Essential Readings in Light Metals: Cast Shop for Aluminum Production.
Edited by John F. Grandfield and Dmitry G. Eskin.

8. OTHER CASTING METHODS

Strip casting processes (twin roll and twin belt casting) have become economically signi.cant for aluminum alloy sheet production, and papers on the formation of defects, the design of molten metal delivery systems, and general engineering have been included. Some papers on low frequency electromagnetic casting have been included for their insights into the physics of DC casting and solidification.

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THE MECHANICAL AND METALLURGICAL CHARACTERISTICS OF TWIN-BELT CAST ALUMINUM STRIP USING CURRENT HAZELETT TECHNOLOGY

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The Hazelett process, known also as the Hazelett twin-belt continuous casting process, has been in commercial operation for many years. Lead, zinc, aluminum and copper have been successfully cast in the form of a strip or bar. Steel has been experimentally produced. Casting different metals required the development of new casting techniques with some changes in basic caster and metal feeding system design.

In recent years, most of our efforts have been concentrated on improving aluminum strip casting technology. We believe that the aluminum field could be a potentially significant market for our products, not only in the U.S. but also overseas.

Worldwide interest in the Hazelett process for aluminum applications prompted us to make the subject of this paper certain metallurgical phenomena occurring during casting and their effect on further metal treatment and final properties.

Understanding metallurgical differences between different casting processes is the key factor in designing heat treatment as well as rolling schedules to obtain desired sheet properties. Chemistry will also play a very significant role in the final mechanical characteristics of the sheet metal.

The difference in rate of solidification among the processes determines differences in metallurgical and mechanical properties.

To achieve a desired temper of aluminum sheet requires a combination of chemistry, heat treatment and rolling schedules.

DC versus twin-belt cast and rolled sheet, for example, will very likely require different heat treatments and rolling schedules to obtain the same temper.

This paper will attempt to describe basic characteristics of the Hazelett cast aluminum strip and sheet.

Metallurgical Aspects of the Hazelett Process

A. Casting

The Hazelett process can be included in the group of high solidification rate processes.

From the solidification point of view, it is similar to that of the Alusuisse Caster II (block caster), faster than the conventional DC process and slower than the twin roll caster. This specific heat removal rate determines metallurgical and mechanical characteristics of alloys cast on the Hazelett caster. Solidification rates can be increased or decreased to a certain extent by using a combination of "Matrix" coatings and inert gas shrouding.

When comparing Hazelett-cast and DC-cast aluminum alloys, the differences will become quite obvious.

Higher solidification rates achieved on the Hazelett caster will result in smaller grain size, finer dendritic cells, smaller size of secondary phase particles and their different morphology as well as higher retention of certain elements in solid solution. But, in comparison with twin roll cast material, the Hazelett-cast strip has bigger grains, coarser dendritic cells, larger size secondary particles and less retention of elements in solid solution.

Fig. 1 represents several examples of the structures of aluminum alloys cast on a Hazelett caster.

Grain Structure

As can be seen from numerous examples of Hazelett-cast strip, efficient grain refining greatly improves not only grain structure but also centerline segregation, centerline porosity and surface quality.

High solidification rates in the Hazelett process ensure fine, equiaxed and randomly textured grains throughout the whole slab section.

The very important condition to ensure a fine grain structure is a high density of nuclei for grain formation. Most of our customers use Al-Ti-B (5:1 TiB) alloy in the shape of a rod, fed continuously to the melt at the location guaranteeing its highest efficiency. The amount has to be carefully calculated due to the presence of residual TiB in the furnace recycled charge. Obviously, higher additions of Al-Ti-B can be tolerated when primary metal is used.

Table I represents some typical grain size measurements for common aluminum alloys cast on the Hazelett caster.

The cast strip has a grain size gradient between the surface and the center. This is inherent in the process and the size will largely depend on solidification rate and slab thickness.

Dendritic Cell Structure

Structure refinement, described often as size of the dendritic cell, depends mainly on the cooling rate of the melt and the direction of heat extraction.

There is a strong relationship between dendritic cell size and a local solidification time. It says that any part of the structure requiring a longer time for complete solidification will have a coarser dendritic cell structure. This explains the variations in cell sizes which occurs between surface and center of solidified Hazelett strip.

Fig. 2 shows the range of dendritic cell sizes within the slab thickness for different alloys cast on the Hazelett caster for typical conditions.

These variations occur in other processes as well but for DC casting, for example, they are much greater.

Table II shows measurements of dendritic cells (DCS) and calculated corresponding local solidification times (t) for several alloys for the surface and centerline of Hazelett cast 0.750 inch thick slab, 0.750 inch (19mm) produced under typical conditions.

Fig. 3 shows a relationship between DCS and local solidification time.

TABLE I

ALLOY	GRAIN SIZE (μm)	
	Center	Surface
AA 1100	150	300
AA 3003	100	180
AA 3004	80	150
AA 3105	130	250
AA 5052	120	200

TABLE II

ALLOY	SURFACE		CENTERLINE	
	DCS [μm]	t [s]	DCS [μm]	t [s]
AA 1100	16	.67	30	3.12
AA 3105	9	.22	20	2.15
AA 5052	10	.60	25	8.83
AA 5182	8	.37	18	4.71

As previously mentioned, the Hazelett process can be quite flexible, within a certain range concerning solidification. Heat extraction can be altered by using different combinations of Matrix coatings and inert gas shrouding.

Several tests proved that quite significant changes in extraction capability could be achieved. For AA 3105, for example, surface solidification conditions could be changed by way of adjusting belt coating and inert gas mixture in the mold to result in a DCS difference of up to 3μm (between 12 and 9μm on the surface). A combination of coatings, shrouding gases and certain aspects of the caster's mechanical features gives us quite broad flexibility in adjusting the solidification rates. This is very important when casting different alloys. Some other factors include belt topography, metal head in the tundish and metal temperature.

In general, properties of Hazelett cast strip improve with the increasing cooling rates and result in finer and more homogenous structure, especially for higher alloys.

Intermetallic Phases

The size, distribution and type of second phase particles formed during solidification are controlled by alloy composition (chemistry) and solidification rate. Changes in alloy composition, like Fe and Si, and variations in the solidification conditions between different parts of the slab are also important.

The as-cast structure of the Hazelett strip contains coarse secondary phases which form interdendritically during solidification.

Solid Solution

During the fast cooling process of the Hazelett caster, certain elements will be retained in solid solution. For 3XXX series, for example, the most effective in increasing the strength of an alloy is manganese. The 5XXX series relies chiefly upon magnesium as a strengthening element which is effective on a weight basis and has the advantage of being highly soluble in aluminum.

One of the characteristics of the Hazelett cast strip is a high percentage of elements in solid solution that remain there before and during hot rolling. The DC cast ingot, on the other hand, is homogenized before hot rolling, thereby precipitating Mn as dispersoid. As a result, only modest strengthening is achieved.

The solute promotes strain hardening during deformation and has a strong influence on final mechanical properties of the sheet.

The following example will illustrate the interrelationship between chemistry and strain hardening for Hazelett-cast AA3105:

Two samples of 0.100 inch (2.5mm) hot rolled sheet were compared for mechanical properties following identical cold rolling and annealing practices. The only difference was in chemistry, specifically the Mn content.

Tables III, IV and V show exact chemistry, cold rolling and annealing schedules as well as mechanical properties of the samples.

The work hardening curves for the samples of both chemistries are shown on Fig. 4. These figures illustrate the relationship between cold reductions and mechanical properties of AA3105, beginning after 680°F annealing.

As can be seen, Mn content has a significant effect on mechanical properties of Hazelett-cast AA3105.

TABLE III Chemistry of Hot Rolled Strip

CHEMISTRY %	Mn	Mg	Cu	Fe	Si	Zn	Cr	Ti	Ni	Pb
I	.31	.26	.13	.49	.17	.030	.008	.013	.005	.007
II	.66	.25	.15	.59	.23	.042	.015	.021	.006	.007

TABLE IV Cold Reduction Sequence

CHEMISTRY I				CHEMISTRY II			
Pass	Gauge In (Inches)	Gauge Out (Inches)	Total Reduction [%]	Pass	Gauge In (Inches)	Gauge Out (Inches)	Total Reduction [%]
1.	.100	.060		1.	.099	.062	
Anneal 4 hr. at 680°F				Anneal 4 hrs. at 680°F			
2.	.060	.052	13	2.	.062	.051	18
3.	.052	.044	27	3.	.051	.043	31
4.	.044	.033	45	4.	.043	.033	47
5.	.033	.025	58	5.	.033	.024	61
6.	.018	.018	70	6.	.024	.018	71
7.	.018	.014	77	7.	.018	.014	77

TABLE V Mechanical Properties

STATUS	CHEMISTRY I				CHEMISTRY II			
	Gauge [Inch]	TS [kpsi]	YS [kpsi]	E [%]	Gauge [inch[	TS [kpsi]	YS [kpsi]	E [%]
As received	.0997	33.4	30.0	6.8	.0985	37.1	34.7	7.6
Before anneal	.0604	37.2	37.0	3.3	.0622	41.6	41.5	4.0
After anneal	.0604	16.7	8.3	21.6	.0622	22.6	14.2	15.1

B. Hot Rolling

Different solidification rates for the Hazelett and DC processes lead to differences in microstructure and mechanical properties of cast products. Therefore, continuously cast strip and DC cast ingot would have to be treated differently during subsequent steps of thermal and mechanical processing.

It is important to realize that all Hazelett strip is directly hot rolled.

The direct hot rolling has no major influence on retention of the solute in solution but sparsely distributed dispersoid starts to precipitate. Hot rolling fractures coarse solid eutectic phases redistributing them into more uniform configuration. For example, 0.169 inch (4.3mm) thick hot rolled strip of AA3004 contains particles of Al_6 (Fe, Mn) with maximum diameters of 15 μm.

The exit temperatures of hot rolled strip depend largely on casting speeds, mill configuration, cooling techniques, etc. In general, this temperature is not higher than 600°F, but higher temperatures are sometimes achieved.

The exit temperature of 600°F is not enough to recrystallize the rolled structure. High retention of elements in solid solution decrease the tendency of a dynamic recovery during deformation, which is the driving force for recrystallization.

High temperature homogenization of DC-cast ingot lowers the content of Mn and Fe in solid solution through precipitation of coarse and widely spaced dispersoids. This type of dispersoid yields a favorable grain structure during recrystallization.

This lack of full annealing of the Hazelett-cast strip, as well as specific hot rolling conditions, requires that further process steps be taken if final properties are to match those of conventional sheet.

C. Cold Rolling and Intermediate Annealing

Work hardening is the principal method of strengthening the wrought product in non-heat treatable aluminum alloys. In the Hazelett process, it is achieved by hot and cold rolling, the latter being much more effective.

In some cases, the Hazelett as-cast strip is cold rolled to the final gauge; in others, intermediate annealing is introduced. Cold rolled structure is more homogenous than hot rolled, with finer constituents more evenly distributed.

Fig. 5 shows progressive increase in microstructure homogenity during processing of AA 3004 sheet. As cold rolling progresses, the Al_6 (Mn, Fe) constituents are more homogenously distributed. The maximum Al_6 (Mn, Fe) constituent diameter in approximately 0.013 inch (0.33mm) thick cold rolled AA3004 sheet is 7 μ m.

The solid solution content and eutectic particles play important roles during cold deformation. Not all solute elements are equally effective in promoting work hardening but higher solute levels usually result in enhanced hardening, due to the increased number of dislocations.

The intermediate annealing introduced between the cold rolling passes is the first high temperature treatment in the whole process. It activates precipitation of manganese dispersoid from the solid solution. The very fine and dense dispersoid is precipitated prior to recrystallization interfering with its progress. Fig. 6 shows the comparison in dispersoid density between cold rolled material (55% cold reduction) and the same material annealed at 850°F for four hours. The great density of precipitation reduces nucleation rates for recrystallization by prolonging incubation time for the nuclei.

TABLE VI

HEAT TREATMENT		TENSILE STRENGTH [kpsi]	YIELD STRENGTH [kspi]	ELONGATION [%]
As rolled (no heat treatment)		38.1	37.0	4
Anneal	2 hrs., 650°F	31.5	19.6	14
	4 hrs., 650°	29.8	17.0	13
Anneal	2 hrs., 750°F	27.9	14.5	17
	4 hrs., 750°F	26.9	11.6	18
Anneal	2 hrs., 850°F	25.1	13.2	21
	4 hrs., 850°F	23.7	8.9	23.5

To stimulate nucleation, higher annealing temperatures have to be used. It was found that the Hazelett-cast and rolled sheet requires higher annealing temperatures in order to achieve properties similar to DC-cast and rolled sheet.

To show the annealing response for Hazelett-cast AA3004 0.104 inch thick cold rolled strip, samples were submitted to laboratory annealing tests. The samples were held for two and four hours at the following temperatures: 650°, 750°F and 850°F. Table VI lists the mechanical properties obtained, and Figure 7 shows the softening curve for AA3004 strip.

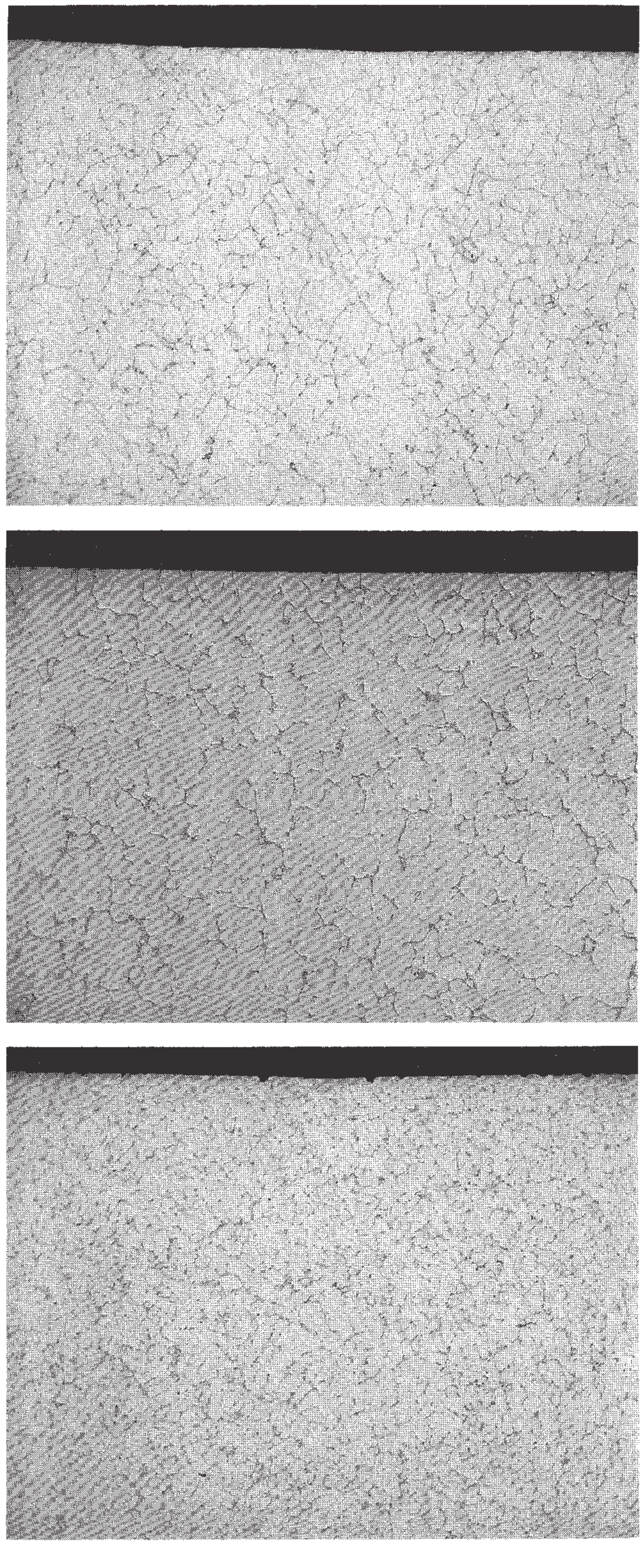
SUMMARY

The Hazelett process has characteristics which clearly distinguish it from other processes. Its "fingerprint" is a range of solidification rates achievable for different alloys. Knowing process capabilities can be very useful in choosing alloy chemistry, its hot and cold rolling schedules and annealing practices to achieve final desired rolled strip properties. Typically, the Hazelett hot rolled material has higher mechanical properties than a corresponding conventional reroll. This, of course, affects the properties of cold rolled sheet.

The variation in chemistry within alloy specification can result in different sheet mechanical properties. This is especially true for Mn and Mg, the elements retained in solid solution during the solidification process. In practice, this means that in many cases, a lower level of Mn and Mg will be sufficient to match the mechanical properties of the DC material with high Mn and/or Mg content.

This is strictly related to the caster solidification rates and subsequent rolling. Solidification rates can be controlled within a certain range by belt coatings and inert gas shrouding.

Mechanical and metallurgical properties of Hazelett-cast slab and rolled sheet will be a result of a specific solidification rate, hot and cold rolling schedules and annealing practices.



Alloy AA 3003

Alloy AA3004

Alloy AA3105

Fig. 1 The structures at the surface of the Hazelett-cast aluminum alloys.

Magnif. 100x

Alloy AA 5052

Alloy AA 5042

Alloy AA 5182

Fig. 1 The structures at the surface of several Hazelett-cast aluminum alloys. Magnif. 100x.

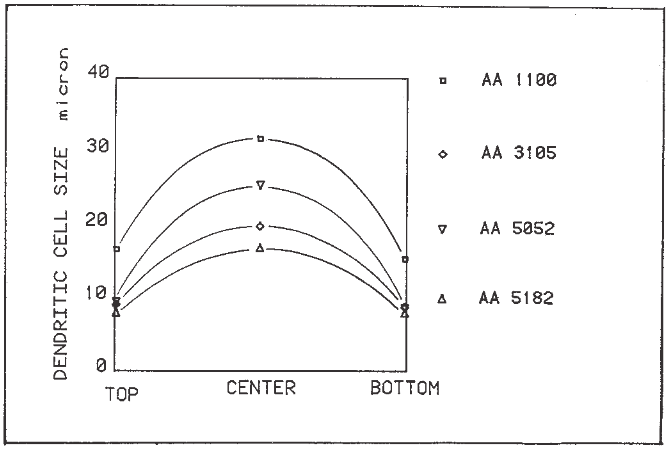


Fig. 2 The range of dendritic cell sizes within the slab thickness for aluminum alloys cast on a Hazelett caster under typical conditions.

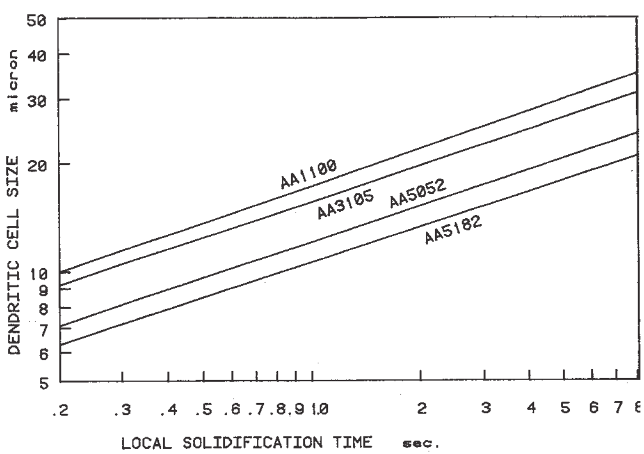


Fig. 3 Relationship between dendritic cell sizes and local solidification times for several Hazelett-cast aluminum alloys.

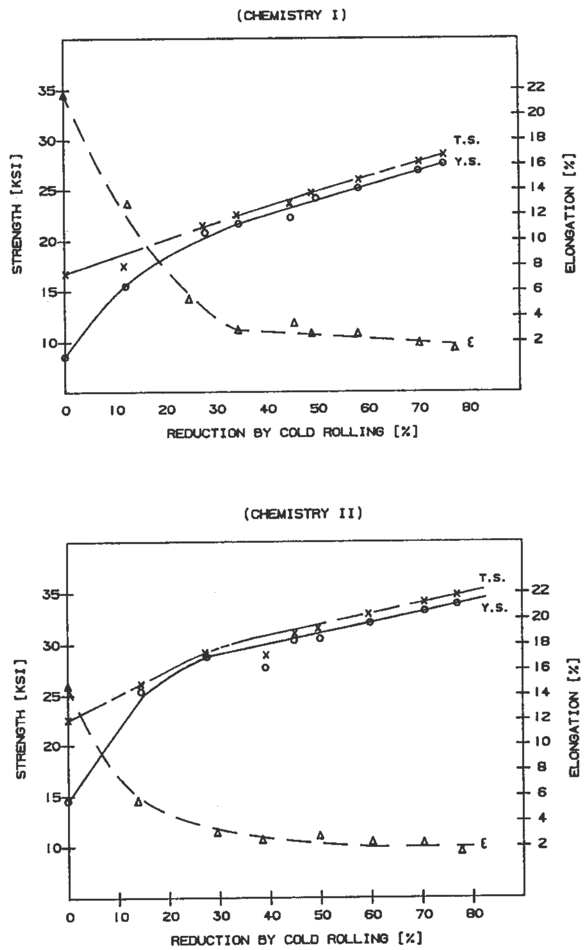
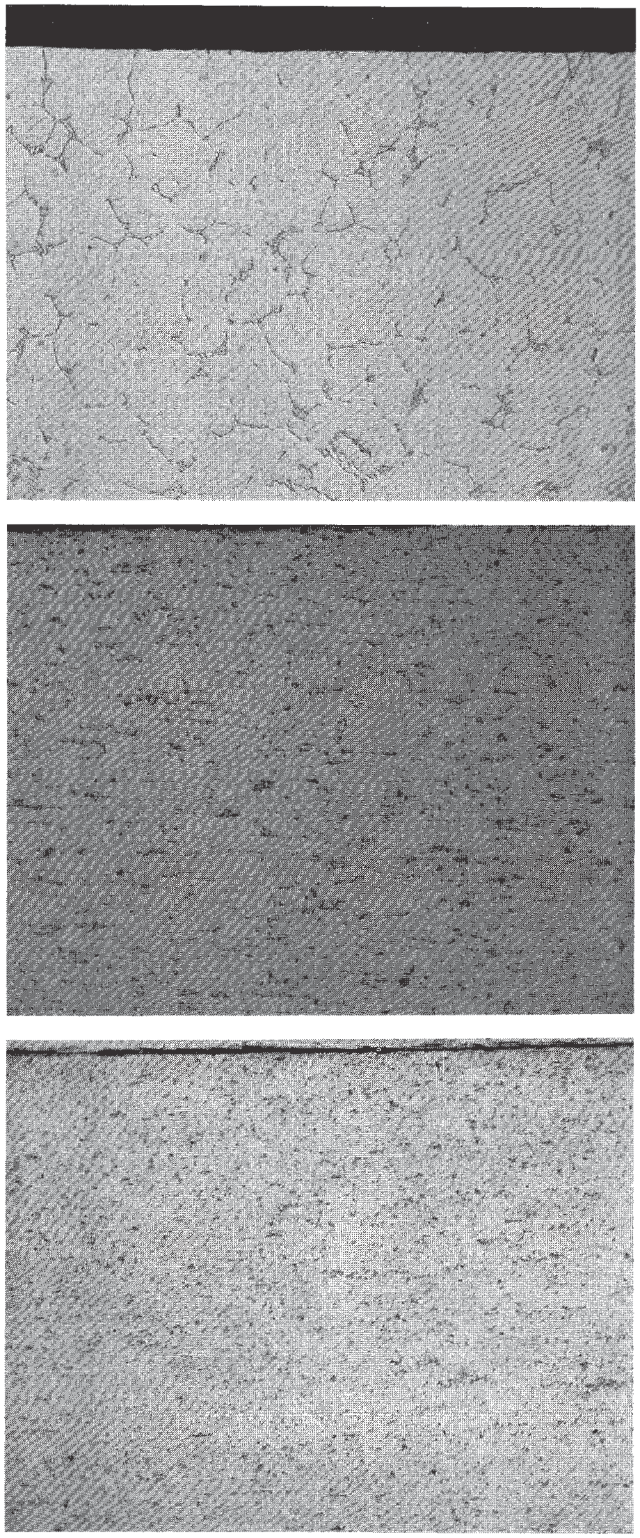


Fig. 4 Work-hardening curves for Hazelett-cast AA3105 sheet for Chemistry I and Chemistry II.



As-cast

Hot rolled. 0.149 inch (3.8mm) thick strip.

Cold rolled. 0.021 inch (0.53mm) thick sheet.

Fig. 5 Photomicrographs of alloy AA3004 showing progressive increase in structure homogenity after various stages of processing.

Etched. Magnif. 200x.

a

b

Fig. 6 Precipitation of dispersoid in Hazelett-cast AA 3004 strip a) 55% cold reduction, b) the same strip annealed for 4 hrs. at 850°F.

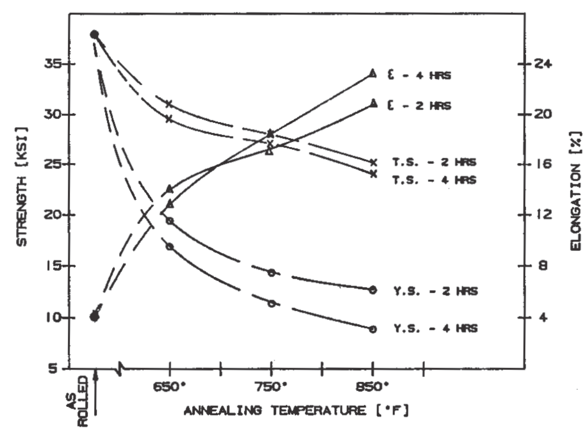


Fig. 7 Softening curves for Hazelett-cast AA 3004 sheet.