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Modern structural materials based on the W-Mo-Re system

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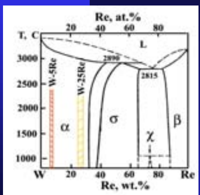
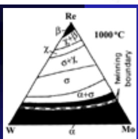
W-Re alloys

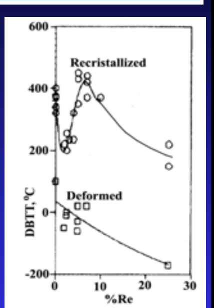
Low and high rhenium alloys W-(2-4) at. % Re and W- (25-27) at. % Re





Solubility of Re in W is high: 37% Re at $T_{peritectic}$ (3000°C) and 28% Re at 1600°C. Re increases solubility of C in W. Re does not form its own stable interstitial phases

Unique ability of 2-4 and 25-30 at.% Re to increase low - temperature ductility and decrease $T_{d/b}$ of cast and recrystallized W – based alloys : «Re effect-1» and «Re effect-3»



- Deformation twins indicate appearance of «Re effect-1» in alloys containing >23at.% Re up to solubility limit of Re in W.
- Re decreases T_m W up to ~3000°C at 37%Re.

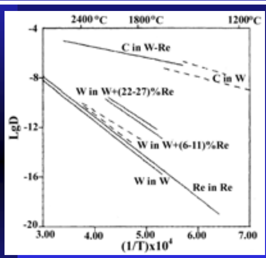
T_m W-Re alloys > T_{melt} Ta, Mo, Nb and their alloys.

The constitution of the valence zone of W-Re s.s. with bcc unordered crystal lattice is complicate. Re content < 5% and > 10% differently affects the electronic structure of W-Re s.s.: distributions of W and Re electrons near the lattice points are different. This affects the values of the binding energy of impurity atoms with dislocations and other lattice defects, stacking-fault energy, etc.

Re in W-based s.s. segregates at grain and subgrain boundaries and at other lattice defects, ousting interstitial elements, e.g. C, from these positions. This phenomenon is one of the reason for the favorable effect of small additions (<4 % Re) on the ductility of W.

W-Re alloys

<u>Development of high-temperature diffusion-controlled processes</u> determines the rate of softening of s.s. at high temperatures and structural changes caused by dissolution of precipitations or coarsening of strengthening phases, polygonization, recrystallization, creep, etc



The minimum coefficient of diffusion D is typical of self-diffusion of W and Re and the tracer diffusion of refractory *Me* (Re, Ta, Mo, and Nb) in W.

The rate of W self-diffusion and the Re diffusivity increase with Re content in W alloys (1.5-3 orders of magnitude)

Addition of 3.9 % Re do not virtually change the diffusivity of C in W.

Addition of 25% Re to W alloys with disperse particles of strengthening phases (ZrC, HfC) increases the diffusivity of C and coalescence rate of *Me*C particles as compared to Re less or low Re W alloys.

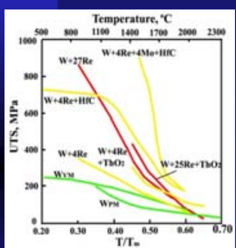
Re accelerates diffusion-controlled processes by decrease in the T_{melt} and ability of Re to segregate at grain boundaries, dislocations, and other lattice defects in W dew to difference in atomic radii: $R_{Re} < R_W$.

Acceleration of the diffusion-controlled processes in deformed high-Re alloys is a reason of more intense high-temperature softening as compared to that in low-Re alloys or in W both upon short-term and long-term tests.

W-Re alloys

<u>Disperse hardening by refractory interstitial phases (HfC. ZrC, ThO2)</u> sharply increases high-temperature strength of both low- and high-Re alloys and decelerates their softening upon heating

As deformed wire ø 0.1-03 mm

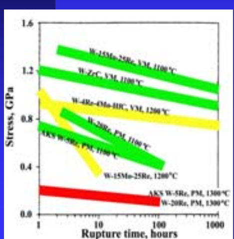


UTS

General tendency is: the higher intensity of the softening of high-Re alloys as compared to that of the low-Re W alloys (s.s. or alloys with 0.1-0.3 % HfC or ZrC.

The higher is Re content in s.s. (25-30% Re), the higher is the UTS at T <1500°C

As temperature increases from 1700 to 2300°C, the maxima of UTS and YS shift to the alloys with low-Re content (3-4%).

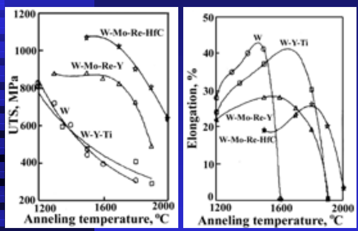


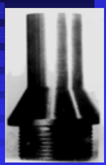
Long-term strength

VM alloys W-25Re-Mo-(0.1-0.3)wt.%HfC(ZrC) have higher long-term strength at 1100°C than that of the alloys with 4% Re with the same content of carbide phase, but have lower long-term strength at 1200°C.

Specific features of <u>low-Re W-based alloys,</u> including alloys with Mo, (l-2)%ThO_2, and (0.14-0.3)%ZrC(HfC), determine their advantages and shortcomings and the efficiency of their application

Effect of annealing temperature on UTS and El of low-Re and Re-less W-based alloys





Properties of castings

T, °C	UTS, MPa
1800	350-450
2000	220-350
2300	150-200

Advantages of W-(2-4)%Re alloys

1- more ductile than Re-less alloys, less tendency to longitudinal cracking upon deformation;
2- more intense strain-hardening upon deformation than Re-less alloys, especially alloys with ZrC(HfC);
3- higher strength, short-term and long-term high-temperature strength, and creep resistance as compared to the W-(20-27) % Re;
4- are not susceptible of the σ-phase formation;
5- less expensive than the W-(20-27) % Re alloys

Shortcomings of W-(2-4)%Re alloys as compared to W - (20-27) % Re alloys.

1 - less ductile;
2 - lower resistance to thermal cycling

Application of W-(2-4)%Re alloys :

1. Castings of complex shape and large section (including centrifugal castings);
2. Deformed large-sized semiproducts for high-temperature articles operating under cyclic loadings and high temperature gradients;
3. wire (including the PM wire) for MMCM.

<u>Specific features of high-Re W-based alloys,</u> including alloys with Mo, (l-2)%ThO_2, (0.14-0.3)%ZrC(HfC), Al-K-Si, determine their advantages and shortcomings and efficiency of their application

Advantages of W-(20-27) % Re alloys

1- more ductile than all W-based alloys.
2- less tendency to delamination upon deformation
3- surpass the alloys with (2-4) Re in strain hardening;
4- highest resistance to thermal cycling die to the highest ductility as compared to that of other W alloys.
Rank below only plain rhenium.

Shortcomings as compared to low Re alloys:

1- high cost;
2- possibility of the formation of σ phase even in thin-section articles of PM production;
3- lower high-temperature strength and strain stability at temperatures above 1200-1400°C, because of more intense diffusion-controlled processes than those are in W-(2-4)% Re alloys.

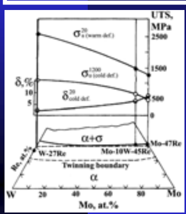
Applications of W - (20-27) % Re alloys

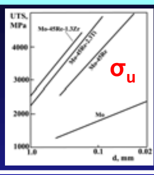
Articles and semiproducts of fine sections for service at temperatures up to 2000°C (including those after high-temperature recrystallization) and under thermal cycling, vibrations, and shock loading.

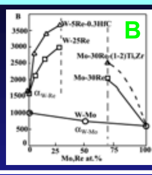
1- volume-wise dominating application - thermocouple wire for high-temperature measurements together with W-3 or 5 % Re counterparts;
2- high-temperature springs;
3- applications, where high temperature strength is required but where low temperature ductility is critical.
4- applications for flat materials are rapidly growing, due to its good high temperature strength also compared to Re at T<1800K

High-Re Mo-Re and W-Mo-Re alloys

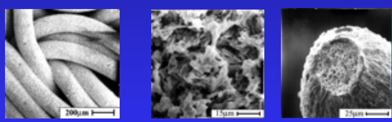
Mechanical properties as function of W and Mo contents in W-Mo-Re alloys with (30±2) at.%Re







Equation $\sigma_u = A - B \cdot \lg d$ reflects increase in strength upon deformation (Ø) of rod (wire). The coefficient B increases with increasing Re content in W or Mo alloys.



Effect of oxidation-reduction treatment on surface appearance and fracture behavior upon tension tests of Mo-W-45wt.%Re

Mo-W-45wt.%Re catalytic elements

"Re effect of strain hardening" was used for the design of elastic elements with the UTS up to 5000-7000 MPa. Tension members, springs, and torsion bars made of these alloys are successfully used in control and guidance devices and in mining instruments. Under dynamic cyclic loading (vibration, impacts), strength and fracture toughness of these material are higher in several times than those of other alloys used for the same purposes. Long-term weather exposure of these materials under conditions of deep cold as well as elevated-temperature tests under high vacuum indicated the high stability of their mechanical properties.

High low-temperature ductility of high-Re Mo and Mo-W alloys determines possibility to use these materials for catalytic elements in some types of devices. High ductility typical of these alloys is retained in the alloy after oxidation-reduction treatment in spite of formation of thin surface layer of molybdenum and tungsten nitrides

Concluding remarks

Rare and refractory metal Re is the only metal that has good strength and ductility over a wide temperature span stretching from the absolute zero (0 K) to 2800 K.

Unlike such bcc cold brittle refractory metals as W and Mo, Re has its best ductility in the recrystallized condition. Due to excellent strength of Re at very high temperatures, Re is especially suitable for various applications under extreme thermal and mechanical stresses.

The only draw-back with Re is the cost involved in making components from it, which to some extent depends on the scarceness of the material but largely to the difficulties in forming and machining products in Re.

Re rich alloys based on Mo and W have outstanding mechanical and physical properties, which make them good alternatives to pure Re in many applications, in particular where the cost for using pure Re is prohibitive. Re rich alloys Mo–(41-47)%Re and W–(25-27)%Re have applications that are similar to those of pure Re. Although their properties at very high and very low temperatures are not as good as those of pure Re, there is a wide temperature range, where they are reasonable and cost efficient alternatives. They are also easier to form using plastic methods and can be welded using the same methods as for pure Re.

Binary low Re alloys (e.g. W-4%Re) can also serve as the basis for high-strength, high-temperature materials, strengthened with nanometric particles of refractory carbides (ZrC, HfC). These materials are less expensive as compare to high Re alloys and pure Re. Binary low Re W-Re alloys are the best materials for large scale articles.

Due to much superior formability Mo-Re alloys have found a number of applications, where pure Re and W-Re alloys are not feasible to use, for example in deep drawing. Mo–(41-47)% Re alloys are as a rule strong candidates as design and construction materials for applications in the temperature range above where superalloys can be used and where rhenium or W - 25 % Re alloys may be required.