Reduction mass improvement by hydrogen addition in lunar resource laser alumina reduction

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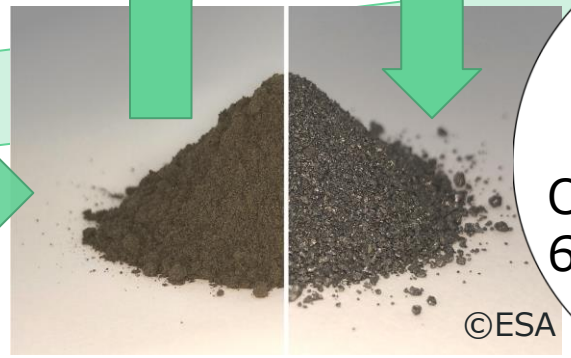
Introduction

ISRU (In-Situ Resource Utilization)

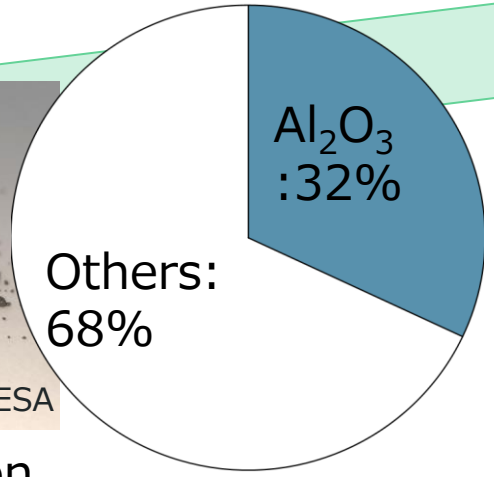
Extraction



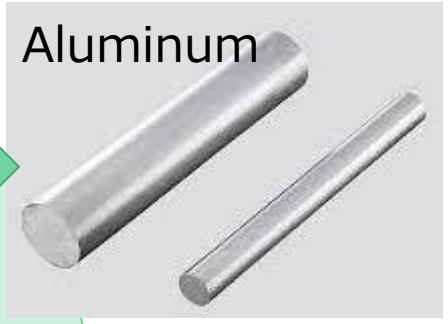
Regolith on the moon

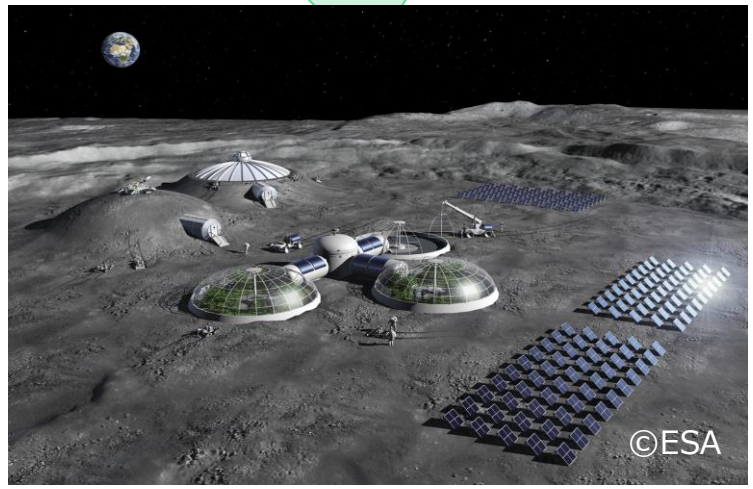
Reduction

Regolith composition



Utilization





Lunar Base

- Cost for transportation(Earth→Moon): **Very expensive**

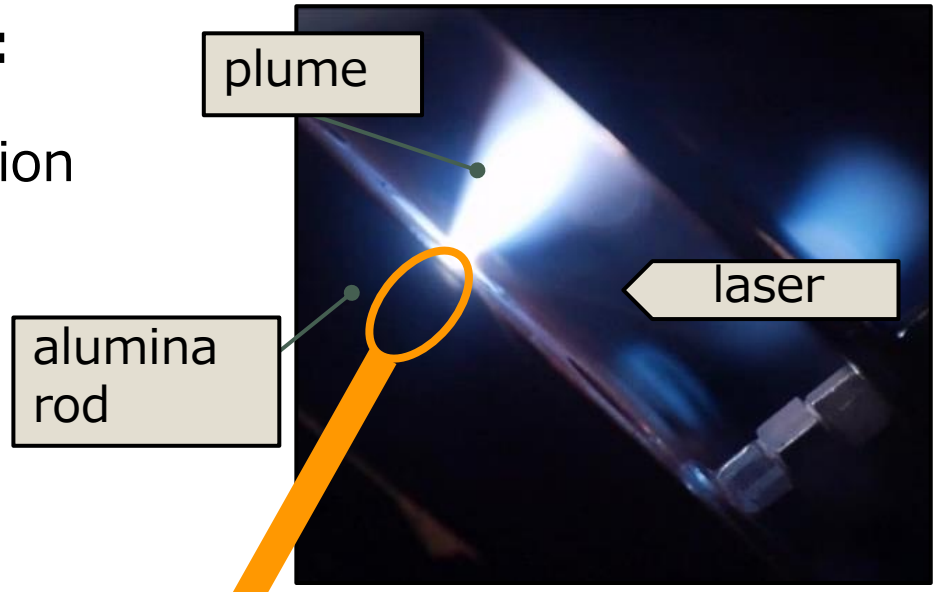
  → Utilization of lunar resource is important

  → Alumina reduction without consumables is necessary

Laser Alumina ablation and collecting method

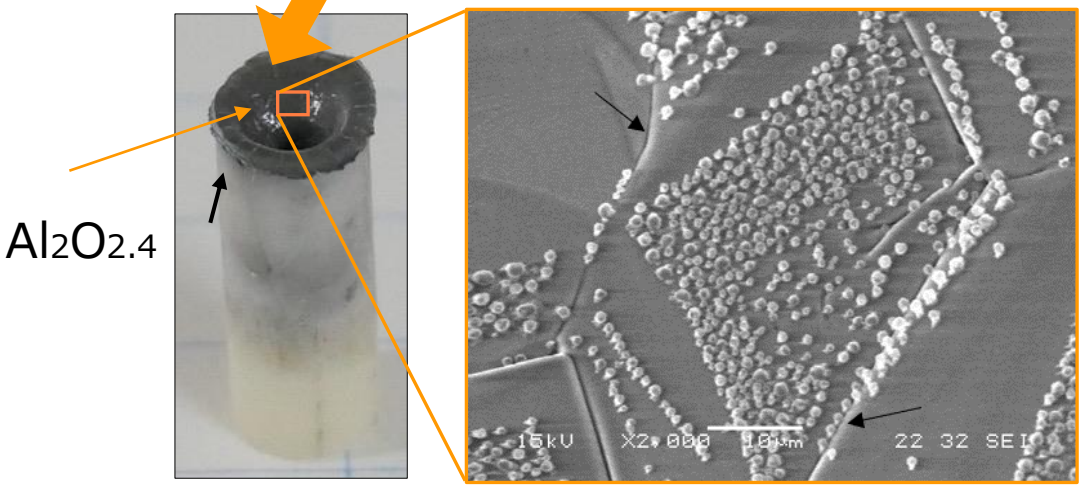
One of the Al collection method in Laser Ablation:

- Al particles are observed on rod surface after ablation
- Al particles are produced by precipitation from Oxygen-deficient alumina



Oxgen deficient Alumina:

- Lower Oxygen content than nomal
- Made by laser ablation
- Al_2O_x (x: Oxgen deficiency, x≦2.9)



To improve collection efficiency, increase the oxygen deficiency is necessary

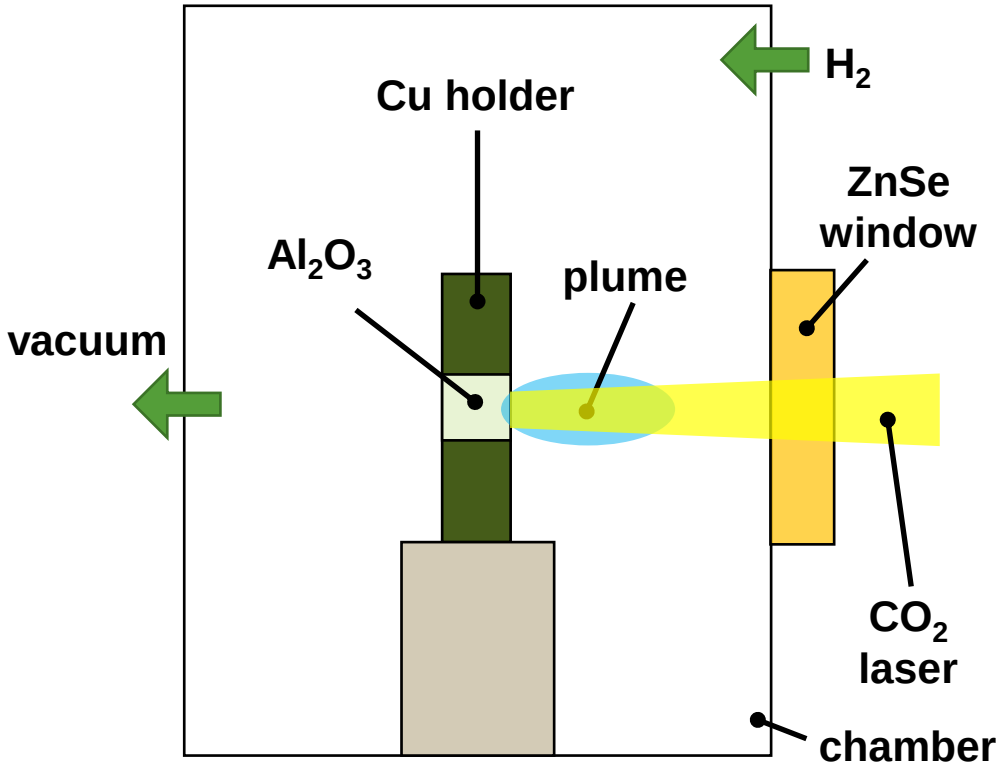
Previous experiment

Previous Research

Reduction experiment in hydrogen atmosphere

Ablation in **1 bar of H2 atmosphere** conducted by N.Tanaka [1]
→Expect H2 to act as a **reducing agent,** to increase **Oxygen deficiency**

Experimental system

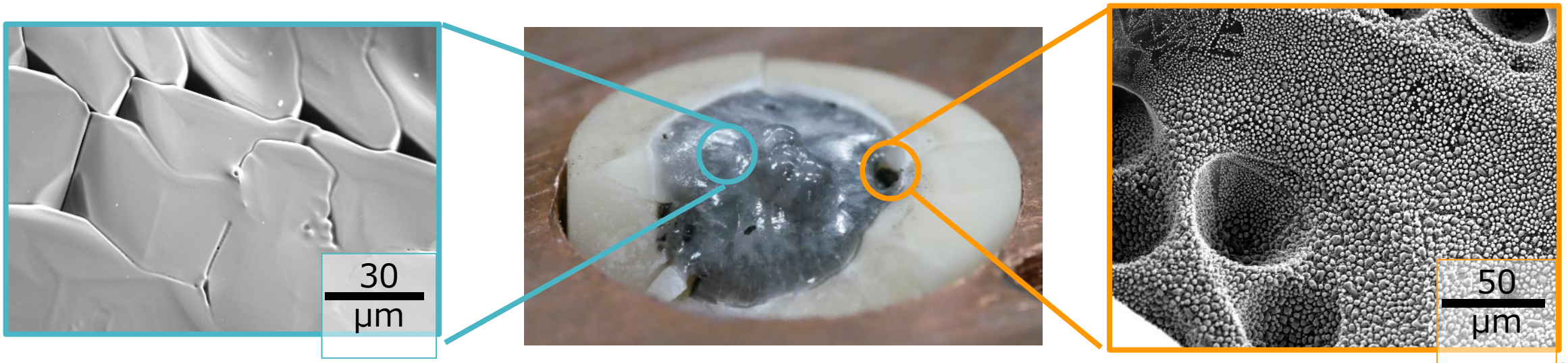


Experimental conditions

Laser: CO2 laser, 2.0 kW
Laser spot radius : 2 mm
Irradiation time : 1.0 s
Atmosphere : **H2 1 atm**

[1] Naoki Tanaka. “アルミナレーザー還元過程における酸素欠陥型アルミナの生成とその制御”. 東京大学修士論文. 2022.

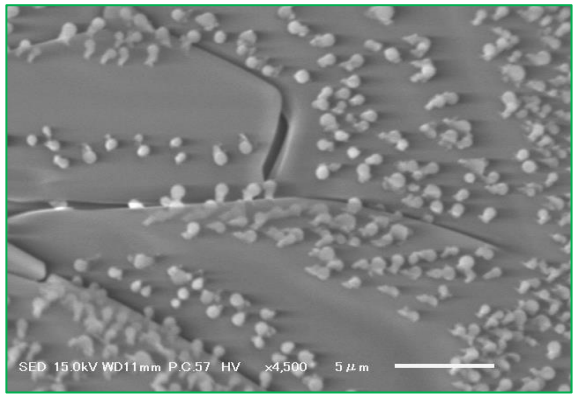
Reduction experiment in hydrogen atmosphere



Al particles in vacancy(13μg/mm$^{2)}$

Result:

- Vacancies at the edge of the melting region, and Al precipitates in high-density inside
- No Al precipitation in other places
- Total amount of Al precitipation was 14 μg, which is same as experiment in Ar atmosphere.



Rod surface after ablation under Ar atmosphere(≈0.3μg/mm^2)

[1]N.Tanaka, “アルミナレーザー還元過程における酸素欠陥型アルミナの生成とその制御,” 東京大学修士論文, 2022.

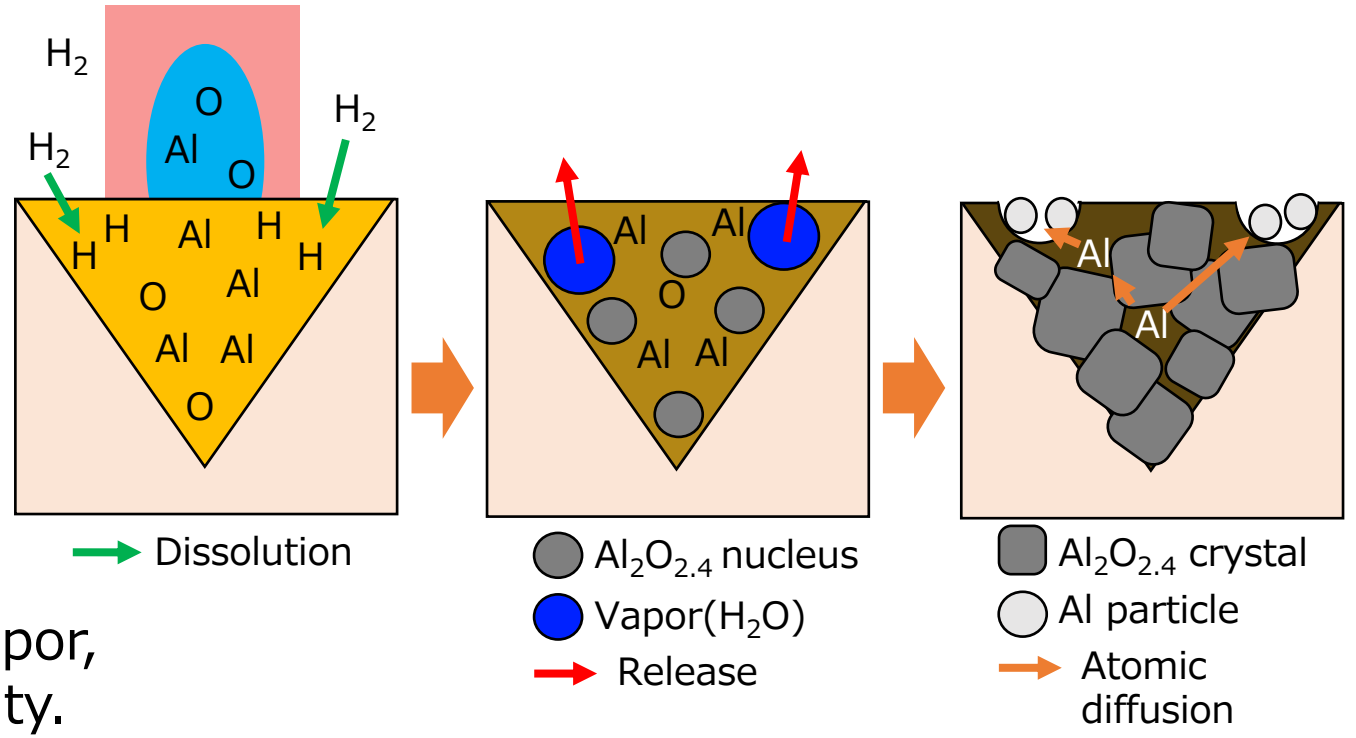
Discussion on the formation process of vacancies

Explanation of results

①Hydrogen dissolves in molten edge of liquid alumina

②After the ablation, vacancies are formed due to the release of gas(H2O/H2) dissolved

③The vacancies become high oxygen deficiency due to release of water vapor, Al particles precipitated in high density.



A clue to increase Al precipitation mass

Being blocked by the plume, H2 was dissolved only in molten edge,
Vacancies with high density Al precipitation occur only at the edge

[2] 山中伸介, “水素と金属, 酸化物セラミックス,” 生産と技術 第*49*巻 第*3*号, 1997.
[3]Ueno, et.al, “一方向凝固法によるロータス型ポーラスセラミックの作製”, まてりあ, 2008.

Objective

Previous research:

- In the reduction experiment with hydrogen, although some vacancies with high density aluminum precipitation were observed, the overall precipitation was not increased

Objective:

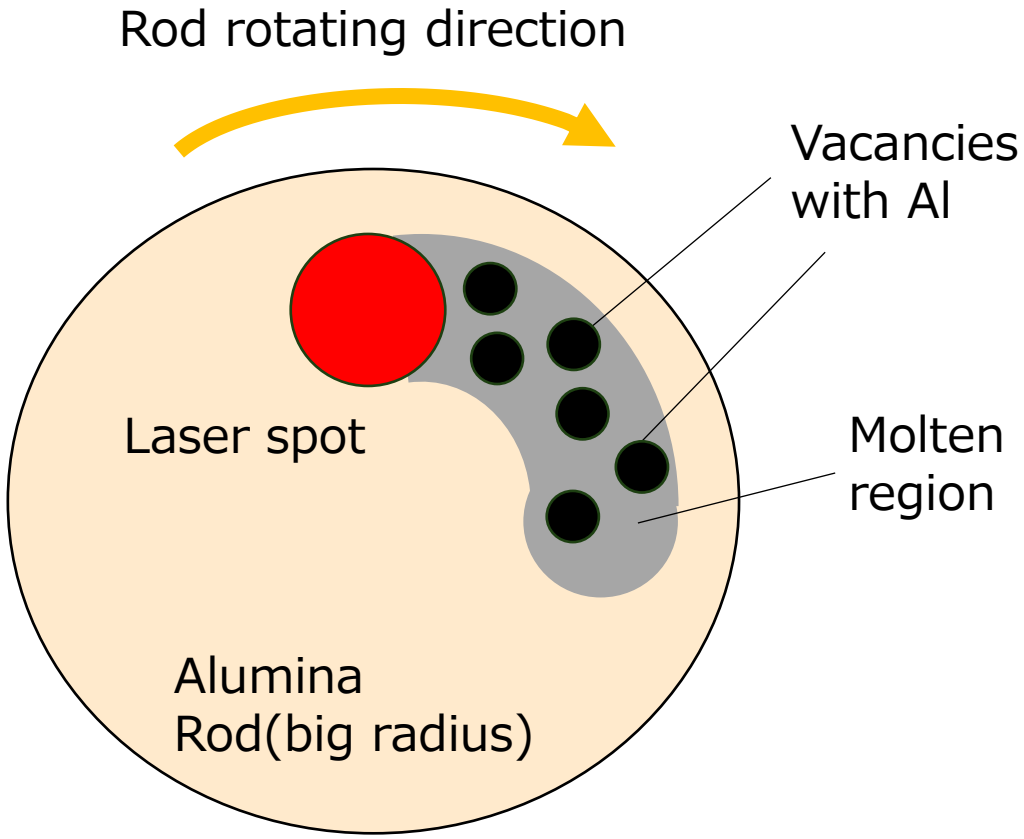
Devise and conduct experiment to let H2 dissolve into entire molten region, increase the number of vacancies with high density Al precipitation ,and **increase Al precipitation mass**

Experiment

Method of dissolving H2 in the molten region

The way to increase the number of vacancies:

- Use large diameter alumina rods rotating at a constant speed
- Laser irradiates off-center of rod rotation

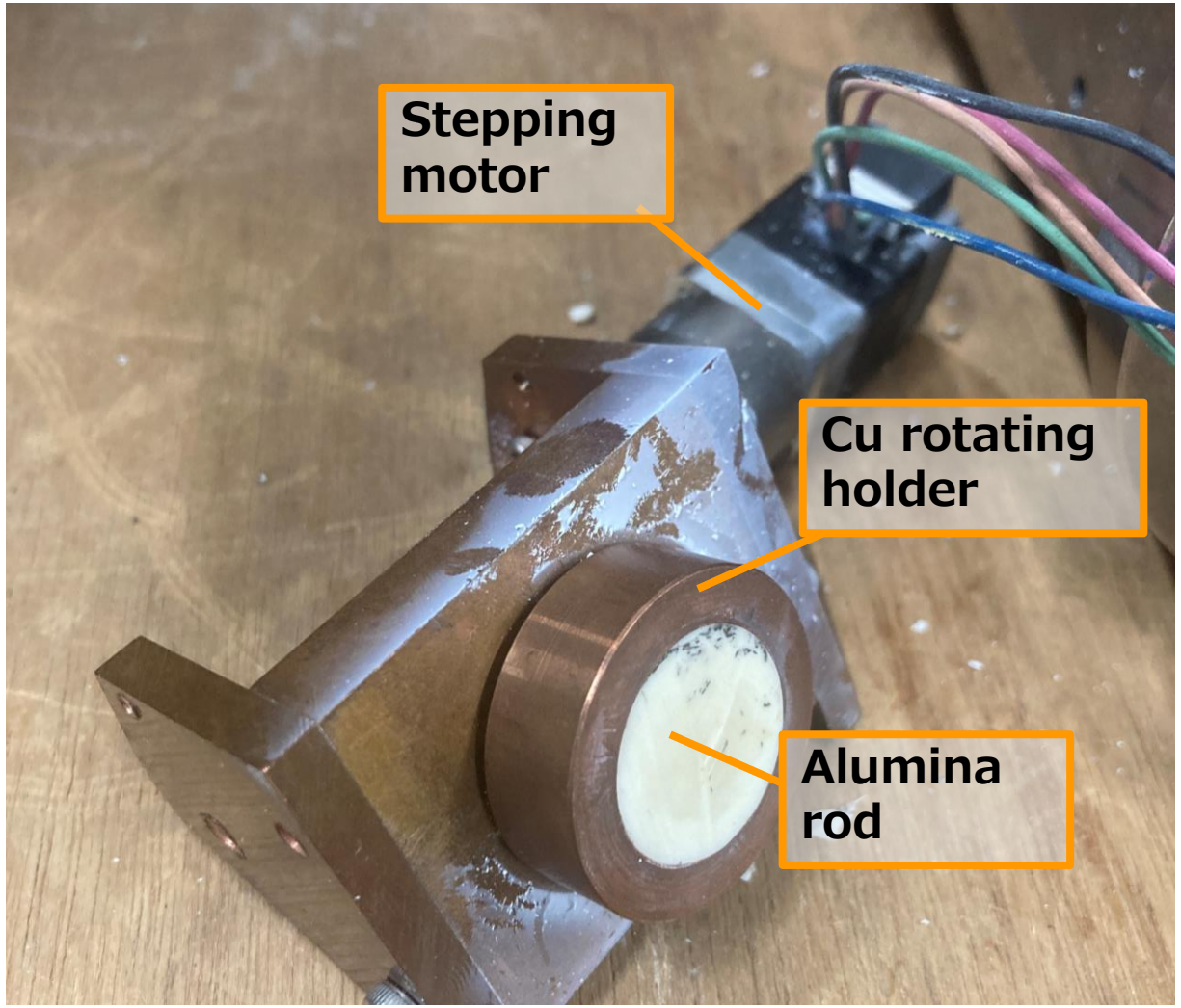


Conceptual diagram of rod rotation system

→The edge of Laser spot sweeps the entire molten region, allowing hydrogen to dissolve over all the region

Overview of rod rotation system

- Using φ20 Alumina rod held by copper holder
- The rod are rotated by stepping motor through bevel gear



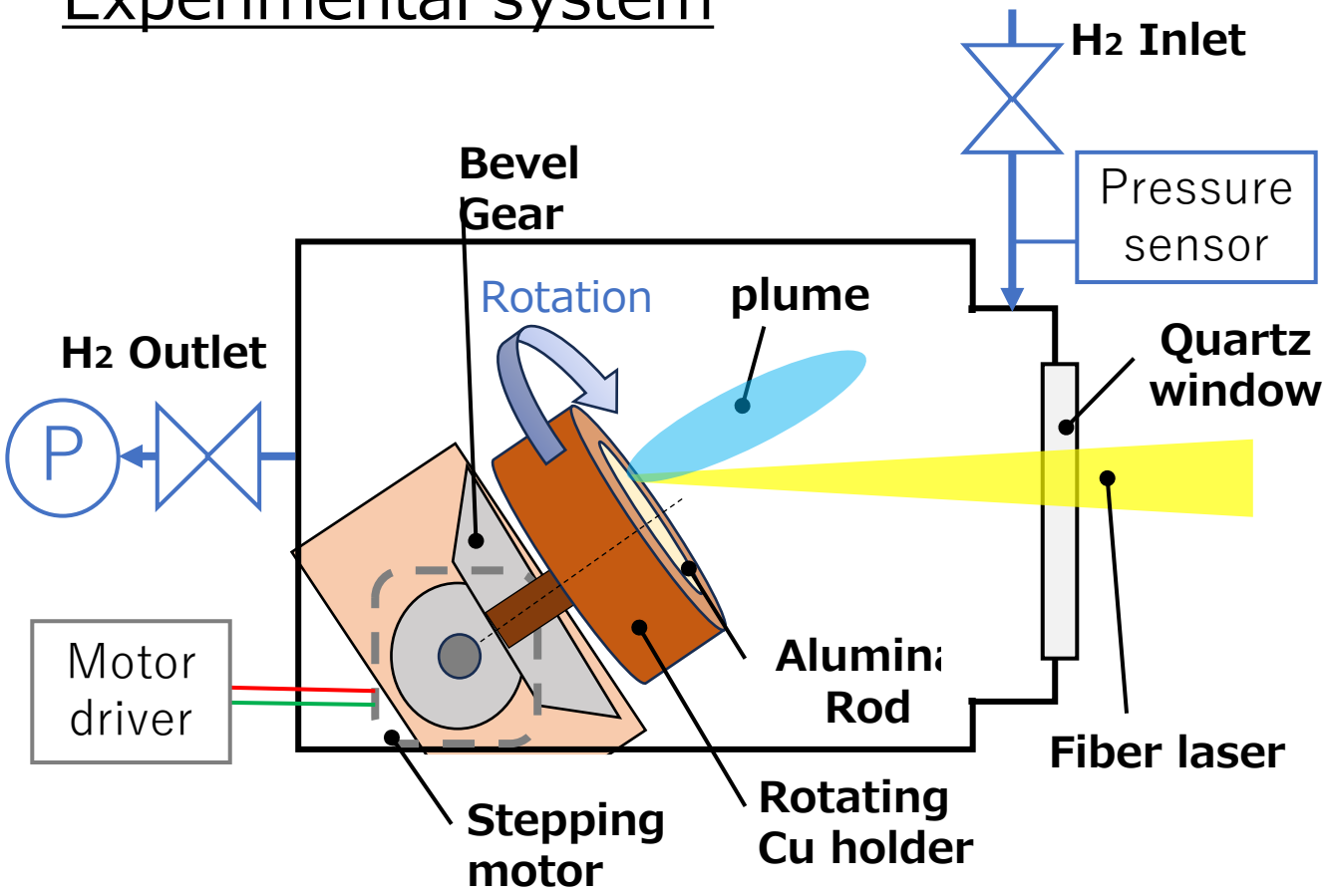
A picture of rod rotation system

Ablation of rotating rod in hydrogen atmosphere

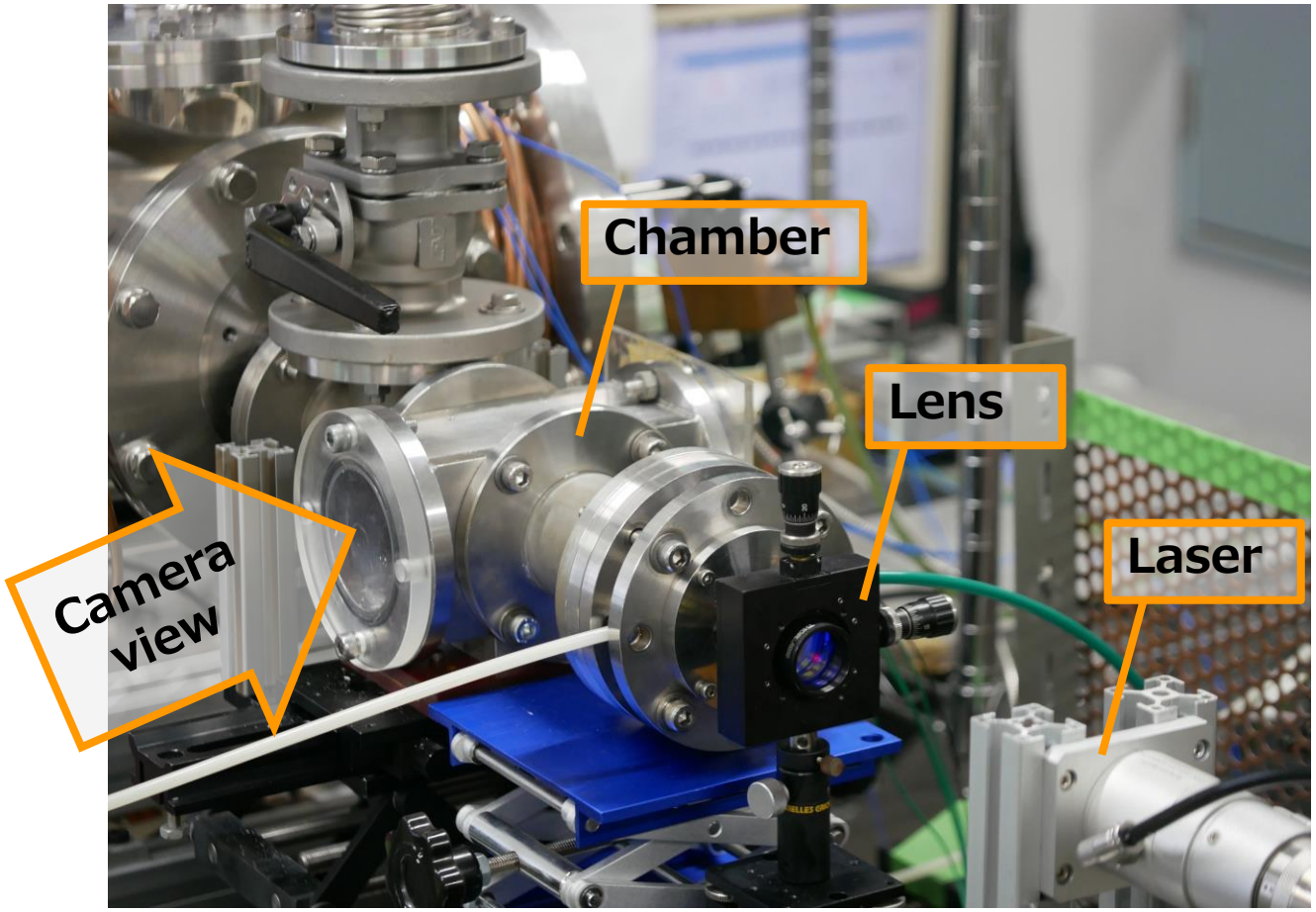
Experimental conditions

- Atmosphere: **H2 0.9 atm**
- Laser: Fiber Laser, 1.5 kW, 5s
- Laser spot radius: 1.22mm
- Intensity: 0.32 GW/m^2
- spot position from rod center: 6mm
- Rod rotation speed: **4rpm/ 8rpm**

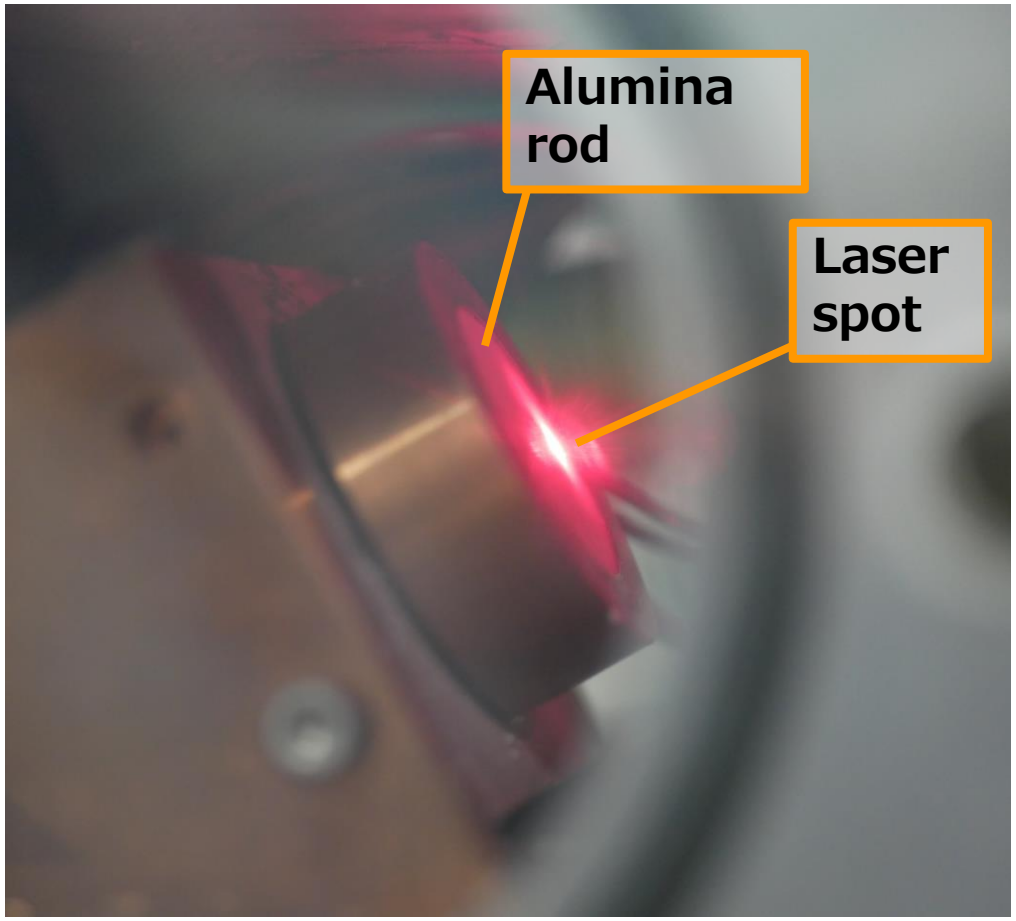
Experimental system



Overview of the experimental system

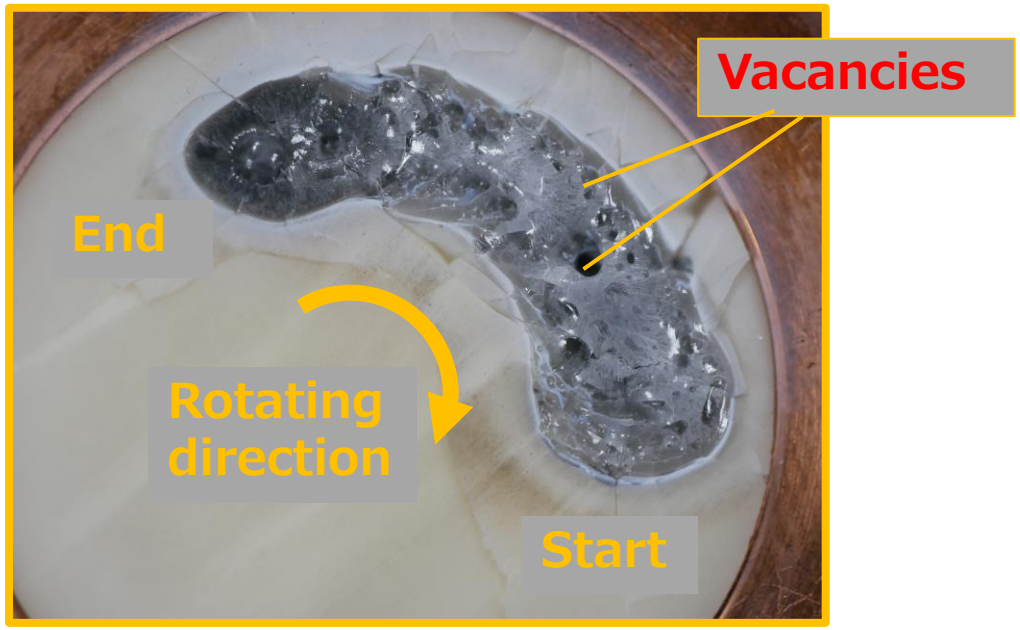


Overview of optics and experimental chamber



The alumina rod set in the chamber

Observation of rod surface after ablation



H2 0.9 atm, 4 rpm

Ar 0.9 atm, 4 rpm

- Under H2 atmosphere, **vacancies were generated entire molten region**
- The molten region swelled in H2 condition, while it deflated in Ar condition
- Vacancies were not homogeneous, and few vacancies in areas with severe swelling

Inside of the rod after ablation in H2 atmoshpere

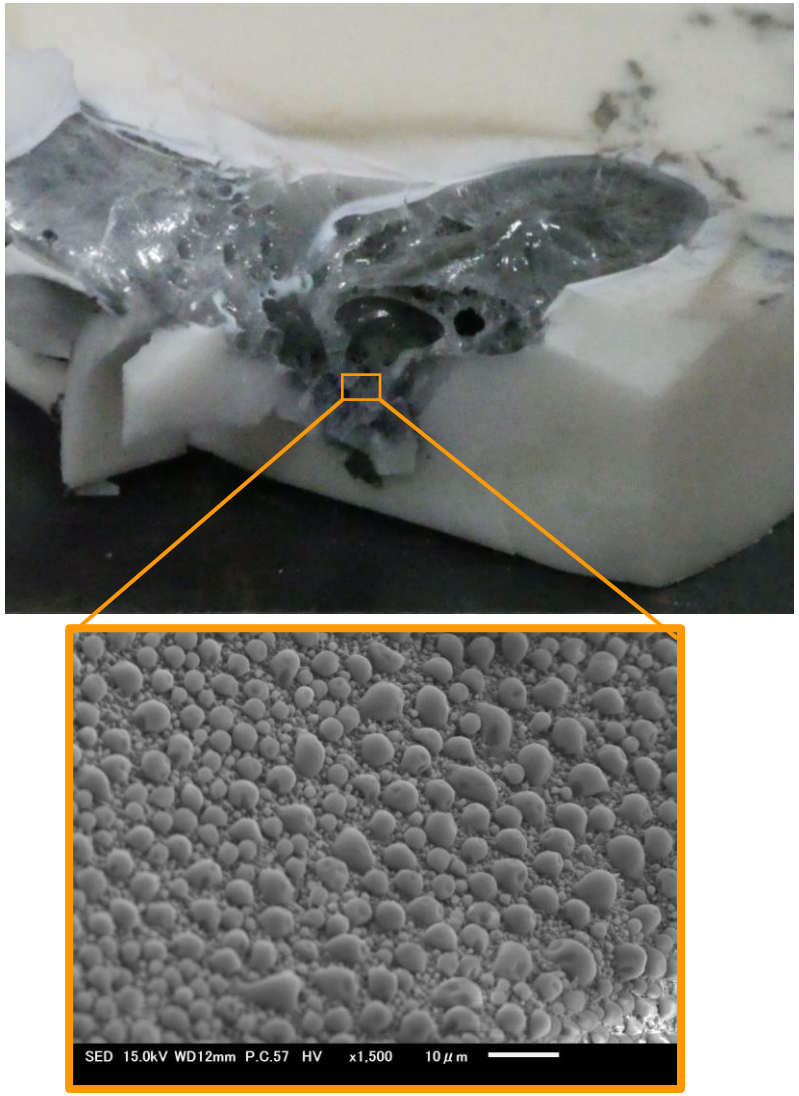
- Split the rod and check the cross section

  →Cavities are generated behind the swelling molten region

Reason why the number of vacancies on the surface was not homogeneous

- Electron microscopic observation of the inside

  →Al particles confirmed on inner surface



Measurement of produced Al mass

Item	Single-shot ablation (Previous research)	**Continuous ablation 4 rpm**	**Continuous ablation 8 rpm**
Condition	H2 1 atm, Fixed rod, Ablation 1s	H2 0.9 atm, Rotating rod, Ablation 5s	H2 0.9 atm, Rotating rod, Ablation 5s
Al production	14 μg	85±8 μg	**93±9 μg**
Al production per sec.	14 μg/s	17±2 μg/s	**19±2 μg/s**

- Compared to the previous study, total production **increased 6.6 times**
- **1.4 times** increase in production per unit time
- No significant difference in produced Al mass at different rotation speeds was observed

[1]N.Tanaka, “アルミナレーザー還元過程における酸素欠陥型アルミナの生成とその制御,” 東京大学修士論文, 2022.

Discussion

- **Total Al precipitation increased 6.6 times**
  → The amount of production will be proportional to ablation time, and this method is useful for mass production

- **Al is also formed inside of the rod in H2 environment**
  →Al particles inside are not good for collection
    - Making the thickness of the melting region thinner
    - Melt again and precipitate on the surface

- **Precipitation mass didn’t change with rod rotation speed**
  →Rotation speed can change heating time, cooling rate, etc.
  Contrary to the expectation that there is an optimal speed
    - Changes may be seen in a wider range of rotation speed
    - Multiple effects may chancel out each other

  →further experiment is required to determine

Conclusion

- By conducting ablation on a rod moving perpendicular to the laser path in a H2 atmosphere, Al precipitation mass increased **6.6 times**, and mass per seconds increased **1.4 times**

- In H2 condition, the inside of the rod also contains Al particles

- In this experiment, there was no significant change in precipitation mass by rotation speed, but further experiments are needed to conclude the relationship between the rotation speed and precipitation mass