A NEW HOT WORK TOOL STEEL FOR HIGH TEMPERATURE AND HIGH STRESS SERVICE CONDITIONS

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Abstract
For hot work applications, the widely used H11 and H13 grades have been improved in many derived compositions including chromium, molybdenum, vanadium as major hardening alloying elements. These steels are not enough resistant when strong friction or close thermal contact with the part or molten metal during service promotes at the same time high cyclic stresses and increased tool surface temperature. A new steel including tungsten and cobalt as alloying elements has been designed for better structure stability, resistance to softening, and higher fatigue resistance with acceptable toughness at high temperature. Hardness level may be adjusted within the 42-52 HRC range. Mechanical properties inside the 550-650 °C interval, and creep resistance are significantly enhanced from reference grades.

Applications in forging dies, die casting dies, extrusion dies will be described proving the performance of this material in severe conditions, and its resistance to thermal fatigue.

INTRODUCTION
The five per cent chromium tools steels family, and especially H11 and H13 grades are today widely used for various applications all over the world, applications including forging tools, die casting moulds (copper, light alloys, etc.), extrusion dies, moulds for glass industry. This extended area of applications is possible because these materials offer a good hardness/toughness compromise at working temperature. For every service condition, the bal-
ance between the properties may be adjusted by the heat treatment conditions that confer room temperature hardness in the HRC 42 – 52 range. Failures occur from different mechanisms like thermal fatigue, wear, creep, softening, more or less interactive and sometimes gross cracking may be observed.

Generally the material surface is submitted to cyclic temperatures variations and, during the top phase of the cycle, the structure softens and the mechanical resistance of the alloys decreases. Softening has for a long time been assessed by the loss of hardness measured at room temperature between a freshly heat treated sample and the same sample after 50 hours exposition inside the range of service for instance 520 to 600 °C. The single temperature exposure does not give a full description of softening. D. Delagnes et al. [1] demonstrated that softening is the result of the combination of thermal and mechanical effects during isothermal fatigue tests on H11 grade in the 500-600 °C range. This "cyclic de-consolidation" is also confirmed when temperature and stress vary at the same time like during thermo-mechanical fatigue experiments [2].

If the cyclic range amplitude of stress and temperature remains in reasonable intervals, performance of the tool is considered acceptable as far as the resulting cycling strain amplitude can be allowed by the material: its toughness is high enough to face to the cyclic plastic strain. But in severe service conditions, when stress increases, and when surface temperature jumps well above 500 °C during long close contact time at every cycle, these conventional 5% chromium steel become too sensitive to softening and the tool life decreases drastically.

**BASIC CONCEPT FOR A NEW STEEL**

Mechanical resistance and resistance to heating of the steel during service is determined by dislocations and crystal defects morphology, distribution, and stability. This stability depending itself on carbides precipitates size and distribution, and on their resistance to coarsening and coalescence. Transmission Electron Microscopy gives some information about this precipitates and their chemical composition even if, probably, the tiniest of them which are efficient for dislocations pinning are not well identified. Roughly, it seems that chromium has a detrimental effect because chromium-rich carbides like M23C6 have a high kinetic for coarsening. So, a basic idea for improving steel performance is partial substitution of chromium by other elements forming MC or M2C type precipitates. For instance, molybdenum
content increase is an alternative to promote $M_2C$ formation and diminution of chromium content delays the transformation from $MC$ and $M_2C$ carbide towards $M_23C_6$ form [3].

Many alternative grades have been tested by steel producers, derived from H11 or H13 alloys by adjusting the balance between, on one hand chromium, and on the other molybdenum or vanadium. Table 1 shows for instance H10 with lower chromium and more molybdenum and DIN 1.2367 which corresponds to H11 with higher molybdenum content. These grades have found successfully specific applications but they all fail by excessive softening when conditions become severe.

Tungsten is an alternative addition element to form more stable carbides like $M_6C$ type and strengthen the steels. H12 grade has a too low level of tungsten to form specific precipitates and really modify significantly the properties from the reference H11 steel. On the opposite, H19 and H21, with a higher content become very brittle. The objective for the new SMR4 steel have been:

- keep the general features of the conventional H11 & H13
- increase resistance to softening to allow an increase of about 40/50 $^\circ$C for compatible service temperature
keep an acceptable toughness.

The balance between carbide former elements has been carefully adjusted; the tungsten percentage is low enough to avoid formation of primary eutectic carbides during solidification, and interdendritic segregation. Cobalt addition participates also in softening resistance enhancement.

Of course, the final quality of the product requires a very tight process control in the steel mill:

- raw material selection and refining route for low inclusions content and low impurities like sulfur, phosphorus, tin and other tramp elements.
- remelting for improved cleanliness, low interdendritic segregation and banding, and fine solidification structure
- thermo-mechanical processing for fine grain structure and isotropic properties.
- heat treatment and particularly quenching control.

**PROPERTIES OF THE NEW STEEL**

For heat treatment practice, austenizing temperature must be adjusted in the 1040 to 1080 °C range for carbide element-formers solutioning. Quenching in high pressure gas medium must be as drastic as possible. Two tempering cycles are recommended in the 560 to 680 °C interval to adjust hardness inside the 42 to 52 HRC hardness range. Practically, the hardness levels under 45 HRC have in fact little application interest.

Figure 1 illustrates the hardness level evolution versus tempering temperature for reference steels and the new grade. Obviously, the later is more resistant to softening and this property is a first condition for use at increasing service surface temperature. An other approach for softening resistance measurement consist in measuring the loss of hardness or Tensile U.T.S. between a virgin material and the same after for instance 50 hours aging at 550 °C. Figure 2 demonstrates the better stability of the SMR4 grade: roughly, it may be considered that the compatible service temperature is increased of about 50 °C.

Figure 3 confirms these properties by description of U.T.S. loss when the testing temperature increases: while AISI H11 (and also H12 and H13 with similar properties) shows a quick depletion of U.T.S. as soon as 500 °C is
exceeded and full collapse at 600 °C, the new composition keeps a significant resistance up to more than 600 °C, DIN 1-2367 showing an intermediate evolution. Microstructure softening is a combined action of temperature and stress. In true service conditions, the material is submitted of the two effects, each of them showing a cyclic evolution. Creep and stress-rupture tests which combine the consequences of temperature and stress are a first step to roughly classify materials, even if the cyclic parameter is not present; time to rupture in a simple stress-rupture test may be approximately linked to creep deformation speed. Creep, and consequently, stress relaxation when the heated surface of the tool is closely maintained in contact with material to be transformed is not significant for 5% Chromium steels for temperatures below 500 °C, but must be taken in account above. Figures 4a and 4b show the better stress-rupture resistance of the new steel. Better creep resistance.
Figure 2. Softening: Percentage of loss on room temperature U.T.S. caused by tempering during 50 hours at 550 °C.

is of course evidence of better mechanical properties, but also the proof of superior structure stability.

All these properties demonstrate the improved resistance to tempering and to high temperature service.

Conclusion: The working temperature is raised of about 50 °C compared to regular steels (H13 type).

SOME APPLICATION EXAMPLES FOR SMR4 GRADE

This steel application area is defined by the domains where the reference 5% Chromium steels fail because maximum temperature or maximal stress are too high; the minimum temperature of service cycles must not also be too low because room temperature toughness is of course a little lower.
Figure 3. Tensile properties: Influence of temperature on U.T.S. for new steel SMR 4 and two reference grades.

EXTRUSION DIES FOR COPPER ALLOYS

The extrusion of tubes in copper alloys made by regular steels (H 13) is today improved by using SMR4, and the results are more than 25/30% higher in tool life.

DIE CASTING OF COPPER ALLOYS

The best results obtained with cavities made of SMR4 are in manufacturing many parts, like door-handles, where the result is improved by more than 4 times.
(a) Time to rupture at 550 °C.

(b) Time to rupture at 600 °C.

Figure 4. Stress-rupture testing.
FORGING DIES

SMR4 is used to make the punch part of the die to transform steels, to obtain pieces of power transmission for the car industry. The result is about 25% more, compared to regular steels (see Fig. 5).

Figure 5. Punch for manufacturing of couplings (Temperature: 875 °C).

REFERENCES
