TU Delft

Memorandum M-726

Two-stage heat treatment of aluminium 7075-T6

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April 1996

Contents

1. Introduction

When the aluminium alloy 7075-T6 sheet is used to repair stringer or frames, and consequently has to be cold formed, the blank receives a solution heat treatment, is bended and age hardened to reach the T62 temper. Up to 1990 KLM Royal Dutch Airlines used a short two-stage hardening treatment (i.e., 3.25h at 121°C followed by 3.25h at 162°C) as the age hardening process. The military specification MIL-H-6088G only specifies a 24h single-stage process at 121°C. This long process is not preferable from a maintenance point of view.

This report describes some literature on which the previously used short two-stage process is based and the results of tensile, hardness and conductivity tests on 7075-T6 clad sheet material in four conditions: as delivered by the manufacturer, a treatment with the specified single-stage process and two two-stage treatments. The aim is to extend the data base for a possible certification of one of the two-stage heat treatments.

The several heat treatments that are mentioned in this report are summarized in Table 1. Treatment #1 in this table is the specified process. Treatment #2 is the actual previously used two-stage process, which was also found in Nock and Wool (1947). Treatment #3 is also a two-stage process already described in old literature and used by other airlines.

Table 1. Heat treatments mentioned in the present report

no.	heat treatment	single or two-stage	description
#1	24h/121 °C	single	current KLM practice, as specified by military spec.
#2	3.25h/121 °C+3.25h/162 °C	two-stage	'old' KLM practice, also found in Nock and Wool (1947)
#3	4h/96 °C+8h/157 °C	two-stage	found in Fink et al (1945) and used by other airlines

The aluminium alloy 7075 was introduced as 75S by ALCOA in 1944. The W-temper of the alloy naturally ages for a year or more, this in contrast with 2024 which reaches its maximum strength within four days. The 7075 alloy has to be artificially aged. Due to this heat treatment the strength (and consequently the hardness) of the material increases up to the maximum value at the T6 temper. When the aging process is continued the T73 overaged condition with a lower strength is reached. The conductivity of the material is different for the W-, T6 and T76-temper as is indicated in Figure 1. With the conductivity of the material it can be determined whether a material which is not at the maximum strength level (T6) is in the overaged or in the underaged condition.

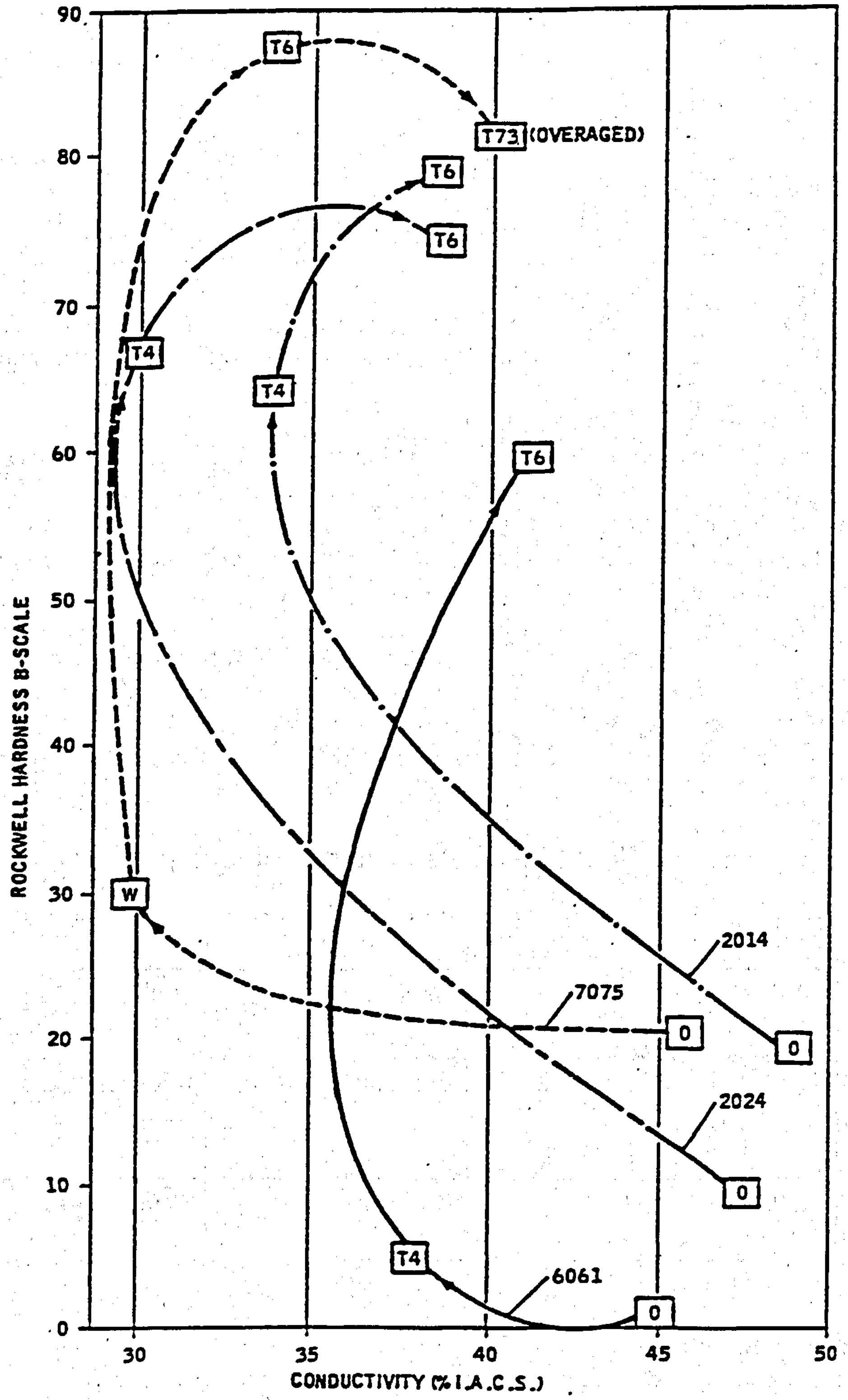

Figure 1. Conductivity-hardness relationship for heat-treatable aluminium alloys in different tempers (DC-10 Structural Repair Manual).

Old literature (Fink et al., 1945) quoted by Altenpohl (1965) shows that shortly after the introduction of the alloy a temperature treatment of 121°C (250°F) for 24h was recommended and that a treatment at 135°C (275°F) at 12h occasionally was used to shorten the cycle. *This practice was changed because the 24h treatment did not show enough formability for the dimpling process.* A slight improvement of the formability was obtained by a multiple stage hardening with a final temprature of 157°C (315°F) or above. After each step the sheet is cooled down to room temperature. Fink et al. gives results for two variants of two-stage processes:

- 2h at 93 to 107°C (200 to 225°F) followed by 2 to 8h at 149 to 168°C (300 to 335°F), and
- 4h at 99°C (210°F), then aging for 8h at 157°C (315°F). This is the process used by other airlines, and also given by the Metals Handbook, see Table 1, treatment #3. This treatment is also specified in MIL-H-6088 (for *plate* material only).

Fink et al. state that also another option is possible: progressive aging, without cooling down the sheet after each step. Progressive aging is done at 200, 250 and 315 °F for 4h at each temperature.

They also show that the tensile strength of the single stage treatment is slightly higher and the yield stress slightly lower than the two-stage hardened material. For 7075-T6 clad, t=1.0 mm in L-direction, the values given in Table 2 were obtained.

Fink et al. claim that accelerated corrosion tests revealed that the corrosion resistance of the two-stage aged materials is equal or better than the single-stage aged 7075-T6. (This indicates that the two-stage aged material is in the overaged condition.) They only reported negative effect is a reduction of the tensile strength of the two-stage aged alloy after cold work (7 MPa lower for each percent permanent strain). This is especially relevant for parts formed by a kind of stretching operation. For bended parts this effect will be very local.

Table 2. Literature data

	F_{tu} (MPa)		F_{ty} (MPa)		e (2in.) (%)	
heat treatment	Fink et al.	Nock&Wooll	Fink et al.	Nock&Wooll	Fink et al.	Nock&Wooll
#1 24h/121°C	545.3	-	466.8	-	12	-
#2 4h/99°C+ 8h/157°C	540.5	543.6	469.5	472.7	10	11.5
#3 3h/121°C + 3h/163°C	-	534.9	-	465.8	-	10.6

Nock and Wooll of ALCOA state in an article of 1947 that *the two-stage interrupted hardening is the standard procedure* (4h/99^{0}C+ 8h/157^{0}C)! But they present another option because this practice has the disadvantage that it takes more time than a single 8h shift per day! Their shortened procedure is: 3h at 121^{0}C (250^{0}F), cooling to about room temperature (100^{0}F) then 3h at 163 ^{0}C (325^{0}F). This corresponds approximately to the previously used KLM procedure that was used for so many years. For both stages KLM used a time of 3.25h instead of 3h. Nock and Wooll did not find an influence of the time between the two steps at room temperature.

Nock and Wooll present tensile test results of a comparison between the two two-stage hardening procedures carried out on three lots of 7075-T6 bare and clad (t=1.6 mm). The results for the *clad* material in L-direction are compiled in Table 2 (the mean value of three batches is taken).

Accelerated corrosion tests revealed better corrosion and stress corrosion properties for the shorter treatment. Nick and Wooll also state that the only disadvantage of the two-stage process compared with the single stage 24h process is the reduction in the tensile strength when the sheet is cold worked after quenching

Altenpohl (1965) states that the short two-stage hardening process is only used for cold formed products, not for forgings, extrusions and hot rolled sheets. He also gives results of ALUSUISSE with a variation of the second stage at 160^{0}C after a first stage of 2 to 4h at 135^{0}C. These results are shown in Figure 2.

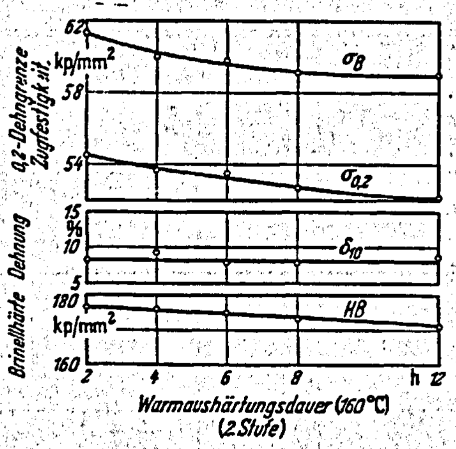

Figure 2. Mechanical properties of Al 7075 after a first stage of 2 to 4h at 135 ^{0}C (Altenpohl, 1965)

The first stage at of 2 to 4h at 135^{0}C is close to the treatment #2, which is the previously used KLM process, and also found in Nock and Wool. Altenpohl indicates that the strength drops as a consequence of the second stage. The second stage at 160^{0}C (as in the 'old'. KLM procedure) has to be between 2 to 4h, because for longer periods the strength drop is unacceptable. As can be seen in the figure a second stage of 2h gives a tensile strength of 61 kp/mm^2 (598 MPa) and at 4h 60 kp/mm^2 (588 MPa).

The test results in the present report have to be judged in the light of the minimum values on A- and B-basis specified by MIL-HDBK-5F for 7075-T6 clad sheet with a thickness of 2 mm (0.08 inch) as given in Table 3. MIL-6088G specifies that for 7075 the conductivity must be between 30.5 and 36.0 %IACS and the minimum required hardness is 84 HRb.

Table 3. Design mechanical properties of 7075-T6 clad given by MIL-HDBK-5F

basis	F_{tu} (MPa)	F_{ty} (MPa)	e (%)
A	L 510 LT 517	L 455 LT 441	L - LT 9
B	L 530 LT 530	L 475 LT 462	- -

2. Experimental details

2.1 Solution heat treatment

The required temperature for a solution heat treatment must be within the range given by military specification MIL-H-6088G: 460-499°C (860-930°F). The specified time in an air furnace for 2 mm (0.08 inch) sheet is: a minimum of 25 and a maximum of 35 minutes. The current KLM procedure M16 gives a temperature range of 475-485 °C.
For the present program on 2 mm sheet a temperature of 460 to 471 °C during 35 minutes in an air furnace was chosen.

The nominal solution heat treatment temperature was 465 °C. The minimum recorded temperature was 460 °C, the maximum 470 °C. The sheets were heated for 35 minutes, taken out of the bath in L-direction and quenched within 10 seconds in water with a temperature of maximal 37 °C after quenching.

2.2 Age hardening

Single stage The following temperature range is specified by MIL-H-6088G: 116-127°C (240-260°F) for 24h. The current KLM-practice, 24h at 121 °C, was used.

The solution heat treatment was carried out in an air furnace. All aging heat treatments were performed in oil baths (Shell Thermia A). The heat treatments were carried out according to MIL-H-6088G. Temperatures were measured with thermocouples attached to the specimens and were recorded as function of time. The size of the Al 7075-T6 clad t=2 mm sheet material was 200x300 mm. From each sheet 14 tensile specimens could be milled.

The four hardening procedures as shown in Table 1 were applied:

#1. The specified procedure: 24h at 121°C (the minimal recorded temperature measured with a thermocouple attached to the specimen was 120°C, the maximum 121°C).

#2. The 'old' two-stage hardening procedure as was used by KLM: 3.25h at 121°C, then 3.25h at 162°C. For the first step the recorded temperatures were between 120 and 123°C, for the second one between 162 and 164°C.

#3. The 'long' two-stage hardening procedure given by the literature of 1945/47: 4h at 96 °C, then 8h at 157°C. For the first step the recorded temperatures were between 95 and 97°C, for the second one between 156 and 159°C.

#4. A variant on #2, using a lower temperature in the first step: 3.25h at 96 °C followed by 3.25h at 162 °C (this treatment was tested by mistake, but is close to a process found in the literature). For the first step the recorded temperatures were between 96 and 98 °C, for the second one between 162 and 164°C.

Also tests were carried out on the material as was delivered in the T6-temper by the manufacturer.

All materials were tested both in L- and LT-direction. All L-specimens were from the same batch, while all LT-specimens were also from the same batch but a different one as the L-specimens. The tensile tests were carried out with the computerized Zwick 2-tons machine on tensile specimens according to ASTM B557 M-84. For each heat treatment 14 specimens were tested. The specimen dimensions are shown in Figure 3.

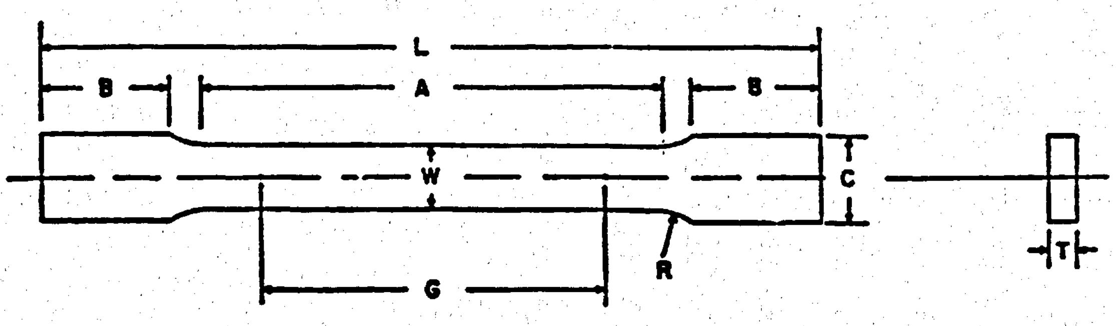

Figure 3. Specimen geometry (W=12.5 mm, L=150 mm, R=12.5 mm, C=20mm, B=35 mm, A=60 mm. The gauge length for the elongation measurements was 50 mm).

Also Rockwell hardness HRb tests were performed on a Wilson Rockwell Hardness Tester Model B524T. Conductivity measurements were performed using a Förster Sigmatest Model 2.067. The hardness and conductivity tests were done on samples after an etching process to remove the clad layers. Five hardness and three conductivity measurements were performed evenly distributed in the length direction of a strip of 300 x 30 mm sheet material.

3. Results

The tensile test results are given in the Appendix and are summarized together with the averaged values of the hardness and conductivity measurements in Table 4. The results of the pairs of hardness and conductivity measurements are plotted in Figure 4, together with the boundaries as specified by MIL-H-6088. The results for the two-stage processes are normalized using the single stage results as a reference. This comparison is given in Table 5.

As can be concluded from Table 4, the difference between the as delivered material and the materials which received a heat treatment is equal to the difference between the single and the two-stage processes (4%). The long two-stage heat treatment #3 gave the best properties of the two-stage processes. Only a difference of 2 to 3% relative to a single stage treatment was found.

As can be concluded from the conductivity measurements, the two-stage processes cause a somewhat overaged condition relative to the single stage treatment.

All hardness and conductivity values were within the specified boundaries of MIL-6088G.

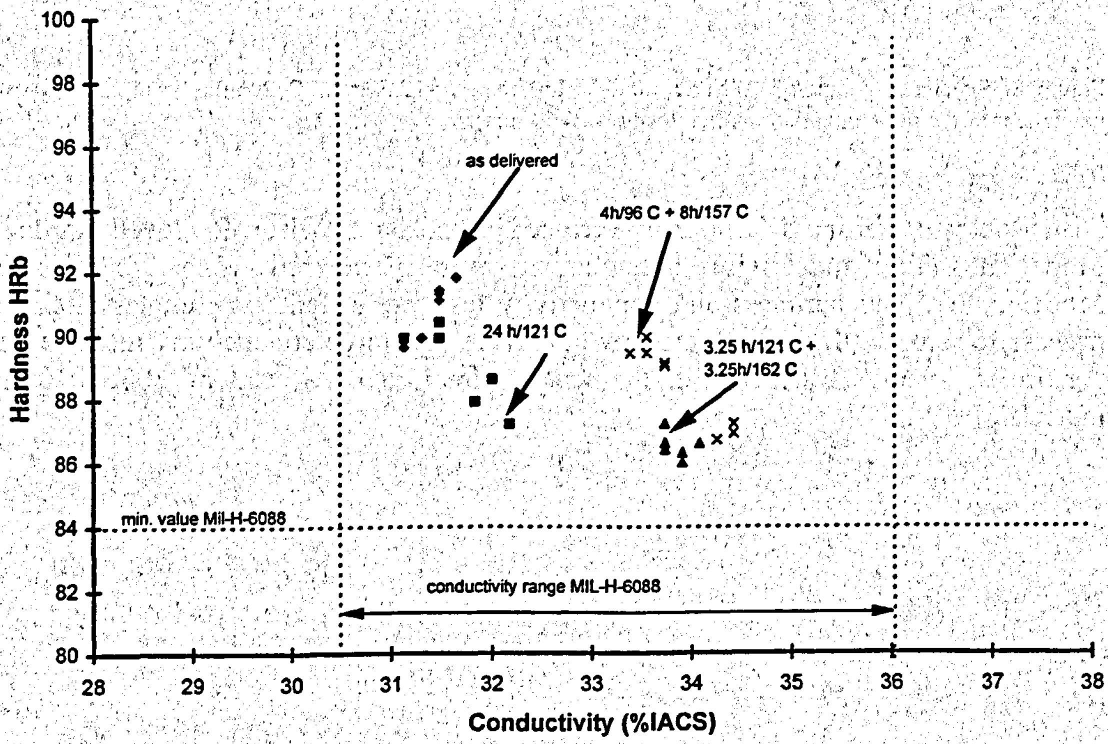

Figure 4. Hardness-conductivity plots for the as delivered 7075-T6 and for three heat treatments.

Table 4. Test results

heat treatment	L/ LT	F_{tu} MPa	sF_{tu} MPa	F_{ty} MPa	F_{ty} MPa	e %	se %	HRb	cond. m/Ωmm^2 (% IACS)
#0 as delivered	L	567.2	2.23	530.1	4.28	13.81	0.50	91.3	18.2 (31.4)
	LT	577.4	1.53	510.7	1.46	13.48	0.56	89.7	18.0 (31.0)
#1 24h/121^{0}C	L	547.8	1.11	493.2	4.52	13.62	0.58	90.2	18.1 (31.2)
	LT	553.2	2.88	494.0	3.88	13.09	0.56	87.9	18.5 (31.9)
#2 3.25h/121 ^{0}C+3.25h/ 162 ^{0}C)	L	523.1	2.70	472.5	3.44	12.22	0.63	86.4	19.6 (33.8)
	LT	532.3	2.74	473.1	2.96	12.50	0.43	86.4	19.5 (33.6)
#3 4h/96^{0}C+8h/ 157^{0}C	L	531.6	4.00	472.7	8.46	12.08	0.52	89.2	19.4 (33.4)
	LT	540.0	2.14	482.2	2.59	11.83	0.58	86.8	19.9 (34.3)
#4 3.25h/96^{0}C+ 3.25h/162 ^{0}C	L	532.6	2.91	475.4	6.68	11.80	0.51	89.1	19.1 (32.9)

Table 5. Test results with the single stage process as a reference

heat treatment	L/ LT	F_{tu} MPa	F_{ty} MPa	e %	HRb	cond. m/Ωmm^2 (% IACS)
#0 as delivered	L	1.03	1.07	1.01	1.01	1.01
	LT	1.04	1.03	1.03	1.02	0.97
#1 24h/121°C	L	1	1	1	1	1
	LT	1	1	1	1	1
#2 3.25h/121 °C+3.25h/ 162 °C	L	0.96	0.96	0.90	0.96	1.08
	LT	0.96	0.96	0.96	0.98	1.05
#3 4h/96°C+8h/ 157°C	L	0.97	0.96	0.89	0.99	1.07
	LT	0.98	0.98	0.90	0.99	1.08
#4 3.25h/96°C+ 3.25h/ 162 °C	L	0.97	0.96	0.87	0.99	1.06

4. Discussion and conclusions

1. The 24h single-stage process according to MIL-H-6088 causes a 3 to 4% lower tensile strength than the as delivered 7075-T6 material.

2. The 1945/47 and 1965 literature based on ALCOA-data shows that the long two-stage process (4h/96^{0}C+8h/157^{0}C) was the regular process in these days. The two-stage processes result in equal (stress) corrosion properties and a somewhat better formability, which indicates an overaged condition.

3. Present test results showed that the two-stage processes give 2 to 4 % lower tensile strengths than the single-stage process. This slightly lower stength is consistent with the literature data. The long two-stage process, which is specified in the Metals Handbook for plate material (4h/96^{0}C+8h/157^{0}C) is slightly better than the previously used KLM-process (3.25h/121 ^{0}C+3.25h/162 ^{0}C). However, both processes lead to hardness and conductivity values within the specified limits of MIL-H-6088.

4. The tested two-stage processes resulted in a slightly overaged condition. The literature shows that for the long two-stage aging process an equal strength can be obtained as for the single-stage process. This might be due to a somewhat shorter second stage.

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Appendix

Table A1. As delivered, L-direction.

specimen	t (mm)	b (mm)	σ_u (MPa)	$\sigma_{0.2}$ (MPa)	δ (50mm) (%)
0-1	1.98	12.62	566.3	535.5	13.42
0-2	1.98	12.62	566.8	530.7	12.93
0-3	1.98	12.62	568.8	534.0	13.94
0-4	1.97	12.62	565.1	525.6	14.28
0-5	1.97	12.62	567.3	528.9	13.68
0-6	1.97	12.57	571.9	537.6	13.54
0-7	1.98	12.59	566.9	528.3	13.68
0-8	1.98	12.59	568.1	526.2	14.40
0-9	1.98	12.57	566.5	525.4	14.23
0-10	1.98	12.59	564.0	528.7	14.82
0-11	1.98	12.56	569.5		13.45
0-12	1.98	12.56	569.5		13.65
0-13	1.98	12.56	567.0		13.95
0-14	1.98	12.57	563.7		13.34

Table A2. As delivered, LT-direction.

specimen	t (mm)	b (mm)	σ_u (MPa)	$\sigma_{0.2}$ (MPa)	δ (50mm) (%)
klm10_01	2.00	12.50	578.8	508.3	13.79
klm10_02	1.99	12.48	580.5	510.0	14.96
klm10_03	2.00	12.50	575.8	509.5	13.63
klm10_04	1.99	12.48	579.2	513.3	13.25
klm10_05	2.00	12.49	576.2	512.4	12.73
klm10_06	1.99	12.49	578.4	512.5	13.52
klm10_07	1.99	12.51	576.4	510.5	13.43
klm10_08	1.99	12.51	575.4	509.6	13.25
klm10_09	1.98	12.48	577.1	511.4	12.80
klm10_10	1.98	12.51	576.4	509.3	13.00
klm10_11	1.98	12.49	577.5	511.4	13.29
klm10_12	1.98	12.49	578.9	509.3	13.31
klm10_13	1.99	12.51	576.4	510.5	14.03
klm10_14	2.00	12.51	576.3	511.7	13.79

Table A3. Single stage hardened (24h/121 ^{0}C), L-direction

specimen	t (mm)	b (mm)	σ_u (MPa)	$\sigma_{0.2}$ (MPa)	δ (50mm) (%)
2-1	1.98	12.54	550.6	499.9	13.27
2-2	1.98	12.55	546.8	491.2	12.87
2-3	1.98	12.54	547.3	496.6	12.35
2-4	1.98	12.54	547.3	483.8	14.72
2-5	1.98	12.54	547.3	492.8	13.51
2-6	1.98	12.54	548.1	490.4	13.32
2-7	1.98	12.54	547.3	499.5	14.06
2-8	1.98	12.54	547.7	487.9	13.66
2-9	1.98	12.54	547.3	490.4	14.09
2-10	1.98	12.54	548.1	492.0	13.86
2-11	1.98	12.54	548.1	497.8	13.98
2-12	1.98	12.54	546.0	492.4	13.37
2-13	1.98	12.54	547.3	494.5	13.98
2-14	1.98	12.54	549.3	496.1	13.57

Table A4. Single stage hardened (24h/121 ^{0}C), LT-direction

specimen	t (mm)	b (mm)	σ_u (MPa)	$\sigma_{0.2}$ (MPa)	δ (50mm) (%)
klm1_01	2.00	12.50	556.2	500.9	13.01
klm1_02	2.00	12.49	556.3	498.5	13.26
klm1_03	1.99	12.50	557.0	499.3	13.45
klm1_04	1.99	12.49	555.8	494.0	13.21
klm1_05	1.99	12.52	555.3	496.1	12.58
klm1_06	2.00	12.56	554.4	494.5	12.71
klm1_07	2.00	12.52	551.3	493.6	12.90
klm1_08	2.00	12.49	551.4	491.5	12.23
klm1_09	2.00	12.49	552.6	494.0	12.83
klm1_10	2.01	12.52	549.7	491.1	12.76
klm1_11	2.01	12.53	551.3	492.8	12.56
klm1_12	2.00	12.52	554.5	493.6	14.25
klm1_13	2.00	12.53	551.2	487.5	13.97
klm1_14	2.02	12.54	547.4	487.9	13.48

Table A5. Long two-stage hardening (4h/96 ^{0}C+8h/157 ^{0}C), L-direction

specimen	t (mm)	b (mm)	σ_u (MPa)	$\sigma_{0.2}$ (MPa)	δ (50mm) (%)
6-1	1.98	12.56	527.1	475.5	11.12
6-2	1.98	12.56	526.6	468.1	11.70
6-3	1.98	12.54	534.9	479.2	12.82
6-4	1.99	12.57	532.2	462.1	12.44
6-5	1.98	12.55	535.7	474.3	12.13
6-6	1.98	12.60	527.4	472.4	11.90
6-7	1.98	12.54	530.0	474.7	12.02
6-8	1.98	12.57	535.7	471.1	12.89
6-9	1.98	12.57	535.3	482.2	12.64
6-10	1.98	12.57	528.7	454.6	12.17
6-11	1.98	12.55	526.2	486.7	11.32
6-12	1.98	12.55	530.4	464.4	12.14
6-13	1.98	12.55	536.1	480.1	12.16
6-14	1.98	12.54	536.6	472.7	11.73

Table A6. Two-stage hardening (4h/96 ^0C+8h/157 ^0C), LT-direction

specimen	t (mm)	b (mm)	σ_u (MPa)	$\sigma_{0.2}$ (MPa)	δ (50mm) (%)
klm7_01	2.01	12.50	541.7	481.3	12.18
klm7_02	2.00	12.51	543.1	487.4	11.67
klm7_03	2.01	12.49	540.5	481.3	13.31
klm7_04	2.01	12.51	540.0	482.6	12.22
klm7_05	2.00	12.50	542.7	484.9	11.87
klm7_06	2.01	12.48	538.4	479.7	12.21
klm7_07	2.00	12.48	539.9	481.2	11.66
klm7_08	2.00	12.50	539.0	482.1	11.95
klm7_09	2.00	12.48	537.8	480.8	11.12
klm7_10	2.00	12.50	537.0	477.2	11.39
klm7_11	2.00	12.50	537.0	482.9	11.33
klm7_12	2.00	12.49	538.2	481.7	12.13
klm7_13	2.00	12.48	541.1	482.1	11.51
klm7_14	1.99	12.52	542.9	486.2	11.05

Table A7. Two-stage hardening A (3.25h/96 ^{0}C+3.25h/162 ^{0}C), L-direction

specimen	t (mm)	b (mm)	σ_u (MPa)	$\sigma_{0.2}$ (MPa)	δ (50mm) (%)
4-1	1.99	12.53	534.3	482.5	12.04
4-2	1.98	12.52	530.4	477.0	11.82
4-3	1.98	12.52	531.6	468.6	11.51
4-4	1.98	12.51	531.2	466.7	12.02
4-5	1.98	12.51	535.4	484.1	12.11
4-6	1.98	12.54	537.4	480.1	12.01
4-7	1.98	12.54	535.3	483.8	12.31
4-8	1.98	12.54	530.0	477.2	10.56
4-9	1.98	12.54	530.8	473.9	11.08
4-10	1.98	12.54	529.5	460.7	12.13
4-11	1.98	12.54	534.1	478.0	12.15
4-12	1.98	12.54	536.6	473.9	12.28
4-13	1.98	12.54	527.9	473.0	11.90
4-14	1.98	12.54	531.6	475.9	11.32

Table A8. Two-stage hardening (3.25h/121 ^{0}C+3.25h/162 ^{0}C), L-direction

specimen	t (mm)	b (mm)	σ_u (MPa)	$\sigma_{0.2}$ (MPa)	δ (50mm) (%)
klm6_01	2.00	12.48	525.5	475.5	12.10
klm6_02	1.99	12.50	526.9	475.5	12.15
klm6_03	2.00	12.49	523.1	471.8	11.90
klm6_04	2.01	12.50	520.5	471.1	11.65
klm6_05	2.00	12.48	523.9	474.3	11.78
klm6-06	2.01	12.51	520.9	471.2	11.98
klm6_07	2.00	12.50	522.6	473.5	11.60
klm6_08	2.01	12.51	520.0	472.0	11.27
klm6_09	2.00	12.50	528.0	478.0	13.20
klm6_10	2.01	12.52	523.7	471.2	12.25
klm6_11	2.02	12.46	521.6	471.5	13.06
klm6_12	2.02	12.50	519.9	466.0	12.33
klm6_13	2.02	12.48	520.3	466.7	12.50
klm6_14	2.00	12.51	525.9	476.8	13.40

Table A9. Two-stage hardening (3.25/121 ^{0}C+3.25h/162 ^{0}C), LT-direction

specimen	t (mm)	b (mm)	σ_u (MPa)	$\sigma_{0.2}$ (MPa)	δ (50mm) (%)
klm5_01	1.99	12.50	534.3	473.8	13.43
klm5_02	1.98	12.50	538.3	479.5	12.48
klm5_03	2.00	12.48	533.7	473.0	12.31
klm5_04	2.00	12.50	534.5	476.8	11.86
klm5_05	2.01	12.50	533.1	472.4	12.47
klm5_06	2.00	12.49	531.5	475.2	12.27
klm5_07	2.00	12.47	535.0	474.6	12.50
klm5_08	2.01	12.51	530.2	470.4	12.64
klm5_09	2.00	12.47	532.9	472.2	12.58
klm5_10	2.00	12.50	531.7	474.7	12.61
klm5_11	2.00	12.47	530.5	471.8	11.95
klm5_12	2.00	12.51	528.8	470.3	13.08
klm5_12	2.00	12.47	528.4	468.1	12.77
klm5_13	1.99	12.50	529.8	470.5	11.98
klm5_14	1.99	12.50	510.0	393.3	11.46