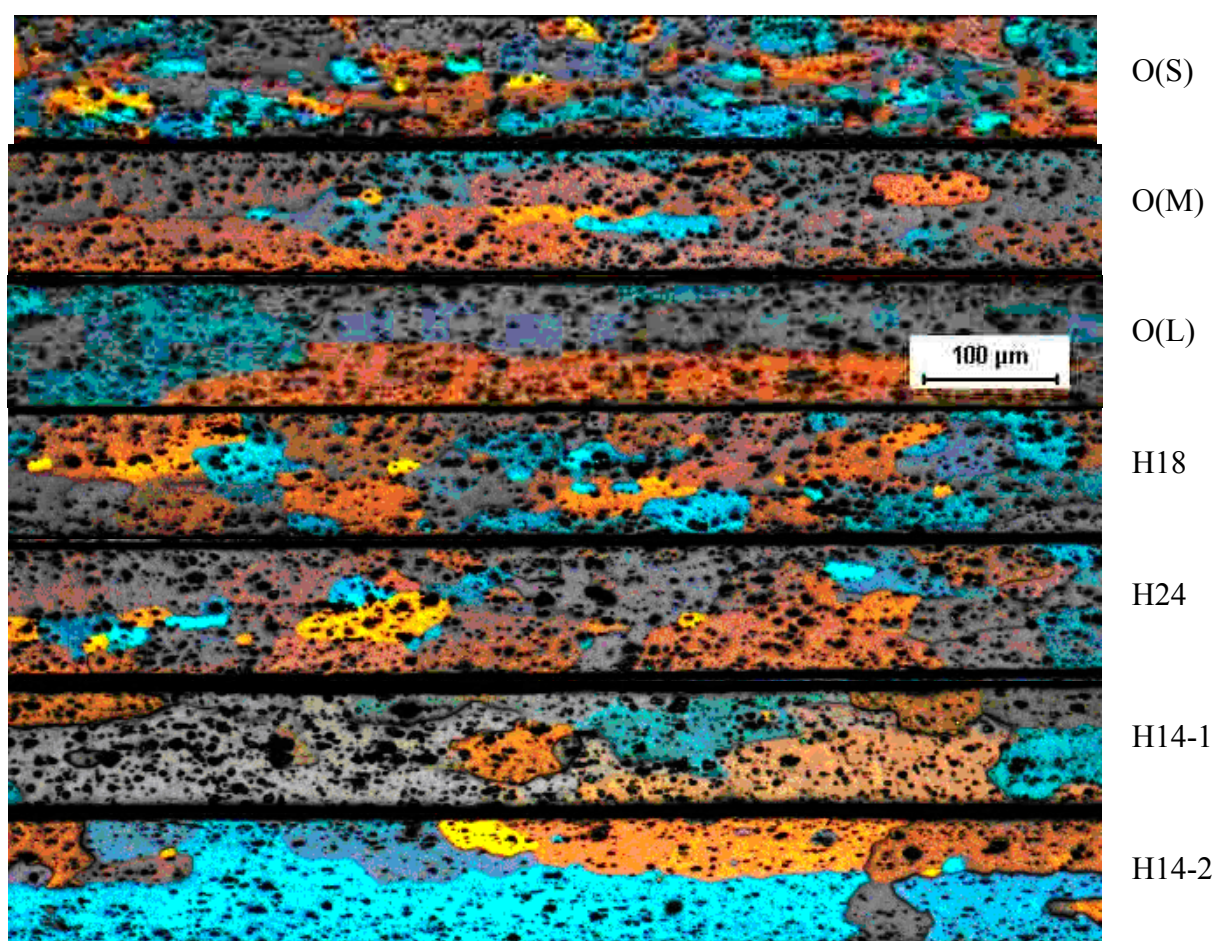

Fig.3 Optical microstructures after heating to 600ºC

It is clear that a close relationship exists between the degree of sagging in Stage IV and the size and shape of the grains. Materials H14-2, O(L) and O(M) which show the least sagging in stage IV have large and elongated recrystallised grains while the others are much smaller and more equi-axed.

Grain boundary sliding (GBS) is a well known mechanism of creep deformation [9] which becomes increasingly important as grain sizes become finer. For the bending loads in the present tests, the shear stress acting on grain boundaries will be greatest for grain boundaries slanted at around 90° to the sheet surface. Accordingly, the larger and more elongated are the grains, the better will they resist deformation by GBS. A clear correlation exists in the present cases leading to the conclusion that stage IV deformation is principally due to GBS and we denote the mechanism as '*creep sagging*'. Figure 4 shows a plot of creep sagging against grain size (length) where a parabolic relationship exists for grain sizes up to about 110μm. For larger grain sizes the creep sagging is small and constant, possibly resulting from other dislocation creep mechanisms.

Although the relationship between sagging and grain size in Fig.4 is quite evident, there is a significant spread in the results. Closer examination has revealed that the shape of the grains plays a role in addition to their length. Long-narrow grains having a high aspect ratio are superior in this regard to thicker grains of the same length. This shape factor minimizes the shear stress along the boundaries when the sheet is loaded in bending so that less grain boundary sliding then takes place.
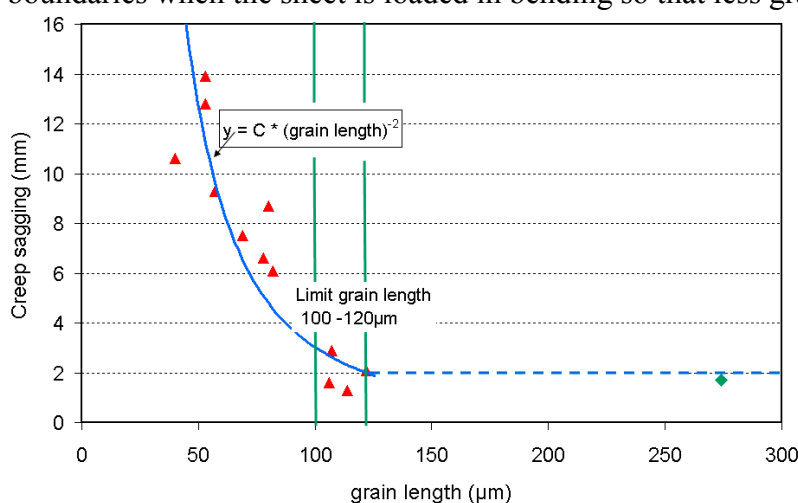

Fig.4
Creep sagging during stage IV as a function of the grain size in the alloys. Grain boundary sliding has a significant influence for grain lengths up to about 110μm

4. General discussion

The development of a method to study the continuous process of sagging during simulated brazing cycles has allowed a completely new understanding of the underlying mechanisms to be achieved. It is evident that this is not a simple thermally activated process that depends only on temperature. Several different mechanisms are involved in different temperature ranges and these are strongly linked to the metallurgical structure of the sheet material and its development during the heating cycle. Most importantly, this knowledge can be used to develop new generations of fin alloys that are highly resistant to sagging during manufacture of heat exchangers [10].

The various contributions that make up the total sagging during a brazing cycle are shown schematically in Fig.5. Cold rolled sheets are susceptible to recovery and recrystallisation sagging but the extent of this can be adjusted by suitable prior treatments that control the ways in which these microstructural changes take place. It is illuminating to note that a plateau exists in most cases where no deformation takes place despite the relatively high temperature. This demonstrates clearly the fact that sagging tendency is intimately connected with the microstructural condition as well as changes that take place in the microstructure. It should also be remembered that sagging, although an undesirable phenomenon, is only one aspect that must be taken into account in a successful brazing treatment. For example, although some of the O-temper materials responded well in the present tests they could be susceptible to intrusion of liquid metal films [11] which have undesirable negative effects on strength and corrosion resistance.

The present paper has described only the behaviour of bare fin-stock alloys without the complications that arise when liquid braze metal forms on the surface of clad alloys. Other work [12]

has investigated sagging in braze-clad sheets. Stage IV creep sagging can become more important in these cases but the underlying relationships to the alloy microstructure still remain as the important controlling factors.
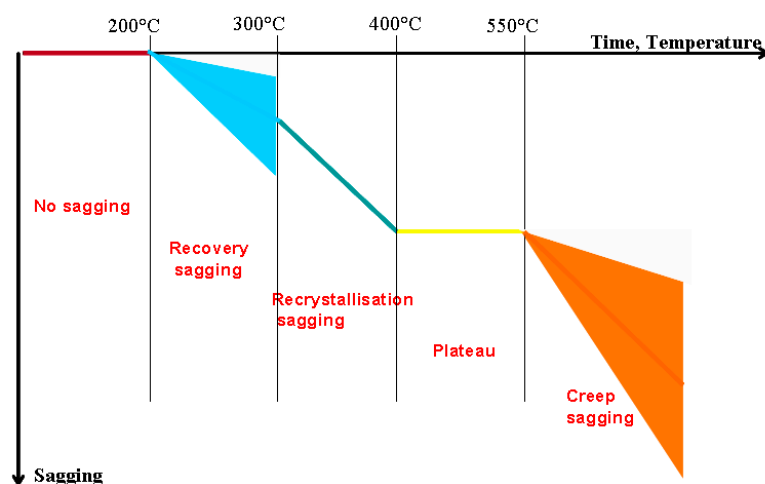

Fig.5
The various stages in which sagging can occur during a typical brazing cycle for heat exchangers. The amount of sagging in each stage is strongly dependent on the metallurgical condition of the alloy sheet.

5. Conclusions

Sagging does not occur by a single thermally activated process but results from a combination of different mechanisms taking place at different temperatures. It can be divided into recovery sagging, recrystallisation sagging and creep sagging principally associated with grain boundary sliding. The respective importance of these depends critically on initial microstructures as well as the changes that take place during heating. There is frequently a stable plateau existing between the recrystallisation and creep sagging temperature ranges. Better understanding of these metallurgical processes allows development of superior sagging-resistant alloys for heat exchanger applications.

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