The Seventh Triennial International Fire & Cabin Safety Research Conference
Philadelphia Marriott Downtown, December 2-5, 2013.

Kumamoto University

Flame-resistant Magnesium Alloys with High Strength

Magnesium Research Center, Kumamoto University

mrc.ku

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13:30 to 14:00 (30 min.), December 3, 2013.

Contents of My Talk

1. Magnesium Alloys and their Major Problems
2. *KUMADAI* I/M Mg Alloys
3. *KUMADAI* RS P/M Mg Alloys
4. FAA-Flammability Tests of *KUMADAI* Mg Alloys
5. Spreading Effects and Future Challenges

What is Magnesium ?

■ Magnesium is a promising sustainable metal in the 21st century.

Advantages of Magnesium

Lightweight

Resourceful

Practical metals
in the earth's crust

1. Si
2. Al
3. Fe
4. Mg

Green

Metals
in human body

1. Ca
2. K
3. Na
4. Mg

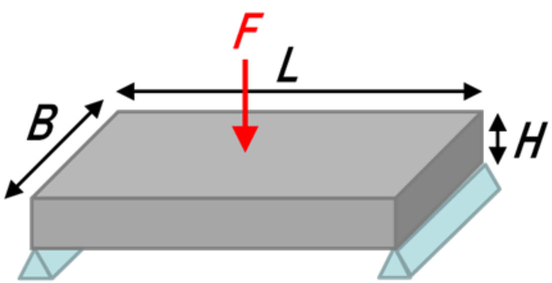
Recyclability

Low
melting temperature

Advantage of Magnesium Alloys as Structural Materials

- Magnesium alloys have the highest specific stiffness among metallic materials.

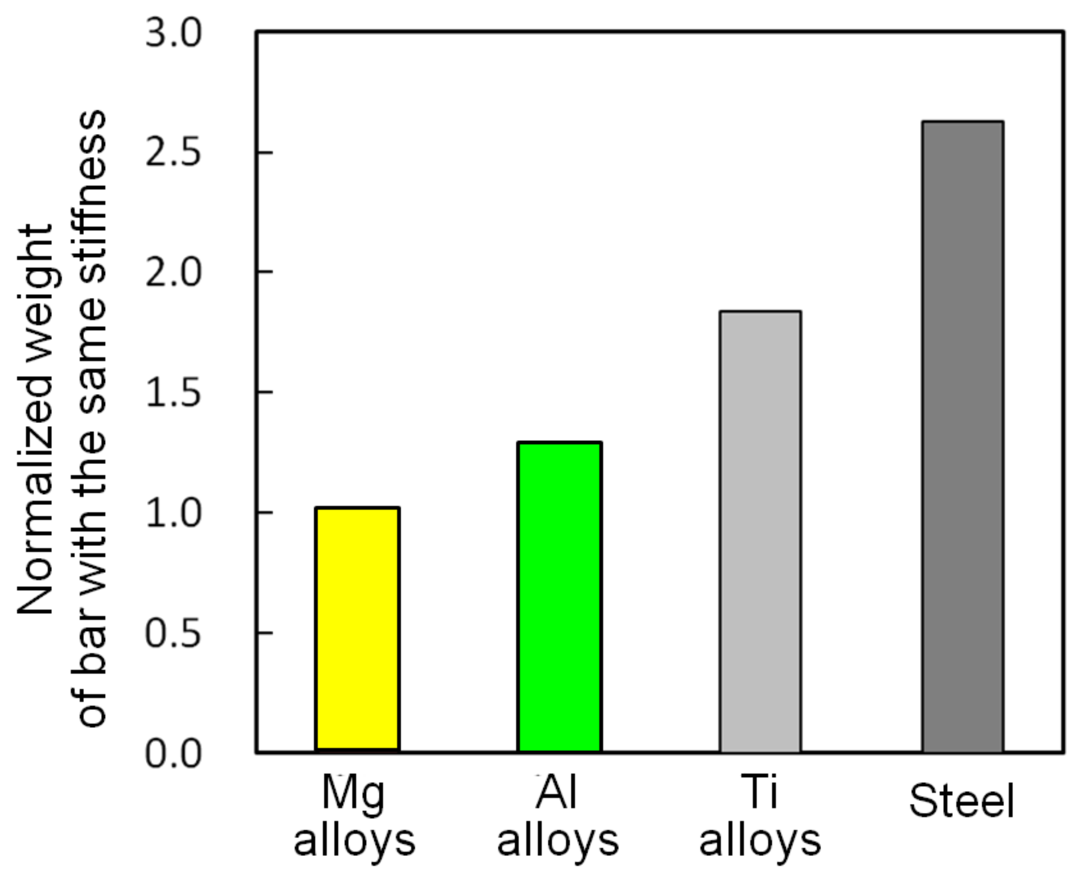
Weight of bar with the same stiffness



The elastic deflection of a beam loaded at its center

$$\delta = FL^3 / 48EI$$

$$I = BH^3 / 12$$



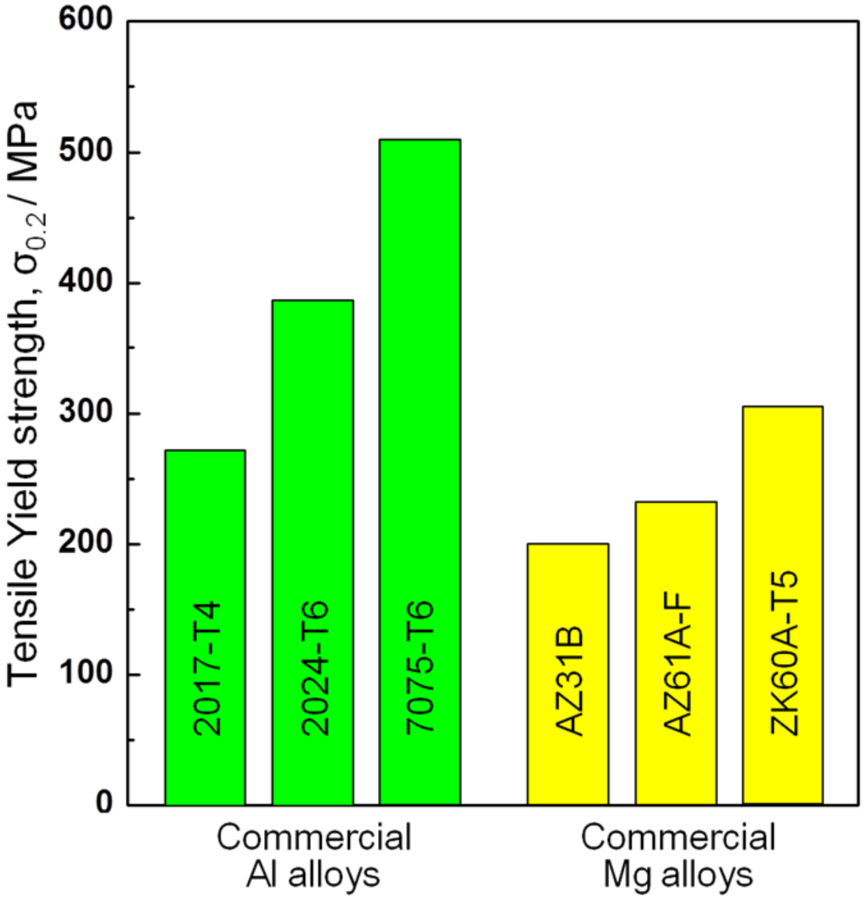
Major Problems to Solve in Magnesium Alloys

- Mechanical strength of magnesium alloys is inferior as compared with aluminum alloys.

Low mechanical strength

Low ignition temperature

Low corrosion resistance



Major Problems to Solve in Magnesium Alloys

- The ignition temperature of magnesium alloys is low, resulting in flammable material.

Low mechanical strength

Low ignition temperature

Low corrosion resistance

Fire and Its Spread at Mg-recycling Factory
(Japan, May 22nd, 2012)

Fire fighting was restricted because the discharge of water or extinguisher brings out hydrogen explosion. It took one week to die down the fire of 200 tons Mg scraps.

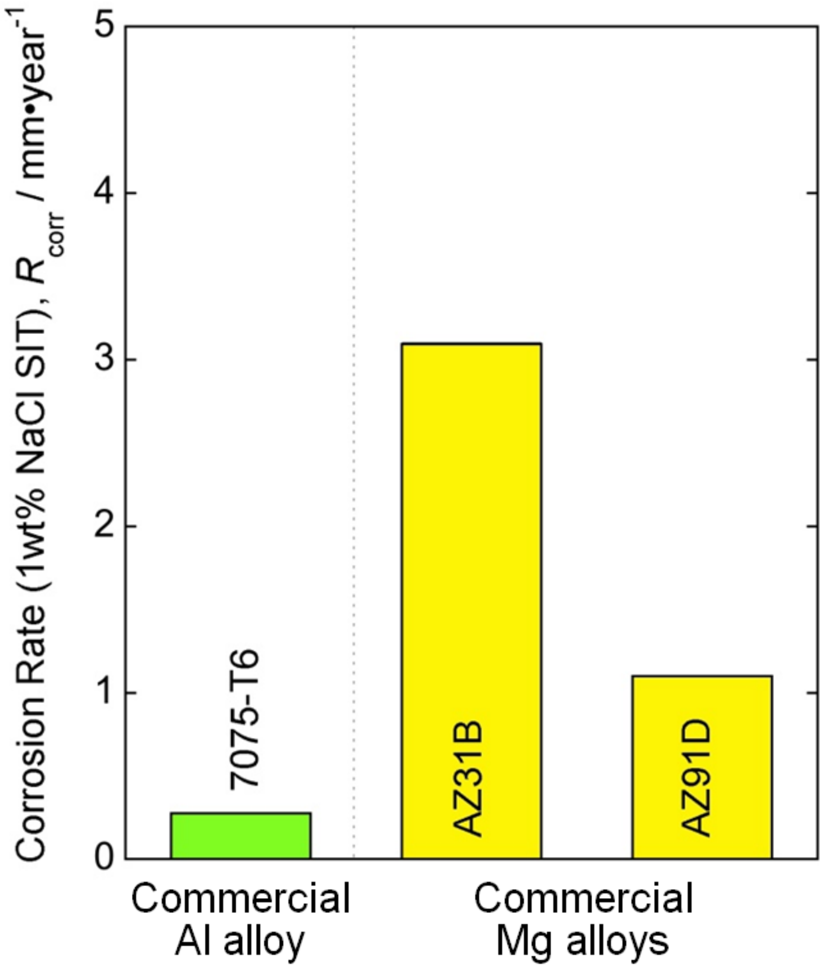
Major Problems to Solve in Magnesium Alloys

- The corrosion resistance of magnesium alloys is much lower than that of aluminum alloys.

Low mechanical strength

Low ignition temperature

Low corrosion resistance



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Innovative *KUMADAI* Mg Alloys

- Two kinds of *KUMADAI* Mg alloys have solved the major problems in Mg alloys, resulting in an innovation.

Solve the Major Problems in Magnesium Alloys

We have developed new magnesium alloys
with high ignition temperature,
high strength,
good corrosion resistance.

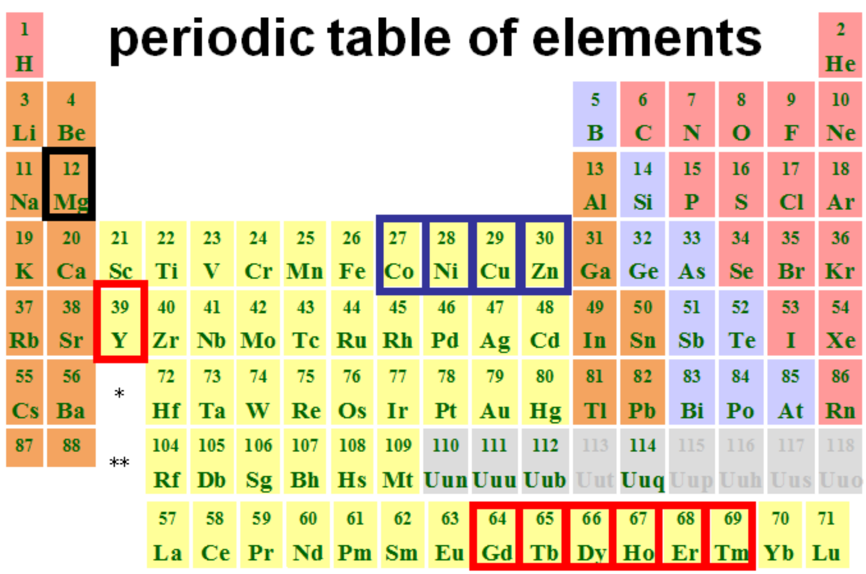
(1) *KUMADAI* Heat-resistant Mg Alloy
(2) *KUMADAI* Non-flammable Mg Alloy

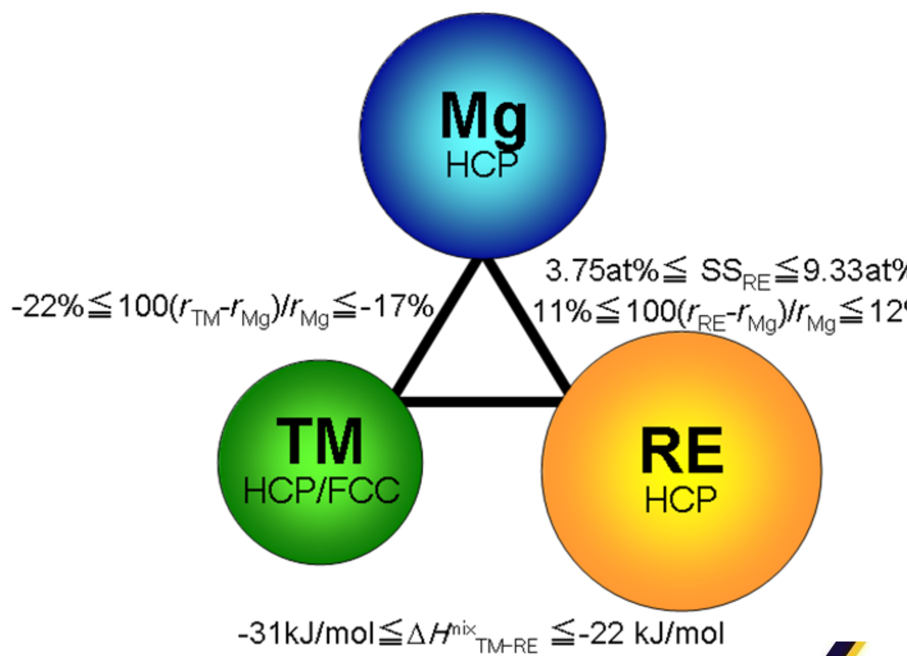
Alloy Compositions of *KUMADAI* Heat-resistant Alloys

- *KUMADAI* heat-resistant Mg alloys are Mg-TM-RE system, in which TM is Co, Ni, Cu or Zn, and RE is Y, Gd, Tb, Dy, Ho, Er or Tm.
- The combination of TM and RE has some roles in crystal structure, atomic radius, mixing enthalpy and solid solubility limit.

Mg-TM-RE

TM: Co, Ni, Cu, Zn
RE: Y, Gd, Tb, Dy, Ho, Er, Tm



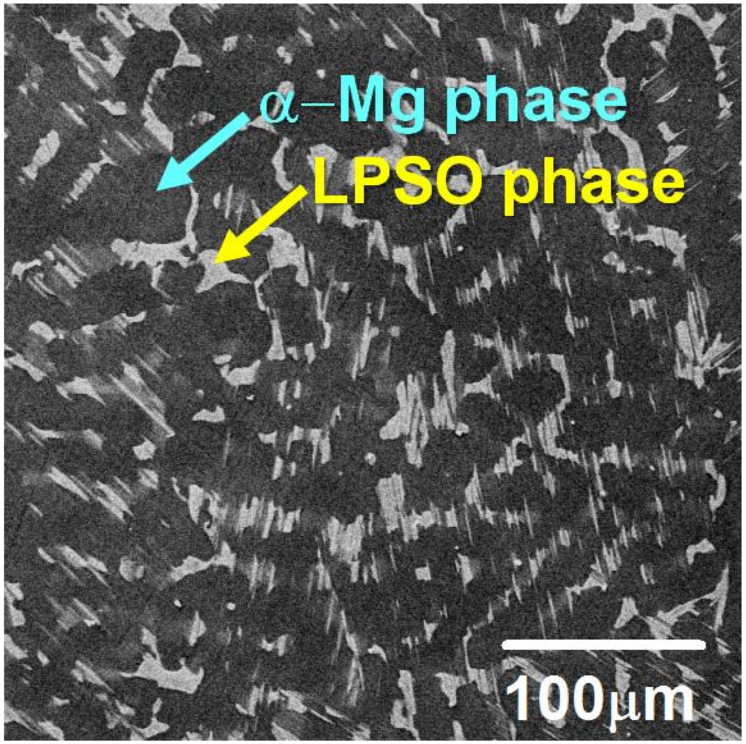


Y. Kawamura et al.: Mater. Trans., 2007

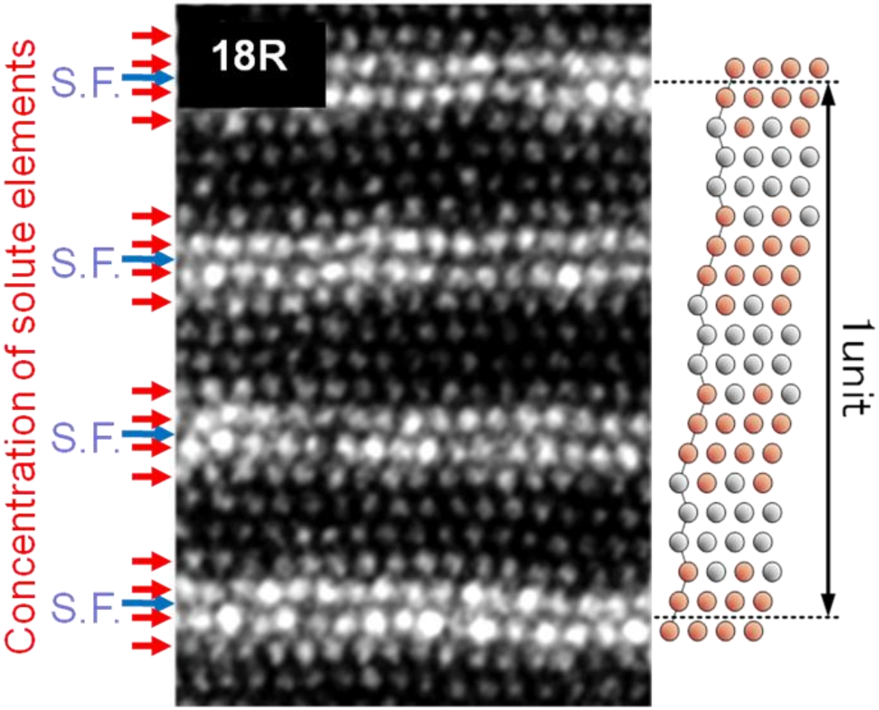
Microstructure of *KUMADAI* Heat-resistant Alloys

- *KUMADAI* heat-resistant Mg alloys are duplex of α -Mg phase and LPSO phase, and are strengthened by LPSO phase.
- LPSO phase has a novel LPSO structure, where stacking and chemical modulations are synchronized.

Microstructure of as-cast $Mg_{97}Zn_1Y_2$ (at%) alloy



Synchronized LPSO Structure

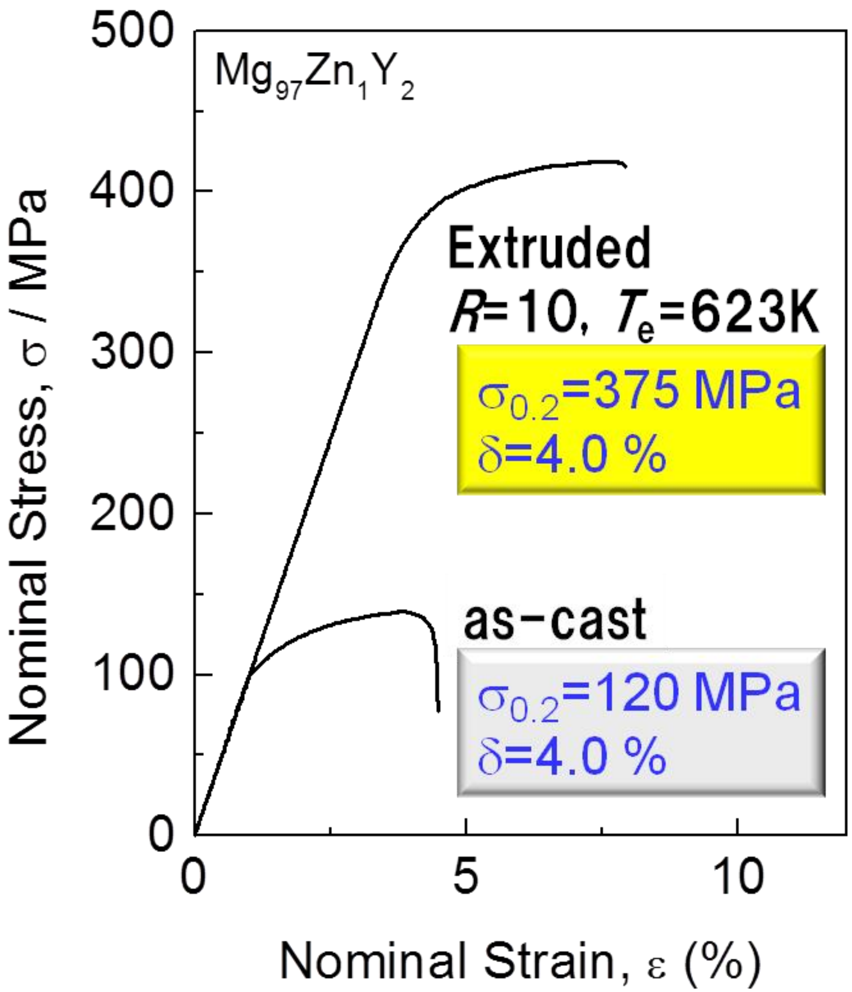


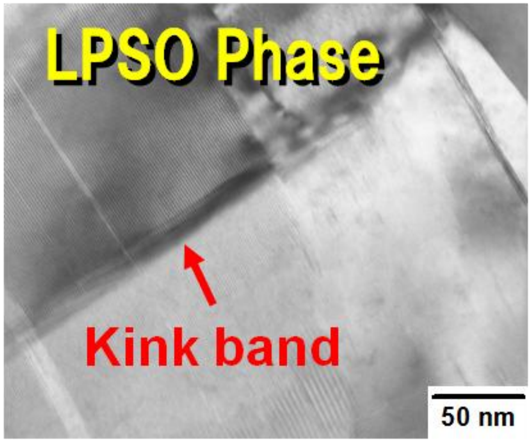
E. Abe, Y. Kawamura et al.: Acta Mater., 2002

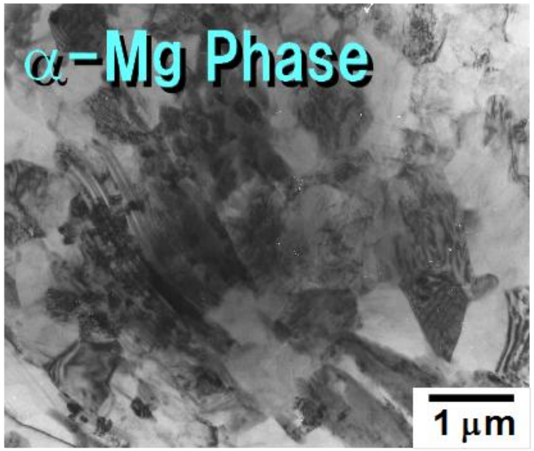
Stacking and chemical modulations are synchronized in LPSO structure

Features of Extruded *KUMADAI* Heat-resistant Alloys

- Mechanical strength of *KUMADAI* heat-resistant Mg alloys is improved drastically by plastic deformation with keeping the elongation.
- The improvement of mechanical properties is due to kind- band formation of LPSO phase and grain refinement of α-Mg matrix.







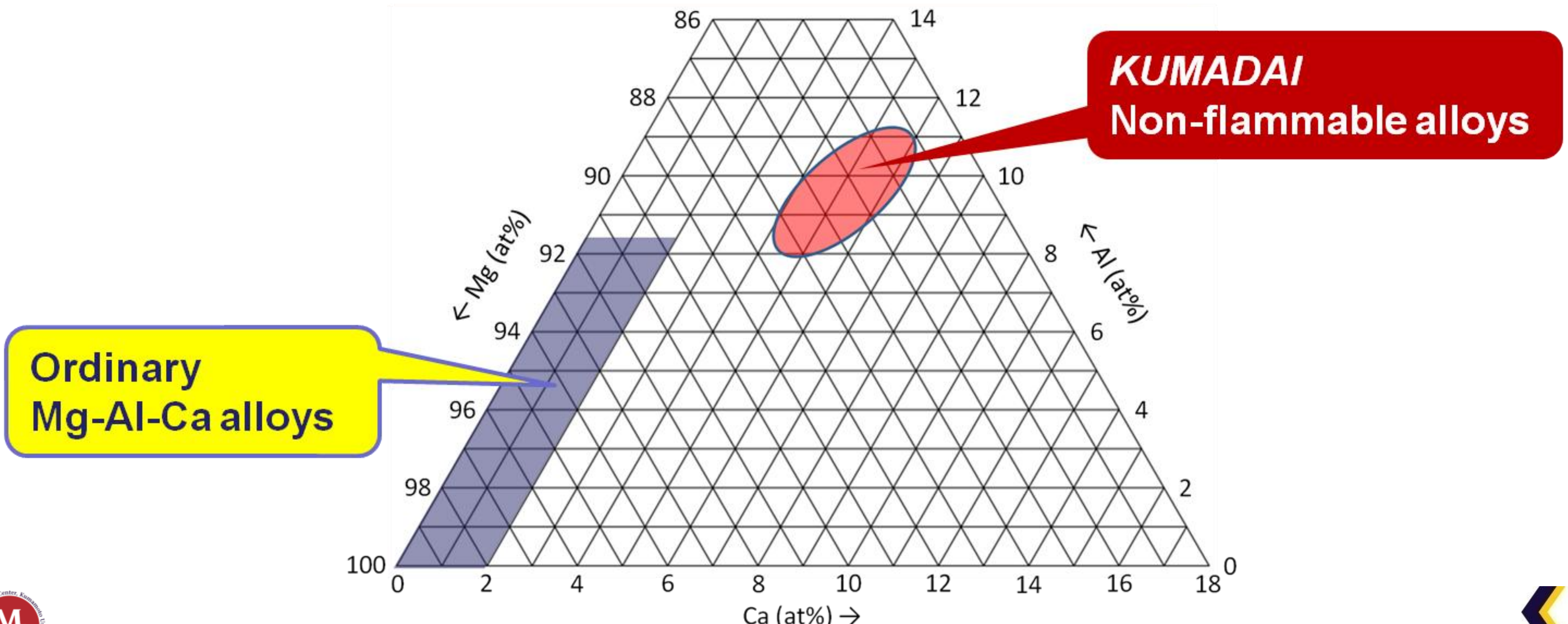
Alloy Compositions of *KUMADAI* Non-flammable Alloys

- *KUMADAI* non-flammable Mg alloys are Mg-Al-Ca system with high Al and Ca contents.

Mg-Al-Ca

Al: 8.0～11.0 at%

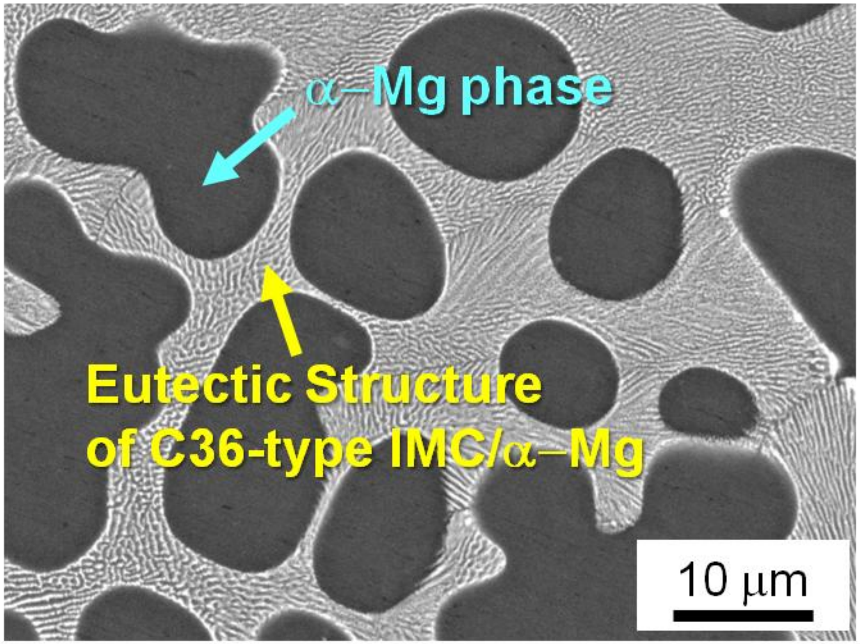
Ca: 4.0～ 6.5 at%



Microstructure of As-cast *KUMADAI* Non-flammable Alloys

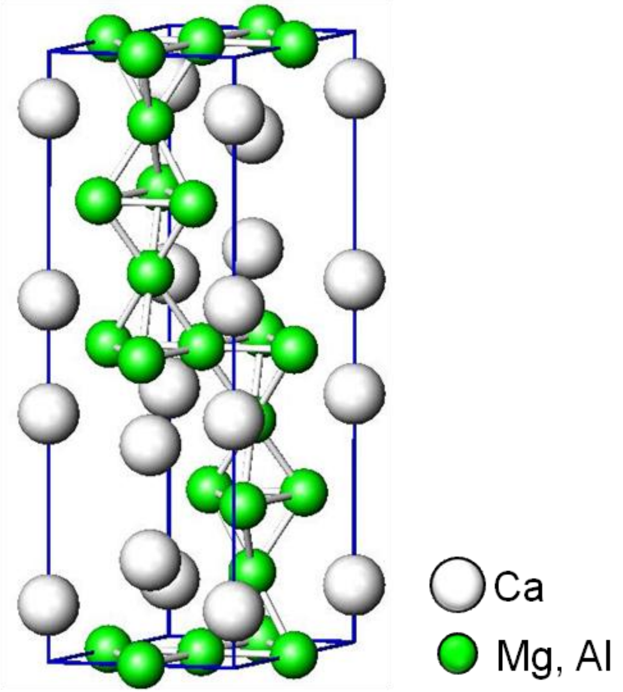
- *KUMADAI* non-flammable Mg alloys are duplex of α-Mg phase and C36-type intermetallic compound (IMC).

Microstructure of $Mg_{85}Al_{10}Ca_5$ (at%) alloy



C36 structure

$(Mg, Al)_2Ca$



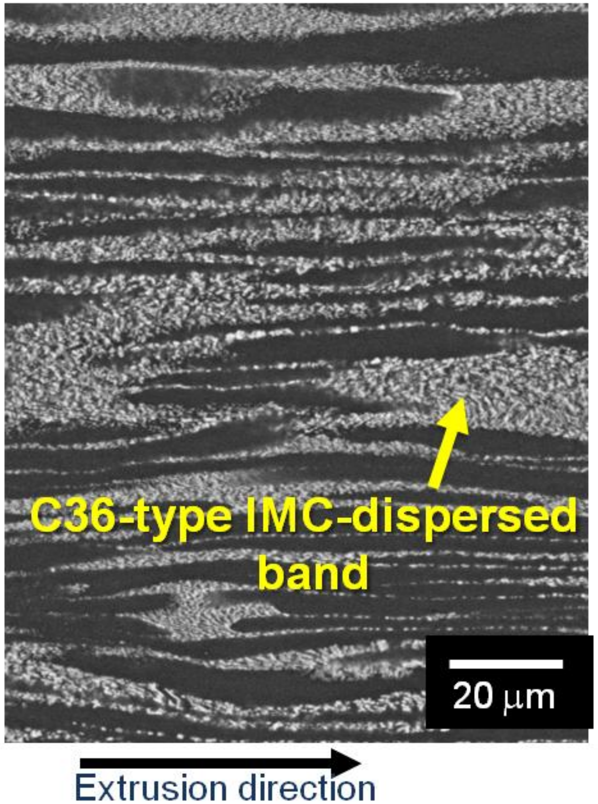
Hexagonal laves phase

Microstructure of Extruded *KUMADAI* Non-flammable Alloys

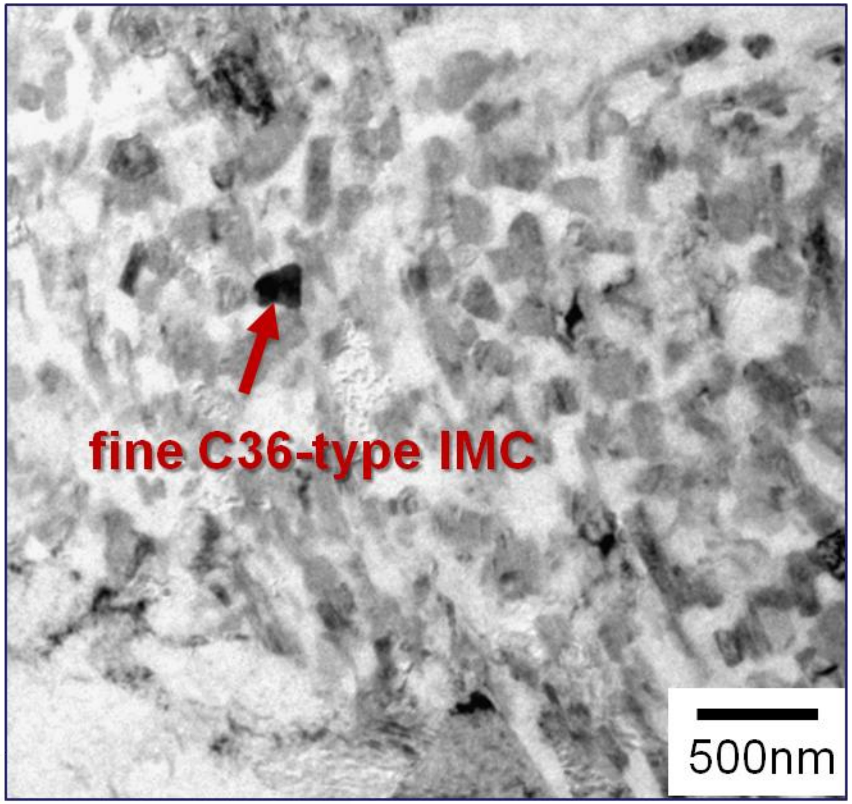
- C36-type intermetallic compound (IMC) is finely dispersed by extrusion, resulting in high strength and reasonable ductility.

Microstructure of Extruded $Mg_{85}Al_{10}Ca_{5}$ (at%) alloy

SEM

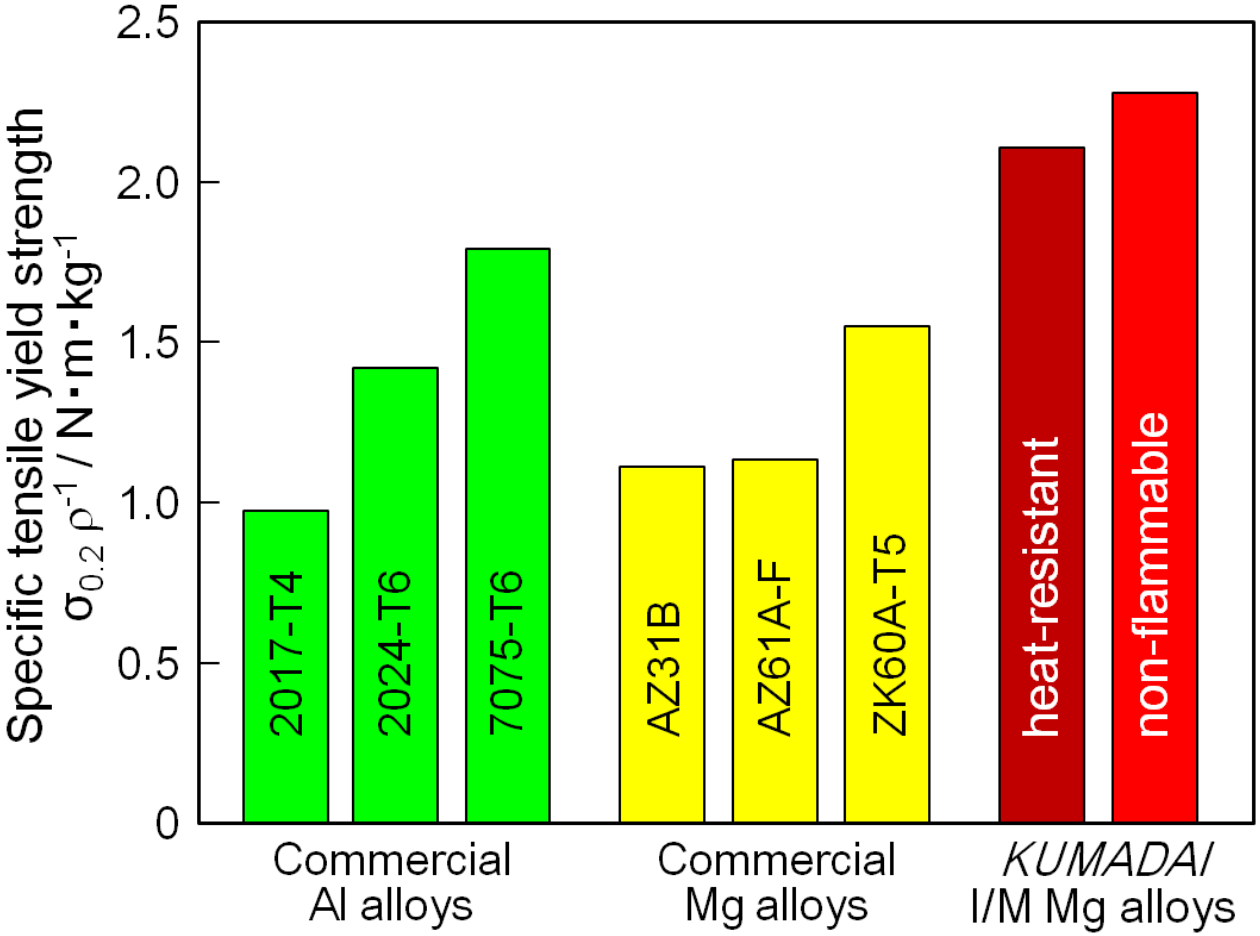


TEM



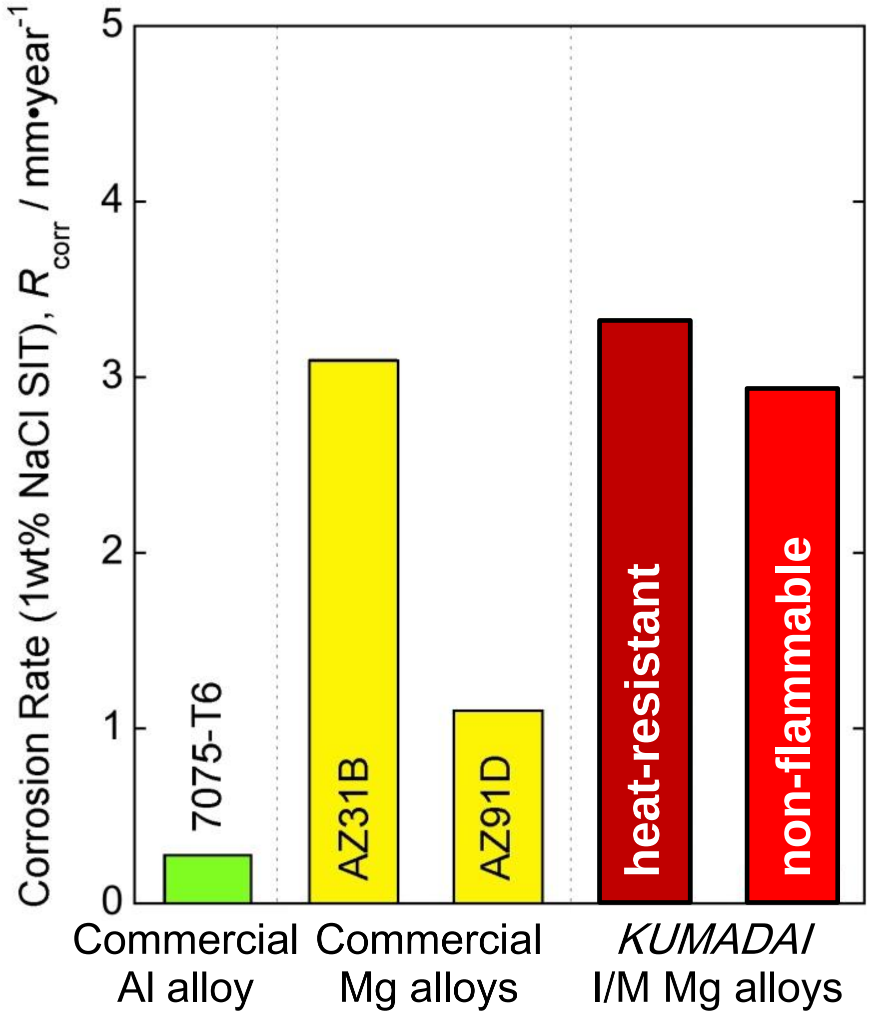
High Mechanical Strength of *KUMADAI* I/M Mg Alloys

- *KUMADAI* I/M Mg alloys have superior yield strength to high strength Al alloys.



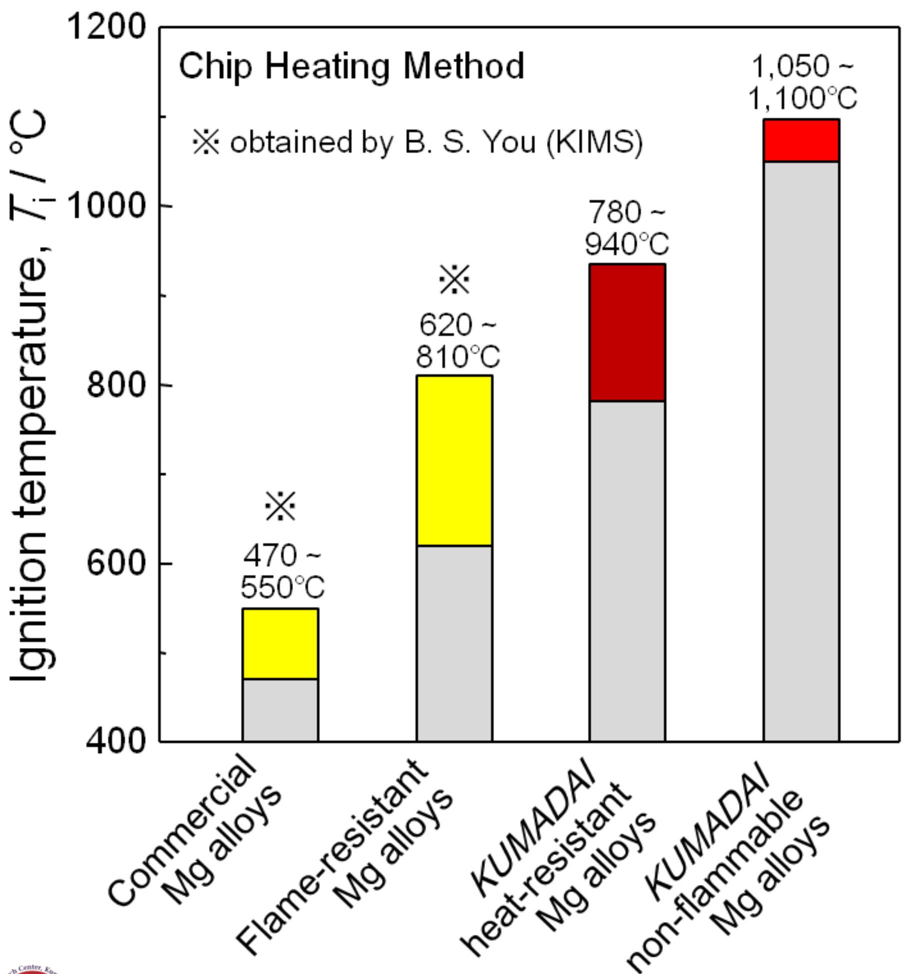
Good Corrosion Resistance of *KUMADAI* I/M Mg Alloys

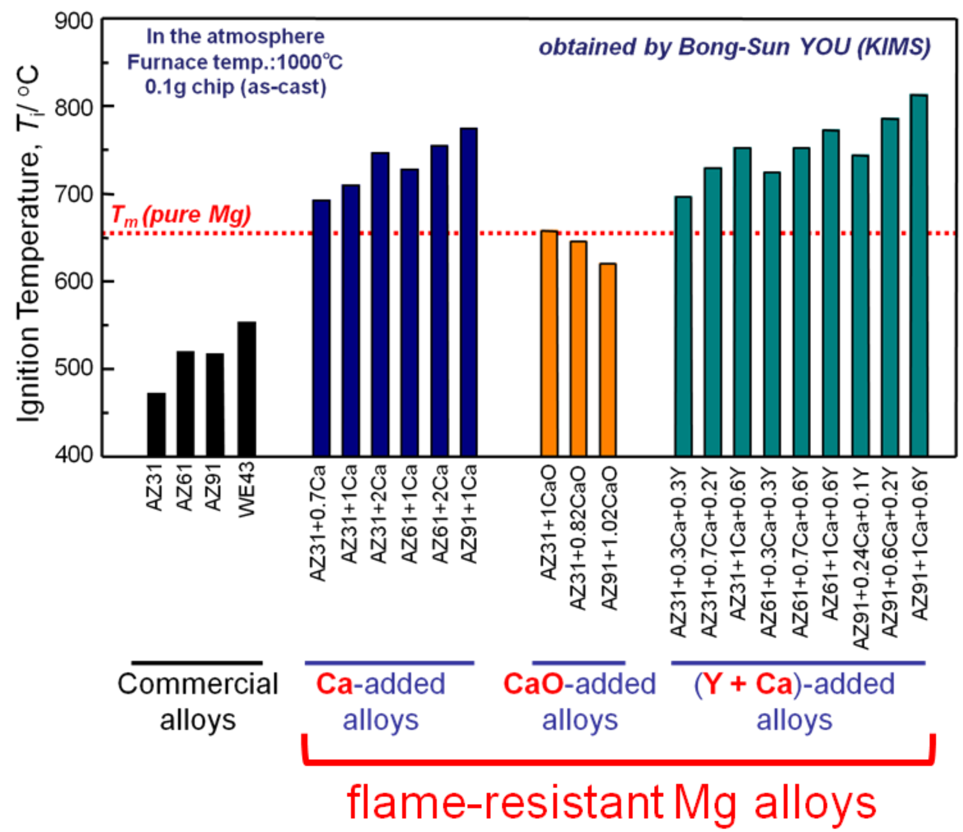
- *KUMADAI* I/M Mg alloys have similar corrosion resistance to commercial Mg alloy (AZ31).



High Ignition Temperature of *KUMADAI* I/M Mg Alloys

- *KUMADAI* I/M Mg alloys have higher ignition temperature than flame-resistant Mg alloys containing Ca, CaO, or Ca+Y.



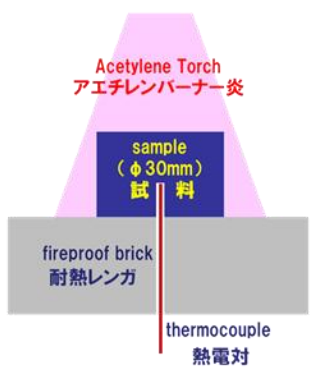


Flammability Tests of *KUMADAI* Non-flammable Mg Alloy

- *KUMADAI* non-flammable I/M Mg alloy did not burn up to 1,117℃ that is higher than its boiling point (1,065℃).

Ignition Test of Molten Alloys with 700℃

Burning Test by Acetylene Torch



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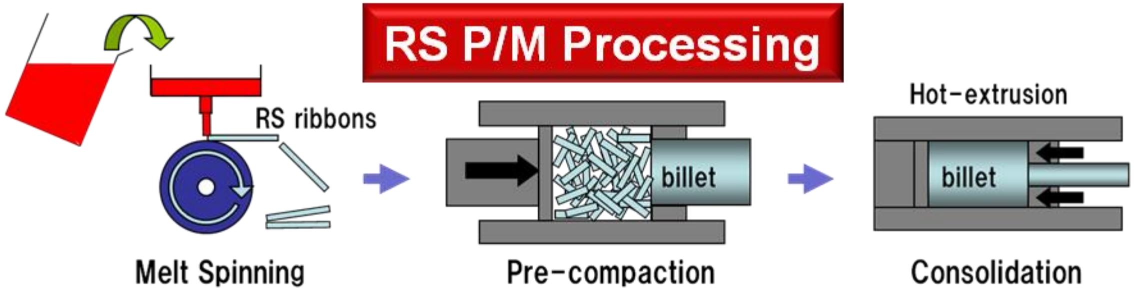
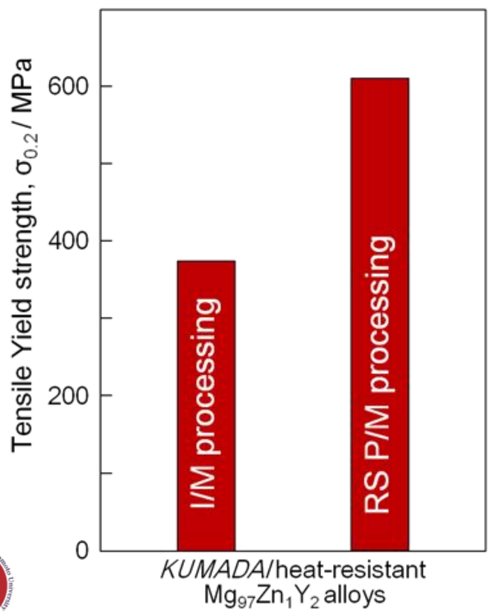
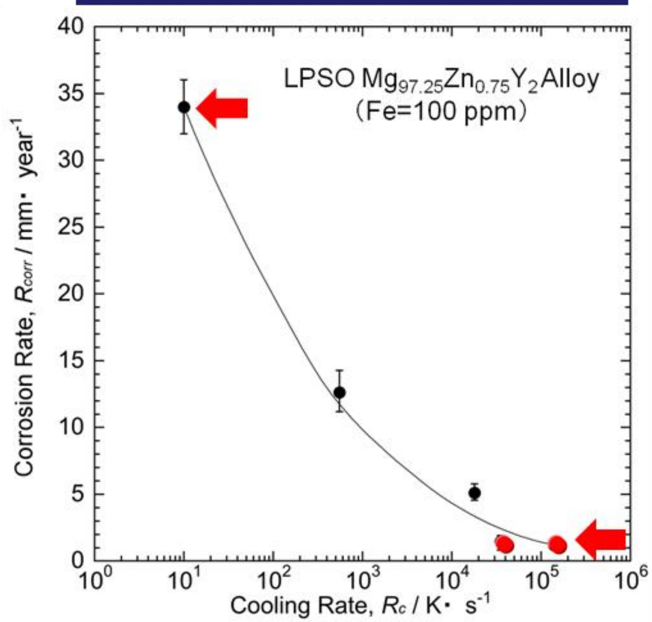
Effects of Rapidly Solidified Powder Metallurgy Processing

- RS P/M processing brings out 1.6-fold yield strength,10-fold corrosion resistance and superplasticity of *KUMADAI* heat-resistant Mg alloys.



1.6-fold Mechanical Strength	10-fold Corrosion Resistance	High-strain-rate Superplasticity





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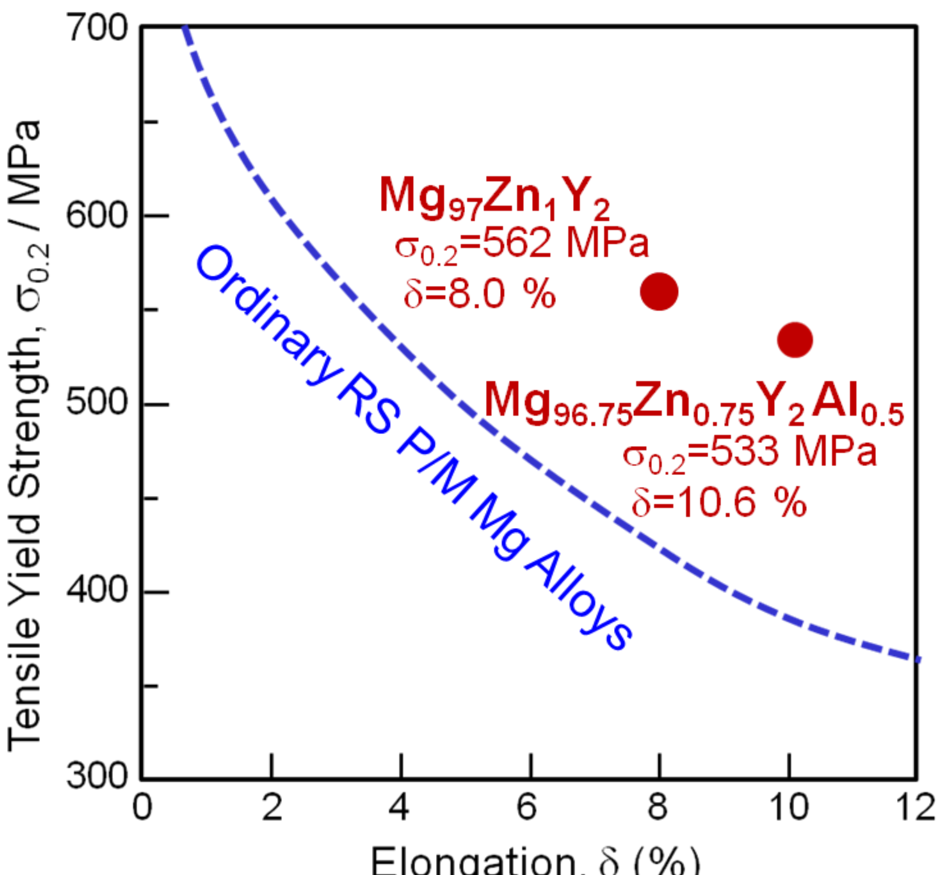
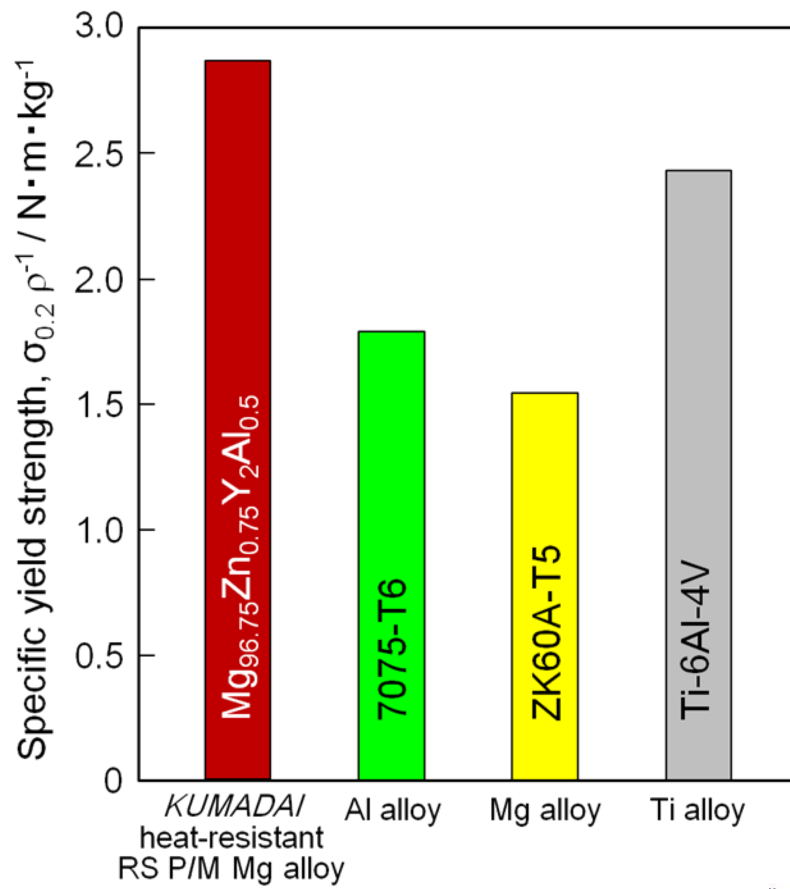
Mechanical Strength of *KUMADAI* Heat-resistant RS P/M Mg Alloys

- *KUMADAI* heat-resistant RS P/M $Mg_{96.75}Zn_{0.75}Y_2Al_{0.5}$ alloys have high yield strength above 530 MPa and reasonable elongation above 8 %.
- Its specific tensile yield strength is approximately 1.7 times as high as that of 7075-T6.

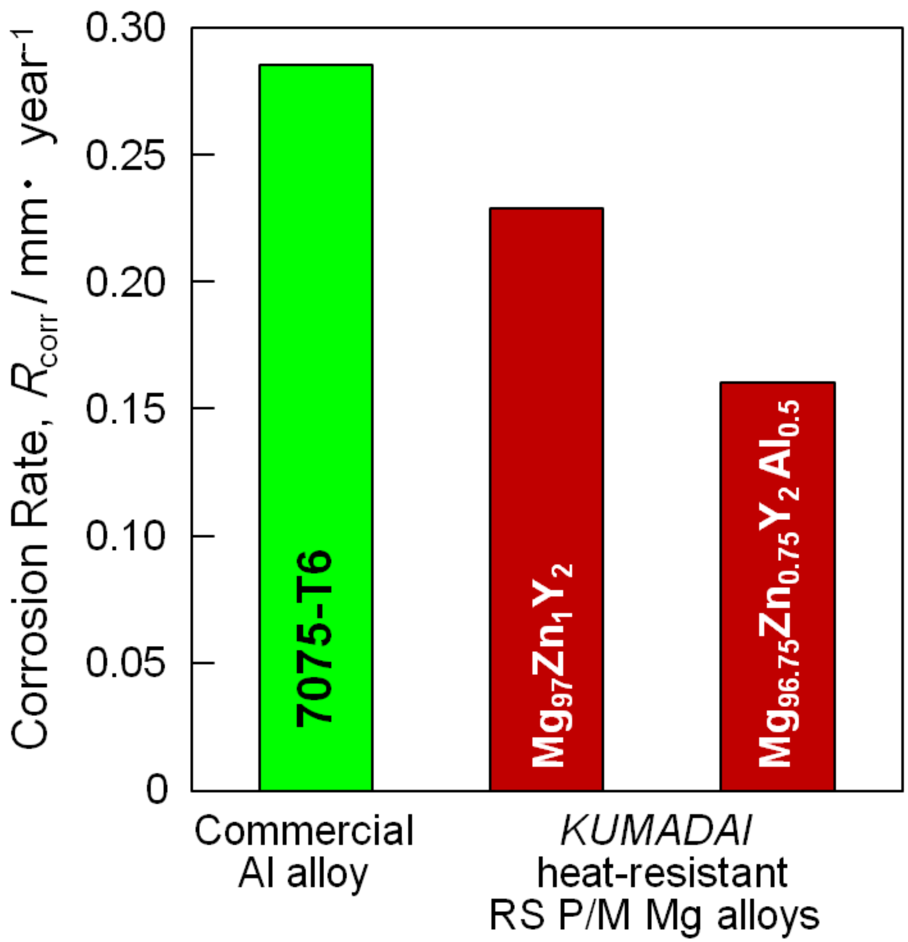
KUMADAI heat-resistant RS P/M Mg alloys (ϕ18 mm)





Corrosion Resistance of *KUMADAI* Heat-resistant RS P/M Mg Alloys

- Corrosion resistance of *KUMADAI* heat-resistant RS P/M $Mg_{96.75}Zn_{0.75}Y_2Al_{0.5}$ alloy is approximately 1.8 times as high as that of 7075-T6.



Corrosion Rate

$Mg_{97}Zn_1Y_2$ alloy
0.230 mm/year
$Mg_{96.75}Zn_{0.75}Y_2Al_{0.5}$ alloy
0.160 mm/year

Extra-super duralumin (7075-T6)
0.285 mm/year

Comparison of Performances with 7075-T6

KUMADAI heat-resistant RS P/M $Mg_{96.75}Zn_{0.75}Y_2Al_{0.5}$ alloy has superior mechanical and corrosion properties to 7075-T6.

	RS P/M *KUMADAI* Heat-resistant Mg Alloy ($Mg_{96.75}Zn_{0.75}Y_2Al_{0.5}$)	I/M Extra Super Duralumin (7075-T6)
Tensile Properties		
Yield Strength	533 MPa	505 MPa
Elongation	10.6 %	11 %
Fatigue Property		
Fatigue Strength at 10^7 cycles	325 MPa	275 MPa
Corrosion Property		
Corrosion Rate	0.160 mm/year	0.285 mm/year

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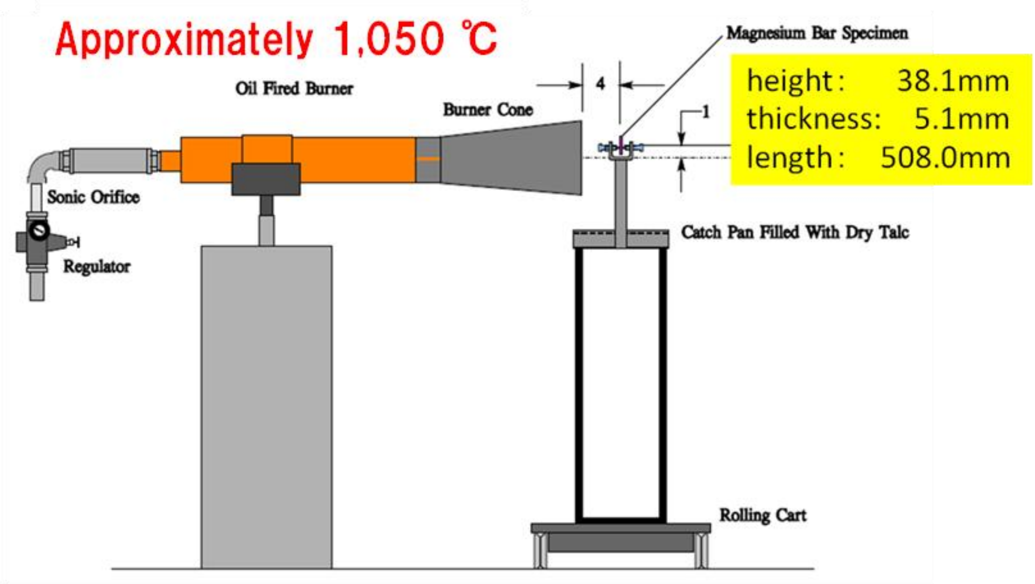
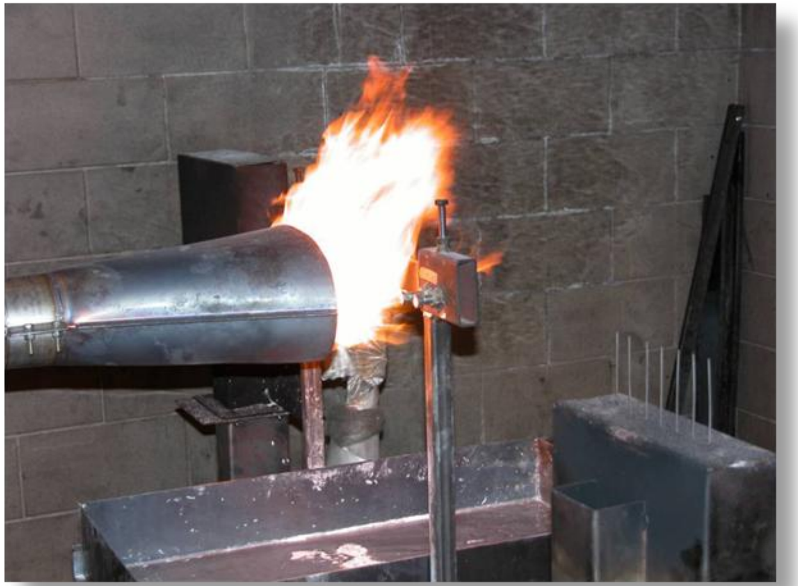
4. **FAA-Flammability Tests of *KUMADAI* Mg Alloys**

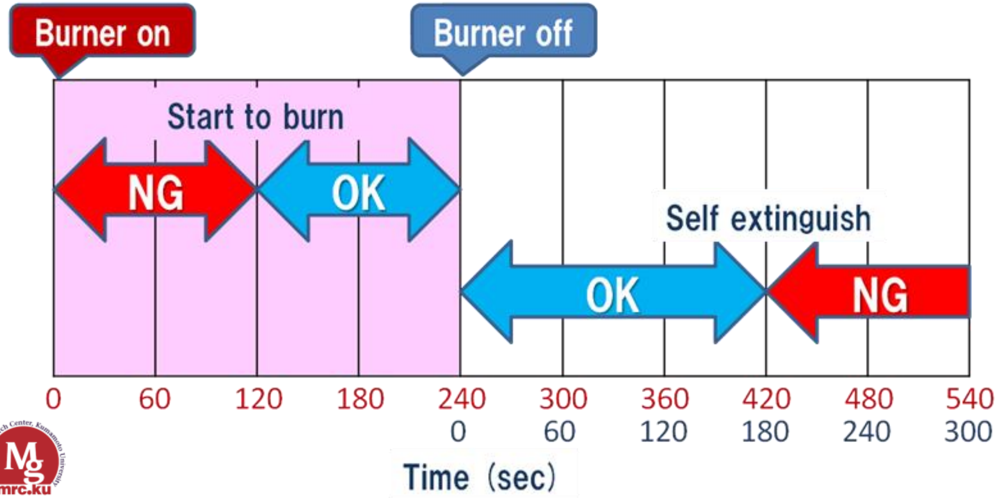
5. Spreading Effects and Future Challenges

FAA-Developing Flammability Test Method

- FAA standard for flammability test is developing on the assumption that Mg alloys burn.







By Timothy R. Marker, January 2013 Final Report (DOT/FAA/AR-11/3), Evaluating the Flammability of Various Magnesium Alloys During Laboratory- and Full-Scale Aircraft Fire Tests.

By Timothy R. Marker, Development of a New Flammability Test for Magnesium-Alloy Seat Structure, International Aircraft Materials Fire Test Working Group, Renton, WA, March 6-7, 2013 (marker-0313-magtask.pdf).

Results of FAA Flammability Test on *KUMADAI* Mg Alloys

- *KUMADAI* heat-resistant alloy and *KUMADAI* non-flammable Mg alloy passed the test very easily, with essentially no burning at all.

obtained by FAA TC

Alloy	Melt (Sec)	Ignition (Sec)	Bar Begins to Burn (Sec)	Residue Begins to Burn (Sec)	Burner Off (Sec)	Bar Out (Sec)	Residue Out (Sec)	Total Bar Burn Duration (Sec)	Total Residue Burn Duration (Sec)	Sample Total Burn Duration (Sec)
KUMADAI Non-Flammability Alloy-1	108	—	—	—	240	—	—	0	0	0
KUMADAI Non-Flammability Alloy-2	111	—	—	—	240	—	—	0	0	0
KUMADAI Non-Flammability Alloy-3	108	—	—	—	240	—	—	0	0	0
KUMADAI Non-Flammability Alloy-4	109	—	—	—	240	—	—	0	0	0
KUMADAI Non-Flammability Alloy-5	106	—	—	—	240	—	—	0	0	0
KUMADAI Non-Flammability Alloy-6	107	—	—	—	240	—	—	0	0	0
KUMADAI Heat-Resistant Alloy-1	113	—	—	—	240	—	—	0	0	0
KUMADAI Heat-Resistant Alloy-2	118	—	—	—	240	—	—	0	0	0
KUMADAI Heat-Resistant Alloy-3	116	—	—	—	240	—	—	0	0	0
KUMADAI Heat-Resistant Alloy-4	122	—	—	—	240	—	—	0	0	0
KUMADAI Heat-Resistant Alloy-5	120	—	—	—	240	—	—	0	0	0
KUMADAI Heat-Resistant Alloy-6	117	—	—	—	240	—	—	0	0	0

KUMADAI non-flammable I/M alloy

KUMADAI heat-resistant I/M alloy

Photographs of Samples After FAA Flammability Tests

- *KUMADAI* heat-resistant alloy and *KUMADAI* non-flammable Mg alloy passed the test very easily, with essentially no burning at all.

KUMADAI
heat-resistant I/M Mg alloy

KUMADAI
non-flammable I/M Mg alloy

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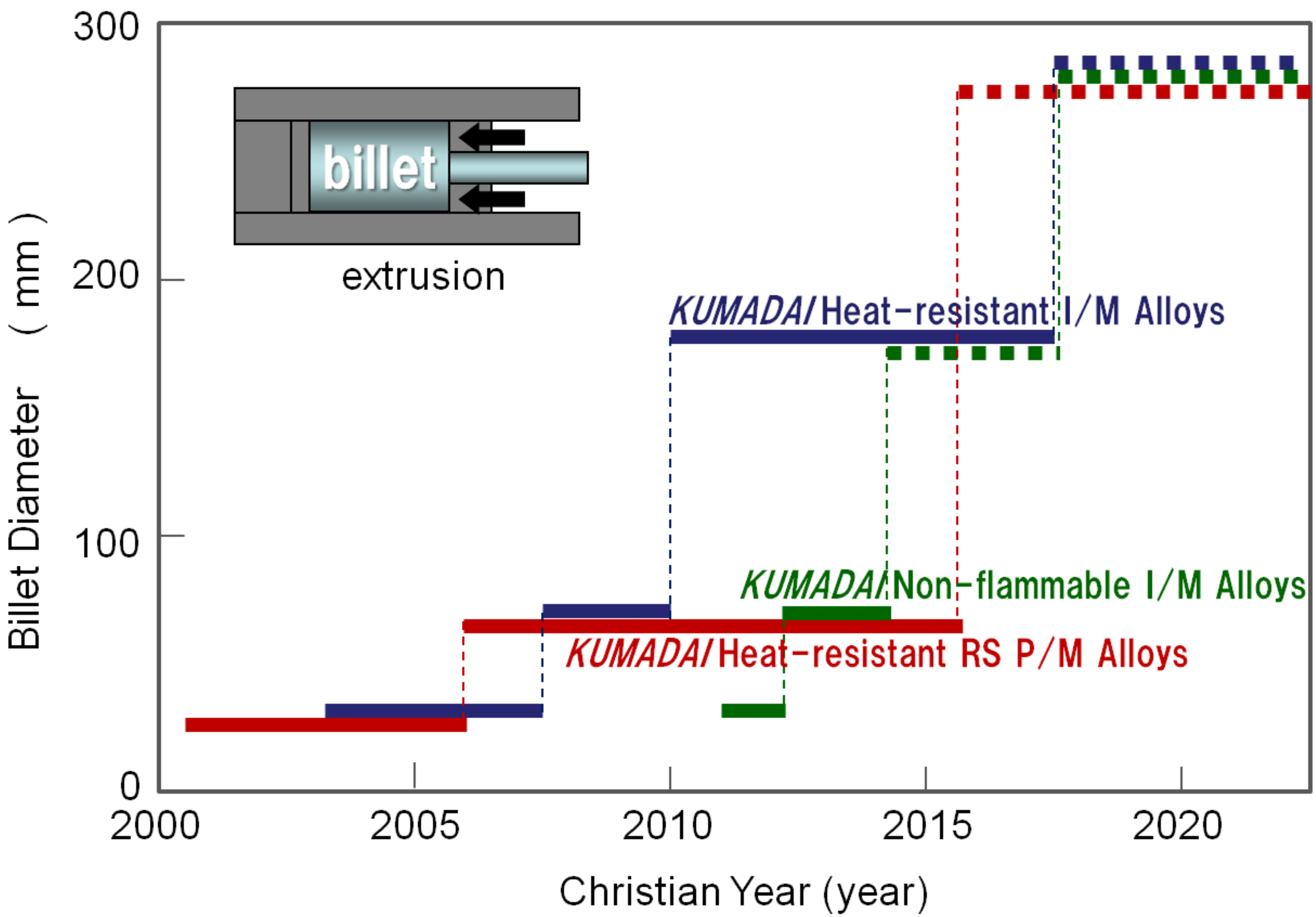
Development Schedule of Large-scale *KUMADAI* Mg Alloys

- Enlargement Technology of *KUMADAI* Mg alloys is steadily developed.



Spreading Effects

1) Expansion of application to the areas that cannot tolerate ignition of material

2) Large reduction in greenhouse gas emission

3) Enhancing safety of melting, casting, machining, and welding process

4) Cost reduction by non-use of cover gas and enhanced safety during operation

Challenges in Future

1) R&D for achieving increased performance of *KUMADAI* Mg alloys.

2) Development of manufacturing-base technology to enable producing large *KUMADAI* Mg alloys（plate, bar, tube, sheet）.

3) Development of applications by provision of prototypes made by *KUMADAI* Mg alloys.

Summary

We have developed *KUMADA*/heat-resistant I/M Mg-TM-RE alloys, which are strengthened by LPSO phase.

- high mechanical strength ($\sigma_{0.2}$ of 350~400 MPa at RT)
- high heat-resistance ($\sigma_{0.2}$ of 300~350 MPa at 200°C)
- high ignition temperature (780~940°C)
- good corrosion resistance (AZ31 level)

We have developed *KUMADA*/non-flammable I/M Mg-Al-Ca alloys, which are strengthened by C36-type IMC.

- high mechanical strength ($\sigma_{0.2}$ of 410~460 MPa at RT)
- high ignition temperature (1,050~1,100°C)
- good corrosion resistance (AZ31 level)

We have developed *KUMADA*/heat-resistant RS P/M Mg-Zn-Y alloys, which are strengthened by LPSO phase.

- high mechanical strength ($\sigma_{0.2}$ of 530~610 MPa at RT)
- high heat-resistance ($\sigma_{0.2}$ of 380 MPa at 200°C)
- high ignition temperature (780~940 °C)
- high corrosion resistance (twice of 7075-T6)
- high workability (high-strain-rate superplasticity)

KUMADA/heat-resistant Mg alloy and *KUMADA*/non-flammable Mg alloy have passed the FAA Flammability Test very easily, with essentially no burning at all.

Thank you for your attention