Substitution potential of refractory metals

Mo, Re, Nb, Ta, W: VTT (Ta), IMN (Mo, Re), ICCRAM (W), TUDELFT (Nb)

Päivi Kivikytö-Reponen, Marjaana Karhu, Katarzyna Bilewska, Santiago Cuesta-Lopez, Rocío Barros, Erik Offerman
CONTENTS

• MSP-REFRAM project goals for substitution work package – general (10 min)
• Element specific (40 min)
  ▫ Mo
  ▫ Re
  ▫ Nb
  ▫ Ta
  ▫ W – Dr. Santiago Cuesta-López

• Discussion and questions
Substitution approaches

- Substitutability assessment – methodology to evaluate, indexing
  - EU study of CRMs
  - Scaling 0.0-1.0

- Substitutes development – development of substitutes - materials science approach – application approach
  - scientific literature review of development
  - patents
  - hidden development
Substitution – WHY?

- If not recyclable and material efficient, energy efficient, healthy and safe to use, locally available or traceable, available with low price or reasonable price, sustainability and safety, supply security, circularity, social responsibility, politics and economics, standard of living, quality of living, consumption of raw materials.
WHAT? to substitute - reasoning and prioritizing

Legislations, politics, funding, mind-set, right players, potential market

READINESS: Ideas TRL, potential substitutes

PERFORMANCE e.g. recyclability %, toxic, mechanical properties...

IMPORTANCE e.g. application volumes and economic importance
HOW? Design substitutes - By using circular design

Application – what is the function or challenge? Need for RE-design?

Properties needed and performance of product

New solution properties and performance

By what other ways this could be done?

New solution recycling, availability and sustainability

9-10/3/2017

REFRAM, Final Conference
Research and design opportunities

- Substitutes for refractory metals exist but typically research and development is needed.
- Substitutes can be other refractory metals or CRMs (e.g. in steel products)
- Long term research (~10 years) investment is needed for technology leap in new material, product or solution development to develop substitutes for refractory metals
- Research of recycled, secondary and un-pure substitutes

element by element  
material by material  
product by product  
product by service
# SUMMARY of refractory metal substitution

<table>
<thead>
<tr>
<th>Refractory metal</th>
<th>Main industrial application</th>
<th>% of usage of current metal</th>
<th>Technical / economical viability for substitution</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>Cemented carbides - WC/Co</td>
<td>72 % of usage in Europe</td>
<td>Mo, Ti</td>
</tr>
<tr>
<td>Nb</td>
<td>Steels - HSLA</td>
<td>90 % of usage to steels*</td>
<td>Ti+Mo, V+Mo</td>
</tr>
<tr>
<td>Mo</td>
<td>Steels</td>
<td>71%** usate to steels</td>
<td>B, Cr, Nb and V in alloy steels; W in tool steels</td>
</tr>
<tr>
<td>Ta</td>
<td>Capacitors</td>
<td>40% capacitors, 21% superralloys</td>
<td>Ceramic, Al, Nb-oxide (capacitors); V, Mo, Hf, Mo, Nb, Re, W</td>
</tr>
<tr>
<td>Re</td>
<td>Superalloys</td>
<td>83-90% superalloys***</td>
<td>CMCs</td>
</tr>
</tbody>
</table>


***Adi Naor, Noam Eliaz, Eliezer Gileadi, Properties and applications of rhenium and its alloys, The AMMTIAC Quarterly, Volume 5, Number 1.
MOLYBDENUM
Substitutability

Distribution of end-uses and corresponding substitutability assessment for molybdenum

<table>
<thead>
<tr>
<th>Application</th>
<th>Share</th>
<th>Megasector</th>
<th>Substitutability index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil and Gas</td>
<td>18%</td>
<td>Oil</td>
<td>1.0</td>
</tr>
<tr>
<td>Chemical/Petrochemical</td>
<td>15%</td>
<td>Chemicals</td>
<td>1.0</td>
</tr>
<tr>
<td>Automotive</td>
<td>14%</td>
<td>Transport-Road</td>
<td>1.0</td>
</tr>
<tr>
<td>Mechanical Engineering</td>
<td>12%</td>
<td>MechEquip</td>
<td>1.0</td>
</tr>
<tr>
<td>Power Generation</td>
<td>8%</td>
<td>Electrical</td>
<td>1.0</td>
</tr>
<tr>
<td>Process Industry</td>
<td>8%</td>
<td>MechEquip</td>
<td>1.0</td>
</tr>
<tr>
<td>Other Transportation</td>
<td>7%</td>
<td>Transport-Other</td>
<td>1.0</td>
</tr>
<tr>
<td>Others</td>
<td>7%</td>
<td>Other</td>
<td>0.5</td>
</tr>
<tr>
<td>Building / Construction</td>
<td>6%</td>
<td>Construction</td>
<td>0.3</td>
</tr>
<tr>
<td>Aerospace &amp; Defence</td>
<td>3%</td>
<td>Transport-Other</td>
<td>1.0</td>
</tr>
<tr>
<td>Electronics &amp; Medical</td>
<td>2%</td>
<td>Electronics</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Reduction potential

- There is little substitution for Mo in major application as an alloying element in steels and cast irons.

- Reason - the availability and versatility of Mo lead to development of new materials that benefit from the alloying properties of Mo.

- Potential substitutes for Mo include B, Cr, Nb and V in alloy steels; W in tool steels; graphite, Ta, and W for refractory materials in high-temperature electric furnaces.

- For material strengthening and refractory properties - Nb
  - Lower and stable prices
  - Nb is the lightest of the refractory metals
  - Nb is unique in that it can be worked through annealing to achieve a wide range of strength and elasticity.

Source: [4, 10]
### MOLYBDENUM Increase potential

**Alternative material**

<table>
<thead>
<tr>
<th>application</th>
<th>Current</th>
<th>alternative</th>
<th>advantages</th>
<th>drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear-resistant hard materials</td>
<td>Cemented carbides</td>
<td>ternary borides, e.g. Mo$_2$FeB$_2$ or Mo$_2$NiB$_2$ particles in metal matrix</td>
<td>equivalent hardness and flexural strength, superior fracture toughness and thermal expansion coefficient</td>
<td>Competitive improvement of cemented carbides – boronizing and other surface protection techniques</td>
</tr>
<tr>
<td>Steel protection</td>
<td>Cermet coatings (laser-cladded Mo$_2$NiB$_2$)</td>
<td></td>
<td>CET of Mo$_2$NiB$_2$ close to steel</td>
<td>Selective removal of Mo$_2$NiB$_2$ particles with time</td>
</tr>
<tr>
<td>high strength and wear resistance, up to high temperatures,</td>
<td>CMCs</td>
<td>CMCs ductile particle reinforced, e.g. Mo-AlN, Mo-Al$_2$O$_3$</td>
<td>Simple production – mix metallic and ceramic powders and sinter; low residual stress</td>
<td>bending strength and fracture toughness depend on Mo content</td>
</tr>
</tbody>
</table>

*CMCs ductile particle reinforced, e.g. Mo-AlN, Mo-Al$_2$O$_3$
MOLYBDENUM 

Increase potential

• Alternative system

<table>
<thead>
<tr>
<th>application</th>
<th>Current</th>
<th>alternative</th>
<th>advantages</th>
<th>drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass industry corrosion resistant protective</td>
<td>Mo metal sheets</td>
<td>Mo-Re plasma-sprayed</td>
<td>Flexibility of plasma spraying – easy to deposit coating on complex shapes,</td>
<td>Contains expensive rhenium</td>
</tr>
<tr>
<td>coatings</td>
<td></td>
<td>coatings</td>
<td>rhenium improves mechanical properties</td>
<td></td>
</tr>
<tr>
<td>HT applications, e.g. turbine blades</td>
<td>Ni-base superalloys like CMSX-4</td>
<td>MoSi₂/Mo₅Si₃ binary composite</td>
<td>High melting temperature (well above 1000 °C), higher yield stress</td>
<td></td>
</tr>
</tbody>
</table>

• Substitution of other elements

→ in stainless steel molybdenum may up to some point replace chromium – it is a matter of careful assessment of conditions of use, price, estimated lifetime
Conclusions

• Molybdenum production is 50% primary and 50% a by-product of copper mining
• Partially depends on mining economy of major metal (i.e. copper)
• Moderate economic importance
• Non-critical metal
• high level of supply risk strongly connected with low political stability of top producer and top reserve holder
• For most applications (87%) – high substitutability index
• Increase of Mo use at the moment is likely to compromise the performance in most applications, research is ongoing to improve properties
RHENIUM
Distribution of end-uses and corresponding substitutability assessment for rhenium

- Super alloys (aerospace): 63%
- Super alloys (gas turbines): 13%
- Catalysts: 9%
- Automotive Parts: 5%
- Others: 6%
- Petroleum Production: 2%
- Automotive Parts: 5%
- Tools: 2%
- Others: 6%
- Petroleum Production: 2%
- Tools: 2%
- Super alloys (gas turbines): 13%
- Other: 1.0
- Mechanical Equipment: 1.0
- Chemicals: 0.7
- Transport-Road: 1.0
- Refining: 1.0
- Transport-Other: 1.0

Easily and completely substitutable at no additional cost
Substitutable at high cost and/or loss of performance
Not substitutable
Role in superalloys

• Why Re? → increase HT creep strength of Ni- or Co-based superalloys single-crystal gas turbine engine blades and other components
• Major consumers → aviation
• Accounts for 83% of Re consumption

Image 3: Jet engine turbine
[https://www.theengineer.co.uk/issues/22-february-2010/turbine-of-the-times/]
## RHENIUM Substitution potential

<table>
<thead>
<tr>
<th>application</th>
<th>↓↑</th>
<th>Current</th>
<th>alternative</th>
<th>advantages</th>
<th>drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>nickel-based superalloys</td>
<td>↓</td>
<td>CMSX®-2/3</td>
<td>CMSX®-7 CMSX®-8</td>
<td>Improved creep-rupture properties, No or reduced rhenium content</td>
<td>Higher tungsten and tantalum content</td>
</tr>
<tr>
<td>Aero engines (high pressure turbines)</td>
<td>↓</td>
<td>superalloys</td>
<td>CMCs</td>
<td>Low density, high fracture toughness, very high resistance to thermal shock</td>
<td>New methods for joining new materials required, due to different heat dissipation in CMCs</td>
</tr>
<tr>
<td>HT reactors, fuel cladding</td>
<td>↑</td>
<td>Mg alloys, Zr alloys, austenitic SS</td>
<td>Mo-, W- and other Re alloys</td>
<td>high strength at HT, good mechanical properties at RT</td>
<td>Behaviour under irradiation needed to study</td>
</tr>
<tr>
<td>Superhard materials</td>
<td>↑</td>
<td>Diamond-based, borides, nitrides</td>
<td>ReB₂</td>
<td>High hardness</td>
<td>Highly anisotropic properties</td>
</tr>
</tbody>
</table>

↓ - reduction, ↑ - increase
Conclusion

• ‘Gas turbines are some of the most technically accomplished and complex machines ever created, but despite considerable effort by engine manufacturers there is currently very little substitution potential for rhenium-containing superalloys in the hottest parts of the most powerful gas turbines.’ Roskill Market Outlook Jul 02, 2015


• If any – reduction potential is most possible in superalloys – the largest companies already invest in development of materials with reduced Re content - CMSX®-7, CMSX®-8, CMCs.

• Substitutes for rhenium in Pt-Re catalysts are being evaluated continually. – Ir and Sn have commercial success in one such application. Other evaluated metals Ga, Ge, In, Se, Si, W, V.

• Possible substitutes for Re – Co and W for coatings on copper X-ray targets, Rh and Rh-Ir for high-temperature thermocouples, W and Pt-Ru for coatings on electrical contacts, and W and Ta for electron emitters. Source Granta CES Selector 2015

• Pontential of increase is seen in new applications – superhard materials, fuel cladding materials, but the research is still ongoing
NIOBIUM

Substitutability

Distribution of end-uses and corresponding substitutability assessment for niobium

<table>
<thead>
<tr>
<th>Application</th>
<th>Share</th>
<th>Megasector</th>
<th>Value (GVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel: Structural</td>
<td>31</td>
<td>Construction</td>
<td>104.4</td>
</tr>
<tr>
<td>Steel: Automotive</td>
<td>28</td>
<td>Transport – Road</td>
<td>147.4</td>
</tr>
<tr>
<td>Steel: Pipeline</td>
<td>24</td>
<td>Oil</td>
<td>50.0</td>
</tr>
<tr>
<td>Superalloys</td>
<td>8</td>
<td>Metals</td>
<td>164.6</td>
</tr>
<tr>
<td>Others</td>
<td>6</td>
<td>Other</td>
<td>63.3</td>
</tr>
<tr>
<td>Steel: Chemical</td>
<td>3</td>
<td>Mechanical Eqpt.</td>
<td>182.4</td>
</tr>
</tbody>
</table>
NIOBIUM

Consumption share

Ferroniobium for steel: Construction 22%

Alloys 10%

(including superalloys)

Ferroniobium for steel 68%

HSLA steel for automotive applications & pipelines

Image 2: Niobium consumption & Products [4]
NIOBIUM Role in steels

Decreasing grain size = Increase strength & toughness

NIOBIUM Role in steels

Precipitation hardening = Increase strength

Nb reacts in steel with Carbon to form nanometer-sized NbC-precipitates

Potential (partial) substitutes in steel

Titanium & Molybdenum combination: Ti reacts in steel with Carbon to form nanometer-sized TiC-precipitates & Mo keeps precipitates small = increase in strength

Vanadium & Molybdenum combination: V reacts in steel with Carbon to form nanometer-sized TiC-precipitates & Mo keeps precipitates small = increase in strength

Conclusion

- EU consumption of niobium → 24% of global niobium consumption.
- No primary niobium production in Europe → scrap is the only available intra-European raw material source
- Ores and concentrates, oxides and niobium metal → Imported

✓ Need to recycle and find potential substitutes to satisfy increased demand
✓ Potential (partial) substitutes for Nb in steel: ‘Titanium & Molybdenum’ and ‘Vanadium & Molybdenum’ combinations
TANTALUM
Substitutability

Distribution of end-uses and corresponding substitutability assessment for tantalum

<table>
<thead>
<tr>
<th>Material</th>
<th>Application</th>
<th>Share</th>
<th>Megasector</th>
<th>Substitutability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tantalum</td>
<td>Capacitors</td>
<td>40%</td>
<td>Electronics</td>
<td>0.3</td>
</tr>
<tr>
<td>Tantalum</td>
<td>Superalloys</td>
<td>21%</td>
<td>Metals</td>
<td>0.7</td>
</tr>
<tr>
<td>Tantalum</td>
<td>Sputtering targets</td>
<td>12%</td>
<td>Electronics</td>
<td>1.0</td>
</tr>
<tr>
<td>Tantalum</td>
<td>Mill products</td>
<td>11%</td>
<td>MechEquip</td>
<td>0.7</td>
</tr>
<tr>
<td>Tantalum</td>
<td>Carbides</td>
<td>10%</td>
<td>MechEquip</td>
<td>0.3</td>
</tr>
<tr>
<td>Tantalum</td>
<td>Chemicals</td>
<td>6%</td>
<td>Chemicals</td>
<td>1.0</td>
</tr>
</tbody>
</table>
• High reliability characteristics and low failure rates, operation over a wide temperature range from -55 to +200°C, can withstand severe vibrational forces, small size per microfarad rating/electrical storage capability
• Major consumers in electronics industry, most of it is used in powder or wire form in manufacture of capacitors
• Accounts for about 60% of the yearly Ta consumption, about 40% (of total in 2011) manufacture of capacitors
TANTALUM in superalloys

- Alloy compositions containing 3-11% tantalum (typically nickel based) offer resistance to corrosion by hot gases, allow higher operating temperatures and thus efficiency and fuel economy.
- Major consumers in aerospace (75% of super-alloy demand, including jet engine and rocket engine nozzles) and defense applications (e.g. missile parts), also suitable for turbine-type equipment, such as gasturbines.
- About 14% to 21% of yearly consumption of Ta.
TANTALUM in cemented carbides

- Increased high temperature deformation, control of grain growth, increases thermal shock resistance and reduces high temperature oxidation of the tools,
- Typically contain about 3% tantalum
- Major consumers: high-speed **cutting and boring tools**, and other tools for environments with high levels of stress and temperatures (e.g. teeth for excavator buckets, mining drills, high-performance bearings and cutting blades).
- Tantalum carbide (TaC) accounts for about 12-14% of yearly consumption of Ta.
TANTALUM Potential substitutes

The following materials can be substituted for tantalum, but usually with less effectiveness:

• **aluminum and ceramics** in electronic capacitors;
• **niobium** in superalloys and carbides;
• **niobium, glass, platinum, titanium, and zirconium** in corrosion-resistant equipment;
• **niobium, hafnium, iridium, molybdenum, rhenium, and tungsten** in high-temperature applications.

Sources: [4, 9, 10, 11]
Conclusions

• At present there are no primary production of tantalum in Europe
• Drivers for substitution (criticality, price, recycling rate) show there are clear need for substitution or increasing recycling rate
• Tantalum can be substituted by other materials but most substitutes have higher costs or adverse properties.
• For Tantalum main application, capacitors, possible substitutes exits (by aluminium and ceramics) and are likely to answer most common needs.
  • Ta capacitors are still used in applications which require high performance
• In other application areas possible substitution of tantalum by niobium (CRM) is possible – rationale?
  • In cemented carbides also titanium carbides (TiC) and nitride (TiN) are possible
  • In corrosion-resistant equipment: glass, platinum, titanium, and zirconium
  • In high-temperature applications: hafnium, iridium, molybdenum, rhenium, and tungsten
TUNGSTEN
Applications of Tungsten in EUROPE

- 72% Cemented Carbide
- 11% Mill Products
- 9% Steel Alloys
- 8% Others (Chemicals)

High temperature applications include:
- Turbine blades
- X-ray tubes

High-speed steels applications include:
- Mining and Construction
- Lamp industry

Catalysts

REFRAM, Final Conference 9-10/3/2017
Global mass flows of tungsten in 2010
Global distribution

Tungsten Production
2015 by Country

World Total: 94100 tons
Cemented carbides (hardmetals)→the most important usage of tungsten today. The main constituent is tungsten monocarbide (WC).

Cemented carbides are materials made by "cementing" very hard tungsten monocarbide (WC) grains in a binder matrix of a tough cobalt or nickel alloy by liquid phase sintering. The high solubility of WC in the solid and liquid cobalt binder at high temperature provides a very good wetting of WC and results in an excellent densification during liquid phase sintering and in a pore-free structure.

WC play a crucial role as they combine high hardness and strength with good toughness within a wide property range, and thus constitute the most versatile hard materials group for engineering and tooling applications.

Cemented carbides are their high modulus of elasticity (about three times that of steel), their extremely high compressive strength (up to 8,000 MPa) making them ideal tool material for high pressure diamond synthesis, and an excellent thermal conductivity.

Hardness increases with decreasing grain size and binder content. Hardness increases fracture toughness decreases and vice versa. In truly abrasive applications, hardness is a good measure of wear resistance.
Role W in Steel Alloys

- Tungsten significantly improves the **hot hardness and hot strength** of steel and leads to increased yield strength and tensile strength without adversely affecting ductility and fracture toughness.

- **Alloying element in steels**: High speed steels, hot work tool steels, cold work tool steels, plastic mould tool steels, heat and creep resistant steels, corrosion resistant stainless steels and valve steels.

- Tungsten has the **highest melting point** of all metals and is alloyed with other metals to strengthen them. Tungsten and its alloys are used in many high-temperature applications, such as arc-welding electrodes and heating elements in high-temperature furnaces.

- Tungsten in steel increase the amount of undissolved and excess carbide in the hardened steel and the eutectoid points is shifted towards lower carbon concentration. The consequence is the precipitation of fine or very fine grained carbides evenly distributed in the steel matrix.

- **Good wear resistance** is the most important property of tool steels, and tungsten, next to vanadium, is the most effective carbide forming element for increasing wear resistance.

### Early history of high speed steels

<table>
<thead>
<tr>
<th>Year</th>
<th>C</th>
<th>Cr</th>
<th>W</th>
<th>Mo</th>
<th>V</th>
<th>Si/Mn</th>
<th>Co</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1868</td>
<td>1.5-2.4</td>
<td>0.5</td>
<td>5.0-8.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.0/2.0</td>
<td>Mushet, first “self-hardening” steel</td>
</tr>
<tr>
<td>1886</td>
<td>2.0</td>
<td>12.0</td>
<td>×</td>
<td>-</td>
<td>×</td>
<td>-</td>
<td>-</td>
<td>Braylen, J. Iron Steel Inst. 1886</td>
</tr>
<tr>
<td>1898</td>
<td>1.8</td>
<td>3.8</td>
<td>8.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Taylor-Wright (“everharden”)</td>
</tr>
<tr>
<td>1905</td>
<td>0.25-2.0</td>
<td>1.0-7.0</td>
<td>4.0-30.0</td>
<td>2-15.0</td>
<td>-</td>
<td>0.1-1.0</td>
<td>-</td>
<td>Mathews US 779, 171</td>
</tr>
<tr>
<td>1906</td>
<td>0.68</td>
<td>5.95</td>
<td>17.81</td>
<td>-</td>
<td>0.32</td>
<td>-</td>
<td>-</td>
<td>Taylor-Wright</td>
</tr>
<tr>
<td>1910</td>
<td>0.8</td>
<td>4.0</td>
<td>18.0</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
<td>McKenna</td>
</tr>
<tr>
<td>1912</td>
<td>0.8</td>
<td>4.0</td>
<td>18.0</td>
<td>-</td>
<td>1.0</td>
<td>5.0</td>
<td>-</td>
<td>McKenna, addition of Co</td>
</tr>
<tr>
<td>1923</td>
<td>0.8</td>
<td>4.0</td>
<td>18.0</td>
<td>-</td>
<td>1.0</td>
<td>12.0</td>
<td>-</td>
<td>McKenna</td>
</tr>
<tr>
<td>1939</td>
<td>1.4</td>
<td>4.0</td>
<td>18.0</td>
<td>-</td>
<td>2.0-5.0</td>
<td>-</td>
<td>-</td>
<td>high C, high V</td>
</tr>
<tr>
<td>1940</td>
<td>×</td>
<td>×</td>
<td>6.0</td>
<td>5.0</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
<td>W replaced fully or partially by Mo</td>
</tr>
</tbody>
</table>
Role W in Super-Alloys

- **Super-alloys** → High temperature strength, high thermal fatigue resistance, food oxidation resistance, excellent hot corrosion resistance, air melting capability.
- W alloyed nickel- and cobalt-based super – alloys are used in aircraft engines, marine vehicle, turbine blades and vanes, exhaust gas assemblies and as construction material for furnace parts

Role W in Mill products

- **Mill products** → Extremely high melting temperature (3414 ºC), low vapor pressure, high stiffness and excellent creep resistance at elevated temperature
- W used in the form of wires, coils and coiled coils incandescent lamps and as electrode in low-and high pressure discharge lamps
Substitutability

Substitutes for most application results in a loss of performance or in an increase of cost.

In cemented carbides and other applications, W and its compounds can be replaced by Mo, Ti, ceramics depleted uranium or hardened steel.

For lightning equipment tungsten filaments can be substituted by carbon nanotube filaments, light-emitting diodes or other light sources.

Distribution of end-uses and corresponding substitutability assessment for tungsten
Summary

- The consumption of W continues to increase as the amount of carbides tool production increases with the expansion of markets in developing countries.
- For Tungsten main application, **WC-based cemented carbides, since to be difficult to substitute: increase of cost and lower performance**
  - Titanium carbides (TiC) and nitride (TiN) are potential substitute but the technology is not competitive at the moment.
- In other application areas possible substitution of Tungsten is possible – rationale?
  - Super-alloys substituted by Ceramic matrix composites (CMCs) made from a silicon carbide/nitride matrix for gas turbine engines. In some applications possible. **Nanostructured n-alloys possible** (but TRL is still 3-4) – 10 y scenario.
  - Difficult to replace in some mill products. Already substitution path in LEDs
  - Steel products can be replace by other CRM (Nb) or refractory metals (Mo). New perspectives via GB engineering and new alloys.
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DISCUSSION

THANK YOU!