

Development of 7003 Aluminum Extrusions for Motorcycle Frame Applications

Rowdy JOSEPH*

Junichi UEDA**

ABSTRACT

要 旨

The 7003-T4 alloy as an acceptable material for production of a motorcycle frame was developed. In the development of the material, a designed experiment was planned by which nine 7003 alloy variants were cast and homogenized. The cast billets were extruded into hollow frame tubes on a production extrusion line and the natural aging response of the material was evaluated. The tendency for recrystallized grains at the surface of the extruded tubes was measured and confirmed to be at an acceptable level for painting. The reversion and recovery of mechanical properties during paint curing was evaluated and curing limits were established for mass production. From the results, parametric equations were derived to describe the relationships between mechanical properties, composition and natural aging time to insure design compliance. This development has resulted in a frame which is 35% lighter than the tubular steel construction applied to previous models.

二輪車用フレームの量産に適した 7003-T4 アルミニウム合金を開発した。この材料の開発では、9種類の 7003 系アルミニウム合金を鋳造し、均質化処理を施したビレットを押出して中空断面のパイプを製造し、自然時効の硬化反応を評価した。表面再結晶粒の生成傾向を測定し、塗装表面処理のための許容レベルを確認した。塗装焼付け時における材料の復元と回復現象を評価し、量産における焼付け条件の限界を確立した。これらの結果から、設計整合性を保証するために、機械的性質、材料組成、自然時効時間の関係を述べるパラメトリック方程式を導き出した。また、7003-T4アルミニウム合金を高級ツーリング二輪車フレームに適用し、前モデルの鋼管製フレームより 35%の重量軽減を達成した。

1. Introduction

In order to reduce vehicle weight and meet the demands of the customer, a new dual spar aluminum frame design has been developed for the 2001 Honda Goldwing shown in Figure 1. A suitable U.S. aluminum alloy, one recognized by the U.S. aluminum industry and capable of performing according to the design requirements, had to be developed for extrusion into hollow tubes for the frame body.

A 7003 Al-Zn-Mg alloy was developed for extrusion into frame tubes for the new Goldwing. Customized alloys based on the 7003 chemistry are currently used to produce frame tubes found on Honda sport class and dirt motorcycles built in Japan. The development of these alloys resulted in restricted chemical compositions to optimize mechanical properties and limit the recrystallized layer depth. The latter control being especially important for those frames having an anodized surface finish. In order to establish a cost merit for the extrusion of aluminum tubes in the U.S., restrictions on

the alloy composition had to be avoided. It was decided to apply a standard 7003 alloy without restrictions on the chemical composition. The standard 7003 alloy is compared to the Honda custom alloy in Table 1. Several designed experiments were conducted as a means to define the aging relationships for the standard alloy.



Fig.1 2001 Honda Goldwing with aluminum frame body

* Honda R&D Americas, Inc.

**朝霞研究所

Table 1 Standard alloy vs. Honda custom alloy compositions

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Zr	Ti	Al
Standard 7003	0.30 max.	0.35 max.	0.20 max.	0.30 max.	0.5-1.0	0.20 max.	5.0-6.5	0.05-0.25	0.20 max.	Bal.
Custom alloy	0.05-0.20	0.15-0.30	0.05-0.15	0.20-0.30	0.50-0.80	0.05 max.	5.5-6.1	0.15-0.25	0.01-0.06	Bal.

Based on the results of the experiments, the material was found to meet the design requirements, and paint curing guidelines were successfully established. This paper describes the procedures used to develop the 7003-T4 alloy as an acceptable material for production of a lightweight, high strength motorcycle frame. The authors are hopeful that this data is a useful benchmark tool for designers and engineers considering extruded aluminum tubing for similar applications.

2. Description of 2001 Honda Goldwing Frame

2.1. Design Requirements

The frame is a welded assembly consisting of extruded tubes and aluminum die castings. The dual spars or main tubes which extend from the head pipe to the pivot plates on either side, are multi-void extrusions having a 3mm outer wall thickness. These tubes serve as the primary load bearing structures in the welded assembly and are the focus of this material development. The down tubes are dual-void extrusions that extend from the head pipe to the front engine bracket locations. The tubes comprising the rear frame are round hollow extrusions which support the seat and saddle bags.

The lightest frame is achieved by minimizing the wall thickness of each extruded tube. Wall thicknesses are based on the mechanical strength of the aluminum and in the case of the new frame, a custom alloy served as the basis for calculating the thickness targets. The standard 7003 alloy had to perform as well as the custom alloy during tensile tests to prevent thickness increases leading to a heavier frame. The development of the 7003 material, resulted in a frame body having an average

weight of 21kg. Although the 20kg target was slightly exceeded, a 35% decrease in frame weight compared to the welded tubular steel construction found on the previous Goldwing was realized. The frame is shown in Figure 2.

Exposing a bit of the frame body provides a mechanical personality but requires that the exposed area have a high quality surface appearance. Several surface finish options were considered at the onset of development. The original idea was to apply a bright anodized surface for a shiny metallic appearance. The anodized option requires special control over the depth of the recrystallized layer which generates at the die interface during the extrusion process. Since grain growth following recrystallization is unrestricted at the surface, the surface grains become large and the surface appears coarsened⁽¹⁾. This coarsening condition is called "orange peel" and an example is shown in Figure 3. Orange peel becomes more noticeable when the grains are strained during bending. Anodizing also enhances this effect, so a powder paint system was chosen as an alternative to prevent strict control over the recrystallized layer depth and increased extrusion costs. The paint would sufficiently cover the recrystallized surface and provide good corrosion resistance. Control over the depth of the recrystallized layer was still required, but to a lesser degree. The frame material design requirements are given in Table 2.

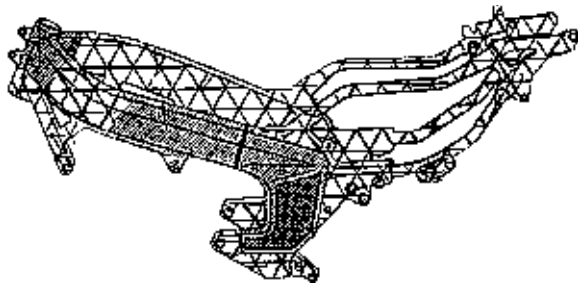


Fig.2 Frame body construction

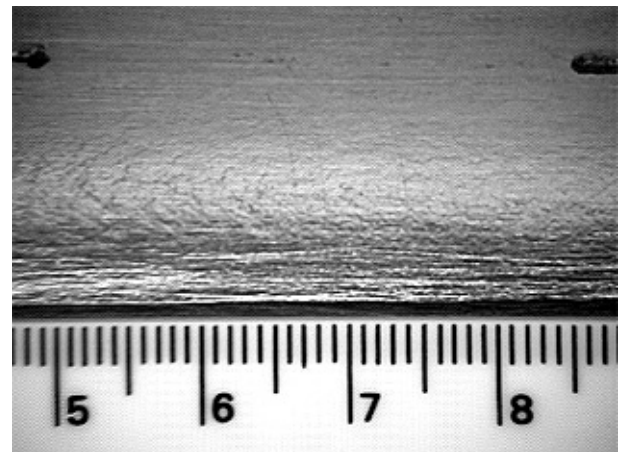


Fig.3 Orange peel effect

Table 2 Frame material design requirements

Criteria	7 day aging	30 day aging	90 day aging
Tensile strength (MPa)	235 min.	275 min.	294 min.
Yield strength (MPa)	118 min.	176 min.	186 min.
Elongation (%)	13 min.	13 min.	13 min.
Recrystallized layer depth (mm)	25 max.		

2.2. Material Selection

Initially, several alloys were considered for the application. The selection criteria are shown in Table 3.

6061 is commonly applied to automotive structural applications where strength, corrosion resistance and weldability are required. Although 6061 is easily arc welded, the room temperature hardness recovery in the heat affected zone is not good and adequate strengths could not be achieved.

7075 was also briefly considered. The high Zn and Mg content in this material promote significant strengthening during natural aging. The Cu content (typically near 1.6%) is a disadvantage since increasing Cu widens the melting range and reduces the solidus temperature⁽²⁾. The effect is to increase the potential for cracking during arc welding. Extruding 7075 into shapes having thin wall sections is also difficult and distortion following press quenching is eminent. Based on these producibility issues, 7075 was eliminated as a candidate for this frame tube application.

The 7003 alloy was selected as the best option for production of the new frame tubes. The Zn and Mg content provide sufficient response to natural aging although the allowable ranges are wider than those of the Honda custom alloy. The low Cu content (0.2% maximum) narrows the melting range and increases the solidus temperature which improves resistance to weld cracking when a high Mg filler metal is applied⁽²⁾. The custom material was developed with anodized frames in mind and Cr promotes yellowing of the anodic oxide surface layer, therefore Cr is controlled to a low level (0.05% maximum) to improve the appearance of the anodized frames. The new Goldwing frames will be

painted, so the yellowing effect from Cr is not relevant and higher levels may be tolerated. The standard 7003 was found to meet the material requirements and was chosen for production of the frame tubes.

2.3. Manufacturing Sequence

The manufacturing sequence required to create the frame body is shown in Figure 4. First, round ingots, 178mm in diameter and 1524mm long are continuously cast and homogenized. The heads and tails are cropped to eliminate extreme variations in composition and microstructures. The ingots are heated to 510 °C and direct extruded into multi, dual void, or hollow tubes. As the tubes exit the extrusion dies, they are quenched and the natural aging cycle begins. The extruded tubes are next cut to length and formed by bending into the appropriate shapes. Minor machining and drilling is performed and the tubes are prepared for welding. The structure takes shape when the cast head pipe, pivot plates and engine brackets are joined to the frame tubes by manual arc welding. The frames pass through a paint booth where a polyester urethane powder is applied. Finally, the powder is cured at 210 °C for 48 minutes and the frames are ready to be assembled into motorcycles.

3. Experimental

3.1. Basis

The aging of rapidly quenched Al-Zn-Mg alloys from room temperature to relatively low aging temperatures is accompanied by the generation of solute rich zones known as GP (Guinier-Preston) zones⁽¹⁾. Strengthening is the result of interference between moving dislocations

Table 3 Aluminum alloy selection criteria

Criteria	Honda Custom Grade	6061-T6	*7003-T4	7075-T6
Tensile strength (MPa)	235	310	324	570
Yield strength (MPa)	118	275	187	505
Elongation (%)	13	12	19	11
Youngs modulus (GPa)	71	69	71	72
Extrudability (hollows)	Good	Excellent	Good	Poor
Formability	Fair	Fair	Fair	Poor
Weldability	Good	Excellent	Good	Poor
Hardness recovery after welding	Good	Poor	Good	–
Availability	Poor	Excellent	Fair	Excellent
**Material costs	\$5.00/kg	\$3.88/kg	\$4.77/kg	No data

*Typical properties after standard aging 7 days at RT

**Includes casting and conversion. Shipping costs are included for the Honda Custom Grade.

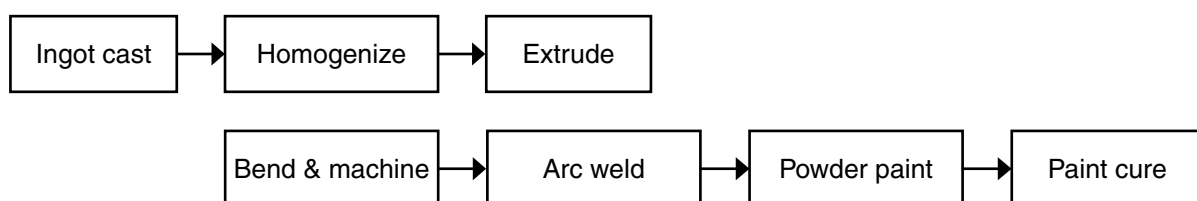


Fig.4 Manufacturing process

and these spherical shaped zones. With increasing aging time, GP zones increase in size, and the strength of the alloy increases⁽¹⁾.

Extended aging at temperatures above room temperature transforms the GP zones in alloys with relatively high Zn-Mg ratios into the equilibrium precipitate known as $MgZn_2$ or M phase⁽¹⁾. In the case of the 7003 alloy where Zn is in excess of Mg, the sequence is in the order GP zones, coherent precipitate, and M phase ($MgZn_2$)⁽¹⁾. Heating and cooling of the extruded tubes during production of the frame body changes the mechanical state of the alloy according to this aging sequence. In the case of the painting process, the stable tubes in the T4 condition, are exposed to moderately high temperatures during the curing step. This exposure causes the sequence to reverse which decreases the hardness, and therefore the strength, of the tubes. This phenomenon, known as reversion, is caused by Zn and Mg diffusion back into the solvent aluminum and subsequent shrinking of the GP zones.

3.2. Experimental Procedures

3.2.1. Mechanical Properties vs. Natural Aging

Relationships between mechanical properties, composition and natural aging time were empirically developed.

The increase in strength during natural aging is a result of the growth of GP zones rich in Mg and Zn solute atoms, therefore these elements were chosen as factors and adjusted to produce nine variants covering the entire 7003 chemical range in the standard alloy. The chemical variants are shown in Table 4. Time and temperature were chosen as the aging factors. These levels were set at 7, 30, and 90 days. With production locations in mind, the aging temperature levels were set at -10 °C, 25 °C and 50 °C to reflect possible natural aging temperature scenarios.

Tensile coupons were machined from the sample tubes representing each of the nine chemical variants described in Table 4. Coupons were made from tubes representing the front, middle and rear of each cast ingot in order to capture inherent process variation. The aging start time ($t=0$) was re-established by solution heat treating the coupons in a small electric furnace at 435 °C for 1 hour and quenching in air to represent press quenching. All tensile coupons were produced according to ASTM B557. The duplicate flat coupons had a gage length of 50mm and the testing was conducted according to ASTM E8.

Table 4 3x5 design experiment: Chemical variants

Chemical variants		Magnesium (%)		
		0.5	0.75	1
Zinc (%)	5.00	A1	A2	A3
	5.75	A4	A5	A6
	6.50	A7	A8	A9

3.2.2. Recrystallization Tendency

Temperatures at the material/die interface are high enough during press quenching to cause simultaneous recovery, recrystallization, and grain growth. Surface quality of the extruded tubes is dependent on the depth of the recrystallized layer and the size of the recrystallized grains at the surface. Coarse grains, which become strained during bending produce an undesirable "orange peel" effect. Controlling recrystallization during extrusion is crucial for anodized frames, since anodizing amplifies the orange peel effect. The selection of powder paint reduces the necessary control over the recrystallized layer depth, however it does not eliminate orange peel as a factor which reduces appearance quality. In order to estimate the recrystallization tendency in the 7003 alloy, a section from each of the alloy variants was taken normal to the extrusion direction. The sections were polished, etched to reveal the recrystallized layer, and observed under a light microscope.

3.2.3. Reversion and Recovery Evaluation

The paint curing cycle was established for mass production by determining the effect of curing temperature and time on the reversion and recovery of mechanical properties.

The painting process consists of pretreatment, powder paint application, and paint curing stages. The gas fired curing oven contains two zones, each having independent temperature control. Frames are placed on hangers and transferred through the curing oven via an overhead conveyor. Curing temperature and time are partially determined by the paint selection since each paint is delivered with a recommended cycle developed to provide the best adhesion and appearance for a given substrate. In the case of the Goldwing frames, a polyester urethane resin material was selected. The best adhesion and appearance is achieved by curing between 182 °C and 216 °C for at least 15 minutes. The curing time is controlled by the speed of the overhead conveyor carrying the painted frames into the curing oven. Minimizing curing time results in maximum line speed and production output but requires a temperature setting near the high side of the supplier's recommended range.

Three trials were conducted in order to establish the optimum curing cycle under normal production conditions. The variables for each trial are given in Table 5. In each trial, the pretreatment temperature was fixed at 177 °C and painting was done according to mass production guidelines. Upon completion of each trial,

Table 5 Reversion and recovery experiment

Process variable	Normal production		
	Trial 1	Trial 2	Trial 3
Line speed (m/min.)	1.22	1.83	1.83
Pretreatment (°C)	177	177	177
Zone 1 (°C)	199	199	210
Zone 2 (°C)	199	204	210
Total cure (mins.)	60	48	48

the test frames were inspected for paint adhesion and appearance. Reversion and recovery of mechanical properties was quantified by measuring the change in hardness in a section cut from the main tube of each test frame over a period of 50 days.

4. Experimental Results

4.1. Mechanical Properties vs. Natural Aging

4.1.1. Composition Effects

The 7 days aging condition was chosen to illustrate the relationship between mechanical properties and composition. One week is the typical time between press quenching and frame welding during production, so it is convenient to express the strength of the formed tubes after natural aging for 7 days. The results of tensile strength, yield strength, and elongation averages are shown in Figures 5, 6, and 7. The data shows that tensile and yield strength targets, set by design, can be achieved across the entire chemical range when natural aging occurs at room temperature or above. The aging

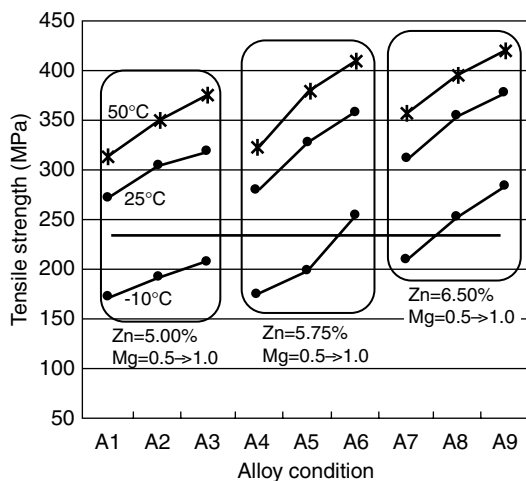


Fig.5 Composition impact on tensile strength at -10 °C, 25 °C, 50 °C

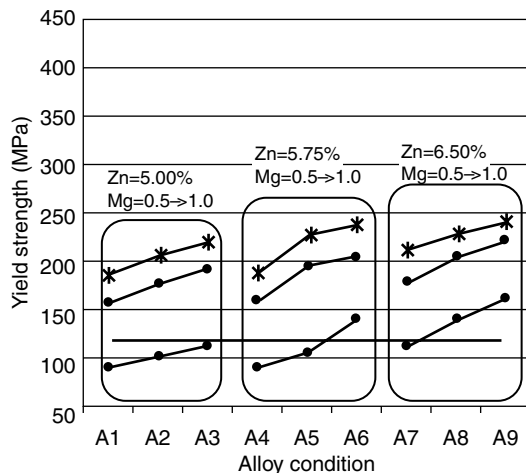


Fig.6 Composition impact on yield strength at -10 °C, 25 °C, 50 °C

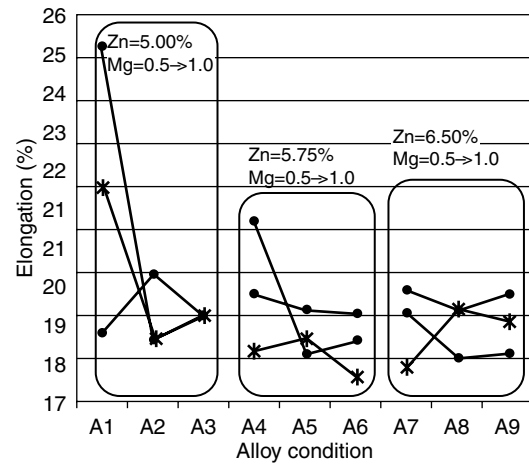


Fig.7 Composition impact on elongation at -10 °C, 25 °C, 50 °C

sequence is slowed significantly when freezing temperatures are encountered so that the 7-day strength targets are only achieved when the Zn and Mg percents are at the high end of the specification range. Acceptable elongation is also achieved for all chemistries. A premise for using the standard 7003 alloy was that custom chemical control be avoided. Based on the results, customizing the alloy composition is not required.

4.1.2. Natural Aging Effects

Figures 8, 9, and 10 illustrate the natural aging response at -10 °C, 25 °C, and 50 °C for 7, 30, and 90 days. The data shows that the tensile and yield strength targets can be achieved after a 7-day natural aging cycle except for the case where aging occurs at -10 °C. The mechanical strengths increase as natural aging proceeds and the increase in strength is proportional to aging temperature. The natural aging rate is inversely proportional to aging time due to the slowed growth of

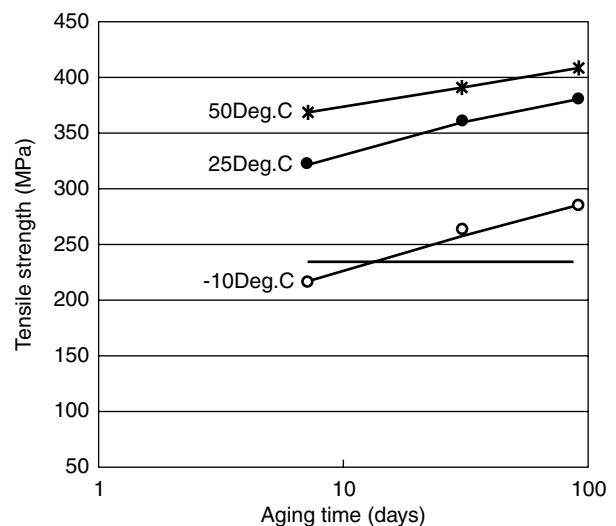


Fig.8 Aging impact on tensile strength

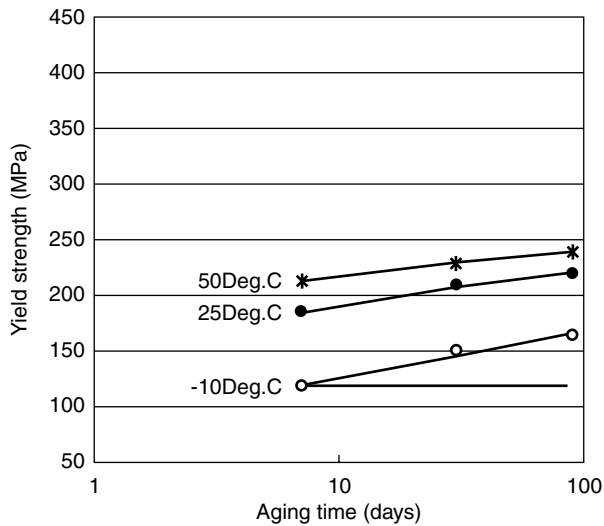


Fig.9 Aging impact on yield strength

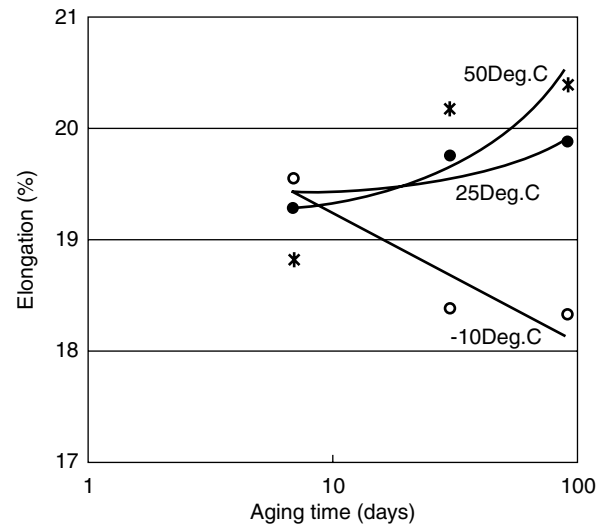


Fig.10 Aging impact on elongation

GP zones. Under the conditions of this aging study, the tensile strength increases at a rate 0.8MPa/day at -10 °C, 0.7MPa/day at 25 °C, and 0.5MPa/day at 50 °C. The yield strength increases at a rate of 0.6MPa/day at -10 °C, 0.4MPa/day at 25 °C, and 0.3MPa/day at 50 °C.

Although these general trends are known and were expected, the data allows quantification based empirical relationships. Regression analysis was performed to generate trend lines and equations for each condition. A statistical check on the accuracy of the strength vs. natural aging equations was made by calculating the R^2 value. The equations and R^2 values are given in Tables 6 and 7. Test error prevented an accurate trend analysis on the elongation data.

The mechanical properties given by the standard 7003 alloy are sufficient after naturally aging for at least 7 days, except when exposed to freezing temperatures. To prevent exposure to freezing temperatures likely when transporting the extruded lengths during the winter, extrusion and bending was established at the same plant location. This decision prevents unexpected changes in the mechanical response to tube bending and improves

control over the dimensions of the finished tubes for easier alignment during welding. Special chemical control is not required to guarantee compliance with the design criteria and the standard 7003 was confirmed to be acceptable for frame production.

4.2. Recrystallization Tendency

The normalized results from each worst case depth measurement are shown in Figure 11 and a photomicrograph showing a typical recrystallized layer is shown in Figure 12. It is seen that the average recrystallized layer depth is less than the specification limit given in Table 2, however there is the potential to exceed this limit. The actual appearance of mass produced frames was acceptable to the visual criteria, so no further action was needed to reduce the potential for recrystallization.

4.3. Reversion and Recovery During Paint Curing

Hardness of the frame material was considered fully recovered when a hardness of 75 HRF was achieved. This value represents the as-welded hardness of the

Table 6 Equations, strength vs. chemistry at 7 days

Property	Natural Aging Temperature	Equation
Tensile Strength (MPa)	25°C	$58.31 + (117.75 * \%Mg) + (30.39 * \%Zn)$
Yield Strength (MPa)		$26.61 + (79.19 * \%Mg) + (19.22 * \%Zn)$

Table 7 Equations and R^2 values, strength vs. natural aging

Property	Natural aging temperature	Equation	R^2 Value
Tensile strength (MPa)	-10°C	$26.86 \ln(\text{days}) + 167.76$	0.98
	25°C	$25.99 \ln(\text{days}) + 270.05$	0.99
	50°C	$14.94 \ln(\text{days}) + 341.69$	1.00
Yield strength (MPa)	-10°C	$19.08 \ln(\text{days}) + 82.50$	0.98
	25°C	$14.89 \ln(\text{days}) + 158.19$	1.00
	50°C	$9.87 \ln(\text{days}) + 197.53$	0.99

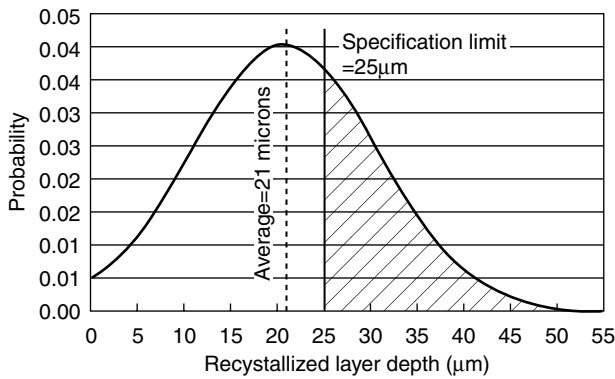


Fig.11 Recrystallization tendency in 7003-T4

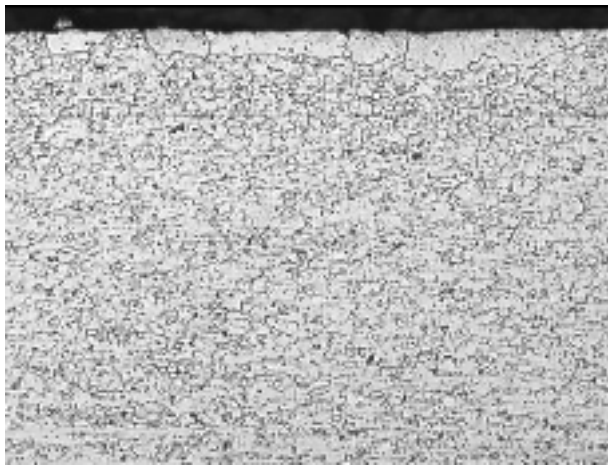


Fig.12 Typical recrystallized layer in 7003-T4, 200x HF

extruded tubes prior to paint curing. Tensile tests were conducted on samples having a maximum hardness of 75 HRF to guarantee acceptable strength and elongation at this target hardness. Based on the correlation, the tube material was considered acceptable when recovery to at least 75 HRF was obtained.

Reversion was found to occur in the 7003 tube material during each of the three paint curing trials. The A356.0 casting material, heat treated to the T6 condition, was not affected by exposure to curing temperatures. This is primarily due to the stability of the Mg_2Si precipitate formed during heat treating. Reversion was found to occur in the welds joining the tubes to the castings, however the high Mg content in the A5356 filler metal promotes rapid recovery and the hardness returned to the as-welded condition within 14 days. These results are illustrated in Figure 13.

Results from the trials conducted under normal paint curing conditions are given in Figure 14. The line speed settings for Trial 1 and Trial 2 were slow enough to allow a significant decrease in material hardness. In each of these two cases, the recovery time was nearly 15 days. Increasing the line speed at both the pretreatment and curing locations during Trial 3 acts to

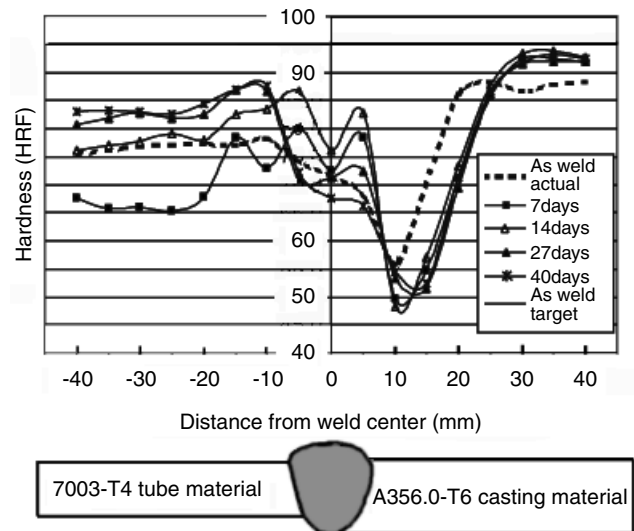


Fig.13 Reversion and recovery in the weldment

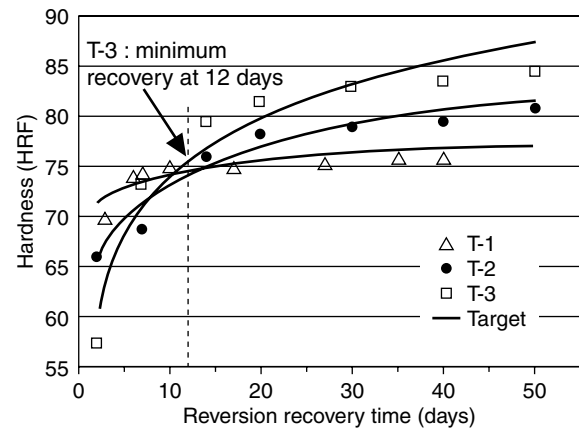


Fig.14 Reversion recovery: Normal cure trial results T1-T3

minimize reversion, despite higher curing temperatures. The frame material exposed to the conditions of Trial 3 required only 12 days to recover to the target hardness. This was the minimum recovery time recorded for the three Trials, therefore the mass production paint curing conditions were set to equal those applied to Trial 3.

5. Conclusions

- (1) The standard 7003-T4 alloy, produced in the U.S., has been developed for production of extruded frame tubes for the luxury touring motorcycle.
- (2) The standard material is shown to meet strength and surface recrystallization requirements for the lightweight, painted frame design.
- (3) Empirical relationships have been established to define mechanical properties as a function of alloying and natural aging.
- (4) A paint curing process has been defined to guarantee the mechanical properties in the final painted product.

6. References

- (1) Aluminum Properties and Physical Metallurgy, ASM, 1984
- (2) ASM Handbook Volume 6, Welding, Brazing and Soldering

7. Acknowledgements

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■ 著 者 ■



Rowdy JOSEPH



上田 順一