Residual Stress

What is residual stress and how to test it in MRS qualities[1]? And above all, how to reduce it?

What is residual stress and how is it caused?
Residual stress is defined as a mechanical stress present in a body that is free of external forces and moments, or temperature gradients. Residual stress can occur at any stage in the manufacture of semi-finished products. This article deals with the main mechanisms of residual stress development in the manufacture of aluminium sheets or strips.

Solution annealing and quenching
Most of the residual stress introduced into the strip during preceding hot and cold rolling operations is reduced during solution annealing at high temperature by relaxation processes.
However, large temperature differences will occur between the sheet surface and center, especially during subsequent quenching at a high cooling rate. The shrinkage caused by the lower surface temperatures is inhibited by the hotter zones in the sheet center, resulting in near-surface tensile residual stress development in the first process step. That residual stress exceeds the yield strength and is reduced by plastic deformation in the hot zone. During subsequent cooling of the sheet center, the center shrinkage involved is inhibited by the surface zone that has already cooled. Consequently, compressive residual stress occurs in the edge region and tensile residual stress in the sheet center.. These marked residual stresses are largely maintained because the yield strength is considerably higher than in hot condition and plastic deformation is reduced.

During practical operation, the material moreover will locally be "nonuniformly" quenched, for example, because the water (water jet) hits the surface selectively and the upper water jet and the lower water jet will have different points of impact on the material surface, which will also lead to temperature differences, which can be partly compensated for by the high thermal conductivity of aluminium but will lead to similar residual stress mechanisms as those described above.

Residual stress from cold forming
Plastic cold deformation is not uniformly distributed over the cross-section, so residual stress will occur during all cold forming processes. When a bending load is applied, for example, to a simple bending beam, compressive stresses will occur inside the bend, tensile stresses outside the bend, and no stresses will occur in the center.

If near-edge stresses exceed the yield strength, the material surface is plastically deformed; the outside fibers are permanently stretched and the inside fibers are shortened, whereas deformation near the sheet center remains elastic. When the external load is removed, the stretched and/or upset edge regions inhibit complete reforming and the elastic stresses near the sheet center cannot be completely eliminated.

Nonuniform cold deformation can occur whenever the strip is deflected by rollers and while the strip is being coiled or uncoiled. Additionally, the coil is naturally aged after solution annealing and thus "remembers" the coil shape. For uncoiling, the sheets must be flattened by plastic deformation, still prior to stretching, so residual stress is bound to be present in the material.

Reduction of residual stress
In the manufacture of the sheets, in particular during solution annealing and quenching to room temperature, care is taken to minimize the strip distortion resulting from the impact of the water front, which is achieved by controlling the water flow rate, the number of cooling headers and the point of impact of the water jet on the strip, if possible. This also allows the cold forming process used to eliminate strip distortion to be minimized, which contributes towards reducing the internal stresses introduced.


Chemically milled sample

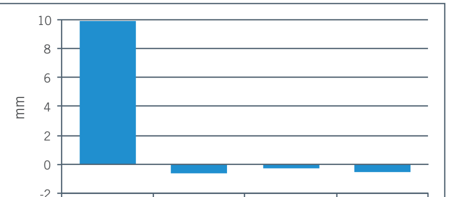
Elimination of residual stress by stretching
Asymmetric residual stress leading to undesirable distortion of the component during machining can only be eliminated by stretching upon completion of the process. For that purpose, the material is stretched in rolling direction in a defined manner. The residual stress developed during preceding rolling and heat treatment processes superimposes on the tensile load applied. Consequently, the yield strength is exceeded and the residual strain correlating with the residual stress is transformed into plastic deformation. As a result, residual stress is homogenized, and a residual stress state is achieved that is uniform and symmetrical throughout the sheet thickness. To increase the production capacity for MRS sheets, AMAG has installed a new coil stretcher specifically designed for sheets up to 8 mm (see report overleaf).

Consequently, regions where tensile residual stress is present must always be in equilibrium with regions where compressive residual stress is present. However, if the residual stress state can be kept approximately constant throughout the sheet thickness using a controlled stretching process, the residual stress equilibrium will still be disturbed when the sheet is machined but the deformation of the machined workpiece is minimized.

Measurement and evaluation of residual stress
Measuring all residual stresses in the material involves a lot a time and effort and in most cases leads to destruction of the material. Measuring and evaluating residual stress by a practical test, the Chemical Milling Test, has proven successful in sheet production. For this test, a sheet sample of standard dimensions is taken and the longitudinal camber of this sample measured at both faces. Subsequently, the sheet is reduced in thickness by 50% by chemical removal. The change in longitudinal camber after chemical removal is a measure of how high the residual stress in the material is. In this case, mechanical milling cannot be performed to reduce the thickness because it would affect the residual stress state.

Fig. 1 shows the effect of controlled stretching on the warpage of the sample after 50% thickness loss. The sample taken from the unstretched sheet has a warpage of approximately 10 mm after chemical milling, whereas after controlled stretching in rolling direction, the sample only has a marginal warpage ranging from 1.0% to 3.0%, irrespective of the currently selected stretch ratio, and therefore can be classified as MRS quality.
For stretched grades, the maximum admissible warpage of the sample after chemical milling is defined in the relevant delivery specifications.

Fig. 1: Difference on the warpage of the sample BEFORE and AFTER chemical milling



	Unstretched	Stretch ratio 1,0 %	Stretch ratio 2,0 %	Stretch ratio 3,0 %
Difference [mm]	9,9	-0,6	-0,3	-0,5

1) MRS qualities (MRS = Minimum Residual Stress): MRS sheets are mainly used for aircraft applications.