Importance of the cooling rate during the heat treatment process of aluminium

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During the last two decades the percentage of aluminium parts in cars has been boosted due to the requirement to reduce the car weight but finally with the result to reduce the fuel consumption. Actually, aluminium solutions reside more than ever in competition with steel solutions, as the steel industry fears to lose market shares. So, the steel industry is eager to develop new alloys with appropriate mechanical properties for high strength, toughness or both combined in duplex steels. Thus, the aluminium industry must give an answer with new alloys and new processes. This paper will show witch possibilities are existing to adapt the process to increase the mechanical properties of aluminium alloys. Beside an excellent temperature control during solution heat treatment and aging the main focus is on the quenching after solution heat treatment and especially the cooling rate.

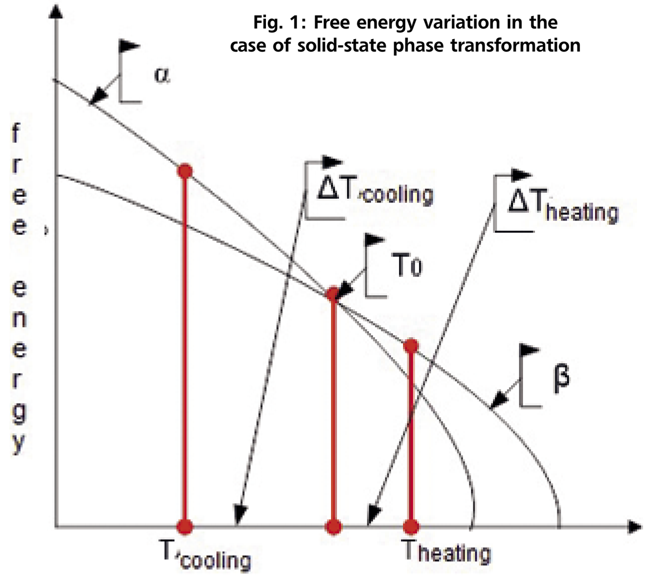

Fig. 1: Free energy variation in the case of solid-state phase transformation

Thermodynamic aspects [1]

Since the driving force of the heat treatment is the variation of the free energy (ΔF > 0), the activation of the solid-state phase transformations during cooling requests an undercooling. Fig. 1 principally shows (in the case of a two-phases α/β system) the variation of the free energy with the temperature and the for the activation of a solid-state phase transformation needed temperature difference (in the case of cooling: undercooling).

If: *F*= free energy, *U* = internal energy; *T* = Temperature, *S* = entropy, *p* = pressure, *V* = volume than the following dependence occurs:

$$\left.\begin{array}{l} F=U-TS\rightarrow dF=dU-TdS-SdT \\ dU=TdS-pdV\rightarrow TdS=dU+pdV \\ V=kt\rightarrow dV=0 \end{array}\right\}\rightarrow dF=-SdT\rightarrow\frac{dF}{dT}=-S<0$$

$$\frac{d^2F}{dT^2}=-\frac{dS}{dT}$$

Quench sensitivity

In the case of the heat treatment processes involving solution treatment the cooling has a seminal importance dictating product properties such as:

- physical properties
  - electromagnetic behaviour
- chemical properties
  - corrosion resistance
- mechanical properties
  - strength, elongation, internal stress
- geometric properties
  - distortion

The most important technological parameters of the cooling are:

- Cooling rate
- Transfer time – quench delay (from solution furnace to the quench medium)

Quenching media

- Fluids
  - Water
    - Aqueous solutions
    - Dispersions
      - Colloids (one phase in another*)
      - Emulsions (liquid in liquid*)
      - Suspensions (solid in liquid*)
      - Foams (gas in liquid*)
      - Aerosols (liquid in gases*)
  - Liquified gases
  - Cryogenic applications (plunge or spray)
- Gases
  - Air
    - Ventilated air or compressed air
    - Controlled air or inert gas cooling in the furnace
    - Various gases with a high heat transfer value like He and H_2
- Solids in gas
  - Fluidized bed
    - Sand particles
    - Al-oxide particles
    - other particles

Water quenching

Water quenching is the most common quenching method. Two of the most important parameters are the quench delay times (see Table 1) and the sizing of the quench tank (see [1] and [3]).

The diagrams next page show the achievable hardness dependent on the quench delay time.

All tests have been performed by the same temperature for the solution and aging heat treatment.

Table 3 represents a very concentrated depiction of the influence of the cooling rate on the mechanical properties. In the present case (Table 3) a high pressure die casting – AlSi10MnMg – was submitted to identical heat treatment conditions excepting the cooling media. In the case of the water cooling (as expected) the strength reaches a much higher level compared to the air cooling; this is due to a much higher cooling rate. An opposite effect can be seen in the case of the elongation.

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Table 1: Quench delay times for aluminium alloys of various thickness [3][iii]

Minimum thickness im mm	Maximum time in sec
Up to 0.41, inclusive	5
Over 0.41 to 0.79, inclusive	7
Over 0.79 to 2.29, inclusive	10
Over 2.29	15
Source: Ref 19	

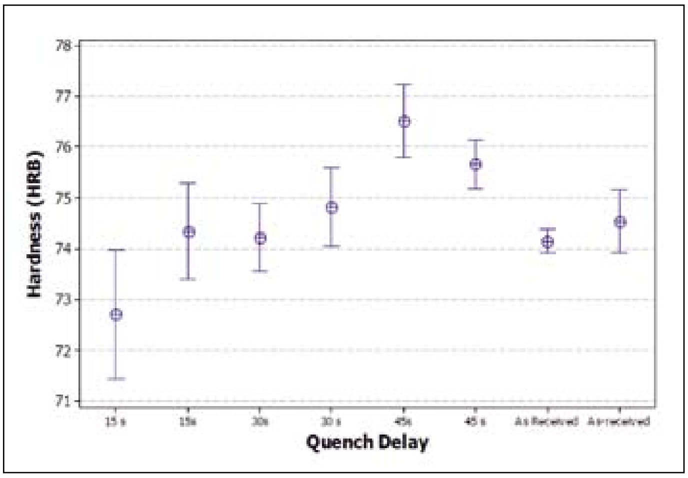

Fig. 2: Hardness dependent on the quench delay time for alloy 2219 [4]

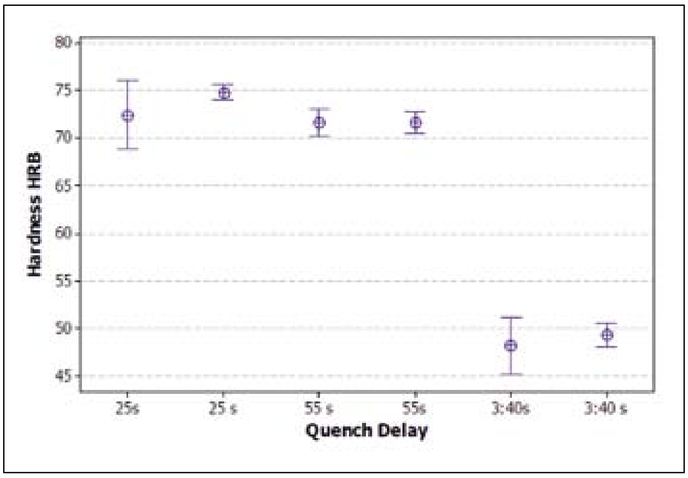

Fig. 3: Hardness dependent on the quench delay time for alloy 6088 [4]

"Because of the very ductile and formable nature of as-quenched alloys, retarding natural aging increases scheduling flexibility for forming and straightening operations" (see Table 4) [5].

The quenching of aluminium parts in **aqueous solutions** aims the reduction of distortion and residual stress.

Liquified gases

The cryogenic applications (sub-zero treatment) presents a continuously increasing importance due to the very high cooling rates (much higher than in the case of water quenching) and the respective high strength which can be obtained. These high cooling rates can provide, for specific applications, a better corrosion resistance. By applying specific alternative cooling and heating processes the distortion can be significantly reduced. For an economically point of view the use of liquid air is preferred to other gases.

Fluidized bed

This very versatile technology is 'on advance' in the field of aluminium applications. Due to a very high uniformity of the heat transfer process, this method offers the advantage of a very low level of distortion.

Heat transfer coefficient (HTC)

The heat transfer coefficient of the quenchant is one of the most important thermodynamic characteristic of the process. The following data depict (as guideline) heat transfer coefficients for different media.

In the case of quenchants having water as solvent is the ebullioscopic behaviour an important technological factor. The ebullioscopic constant of water is 0.521 kg/mole [6].

The use of colloidal suspensions (0.2g TiO_2 in Water by 20 °C – tests in accordance with ISO9950) shows an HTC-enhancement of ca. 20% (when comparing the respective maximum levels) [9]. The same authors as above [9] determined a similar effect when using water with ultrasound agitation vs. water without agitation.

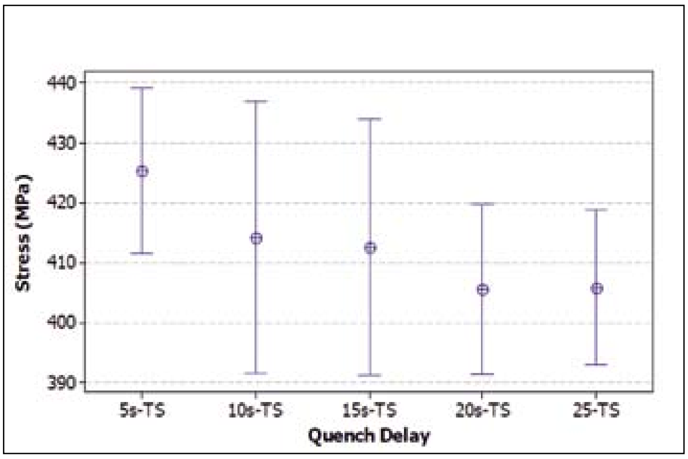

Fig. 4: Tensile strength dependent on the quench delay time for alloy 2219 [4]

The efficient use of fluidized bed technology in the field of aluminium processing is due to a relatively high heat transfer coefficient. Quoting [10] Apelian [11] affirms that "the heat transfer coefficient in a fluidized bed is high, typically between 120 and 1,200 W/m² °C".

Conclusion and outlook

In permanent industrial competition with other materials (especially steel) the aluminium processing industry will have to implement stronger and more effective quenching technologies. This involves not only the development of the quenching media, but also of modern quenching equipment able to provide reduced quench delay times and a high process productivity.

Even if there are various process paths leading to the desired mechanical properties, this does not necessarily mean that conditions for the distortion (geometrical stability) are

Table 2: Complete set of data for the quench delay tests of alloy 2219 [4]

Quench Delay (s)	Average TS (MPa)	Standard Deviation (MPa)	Average YS (MPa)	Standard Deviation (MPa)	Material Temperature (°F/°C)
5	425.28	11.05	304.25	9.81	962/517
10	414.18	18.25	294.50	15.02	931/500
15	412.54	17.16	291.00	10.95	902/483
20	405.58	11.39	284.50	4.04	875/468
25	405.83	10.41	281.25	10.56	850/455

Table 3: Influence of the cooling media on the mechanical properties [12]

Property / State	as cat	air cooling	water cooling
Rp0.2 [MPa]	154	120	223
Rm [MPa]	301	214	300
At [%]	7.6	12.6	7.2

Table 4: Typical time and temperature limits for refrigerated parts stored in the as-quenched condition [5]

Alloy	Maximum Delay Time after Quenching	Maximum Storage Time for Retention of the AQ Condition		
		-12°C (10°F) Max.	-18°C (0°F) Max.	-23°C (-10°F) Max.
2014 2024 2219	15 minutes	1 day	30 days	90 days
6061 7075	30 minutes	7 days	30 days	90 days

fulfilled as well. In order to create sustainable industrial conditions, the heat treatment and quenching program has to be (always) adapted to the very specific framework of the very specific product.

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Table 5: Grossmann numbers[iv] and heat-transfer coefficients (C) of quenchant-to-part films [3[v]] – quenchant: water and aqueous solutions (polymer)

Quenchant							
	Temperature		Velocity		Grossmann number	Effective heat-transfer coefficient (C)	
Type	°C	°F	m/s	ft/min	(H = C/2k)	W/cm² K	Btu/ft² h°F
Water	27	80	0.00	0	1.07	3.55	2460
			0.25	50	1.35	4.78	3105
			0.50	100	1.55	5.14	3565
Water	38	100	0.00	0	0.99	3.28	2275
			0.25	50	1.21	4.01	2785
			0.50	100	1.48	4.91	3400
Water	49	120	0.00	0	1.10	3.65	2530
			0.25	50	1.29	4.29	2970
			0.50	100	1.60	5.31	3680
Water	60	140	0.00	0	0.86	2.85	1980
			0.25	50	1.09	3.62	2510
			0.50	100	1.33	4.41	3060
Water	71	160	0.00	0	0.21	0.70	485
			0.25	50	0.57	1.89	1310
			0.50	100	0.79	2.62	1815
Water	82	180	0.00	0	0.11	0.36	255
			0.25	50	0.21	0.69	485
			0.50	100	0.27	0.89	620
Water	93	200	0.00	0	0.06	0.20	138
			0.25	50	0.08	0.27	184
			0.50	100	0.09	0.30	207
Water	100	212	0.00	0	0.04	0.13	92
			0.25	50	0.04	0.13	92
			0.50	100	0.04	0.13	92
Polyalkylene glycol (UCON A)(a)	30	85	0.00	0	0.19	0.63	429
			0.25	50	0.21	0.70	475
			0.50	100	0.23	0.77	529
Polyvinyl pyrrolidone (PVP 90)(a)	30	85	0.00	0	0.44	1.49	1012
			0.25	50	0.40	1.34	912
			0.50	100	0.42	1.41	966
(a) Polymer quenchants with concentrations of 25% k isequal to the thermal conductivity of the aluminum alloy (7075). Source: Ref 15							

Table 6: experimentally obtained HTC data [7][vi] – quenchant: forced air

Velocity m/s	Air temperature, °C	Relative humidity, %	Orientation	HTC experiment 1, W/m² K	HTC experiment 2, W/m² K	Average HTC, W/m² K
18	15	31-33	Vertical 45°	147.97 153.80	146.40 155.99	174.19 154.89
			Horizontal	139.43	139.32	139.37
		46-50	Vertical	148.71	148.18	148.45
	25	31-33	Vertical	146.48	148.70	147.59
10.5	15	31-33	Vertical 45°	98.66 108.48	102.49 107.99	100.58 108.24
			Horizontal	93.32	96.32	94.82
		46-50	Vertical	106.04	106.00	106.02
	25	31-33	Vertikal	106.29	107.32	106.81
4.8	15	31-33	Vertikal 45°	66.90 69.68	65.83 71.37	66.37 70.52
			Horizontal	58.58	59.32	58.95
		46-50	Vertical	61.90	65.89	63.90
	25	31-33	Vertical	70.50	70.55	70.53

[i] Actually, the quench delay time has to be regarded as a constitutive part of the generic term "cooling rate".

[ii] See [2]

[iii] Ref 19: "Heat Treatment of Wrought Aluminum Alloys," AMS 2770, SAE International, Warrendale, PA

[iv] Grossman numbers (H)...provide useful information about the rate of heat removal from the surface of a part. [3]

[v] Ref 15: C.E Bates, Selecting Quenchants to Maximize Tensile Properties and Minimize Distortion in Aluminum Parts, J. Heat Treat., Vol 5 (No.1), 1987, p 27-40

[vi] Probe material: aluminum alloy 319 [7]

Table 7: HTC for aerosols

Aluminium specimen in spray field [DDD]		
Heat transfer coefficient	W/m²K	source
T > Leidenfrost		[8]
Air pressure = 0.2 MPa; water flow rate = 3.3 l/min	7300	
Air pressure = 0.2 MPa; water flow rate = 5.0 l/min	11700	
T < Leidenfrost		
Air pressure = 0.2 MPa; water flow rate = 3.3 l/min	22800	
Air pressure = 0.2 MPa; water flow rate = 5.0 l/min	29000	

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