JOURNAL OF MATERIALS SCIENCE **39** (2004) 637–640

Influence of residuals resulting from scrap use in the electric arc furnace process on the properties of hot-work tool steels

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Hot-work tool steels are produced by the electric arc furnace route applying scrap as the main raw material. Besides iron being the most important alloying element for the steel production, a number of generally undesired residual elements are contained in scrap. Due to the continuous scrap recycling, some residuals that normally cannot be removed from the melt such as copper and nickel are in the future expected to enrich in scrap as well as in the steel produced with consequences for the material properties not yet known [1, 2]. To extend the knowledge, it was the objective of a project financially sponsored by the ECSC to determine the impact of scrap use on the properties of hot-work tool steels by investigating the influences of the residuals nickel, copper, phosphorus and aluminum.

For the investigation, 13 heats of steel H11 (X38CrMoV5-1) were produced via vacuum induction melting followed by electroslag- or vacuum arc remelting. While the alloying elements were kept on a constant level in the admissible range according to German standard (SEL), the residuals were adjusted according to Table I. From the remelted billets with a weight of 1 ton forged bars with a dimension of 90 mm square were produced for the tests. Besides of the working properties, the mechanical properties and the microstructure were investigated. Details concerning the material production and testing are included in [3].

The residual phosphorus was investigated within the scope of 0.002% to 0.021%. It most notably had a deteriorating impact on the mechanical properties, e.g., toughness and ductility. In impact bending tests at room temperature and elevated temperatures, the impact bending energy was reduced with increasing phosphorus content (Fig. 1). The effect was noticed for unnotched and notched specimens likewise. The reason for this behavior most likely is the segregation of phosphorus at grain boundaries and at interfaces between martensite laths and carbides, a phenomenon that has been discussed in connection with the role of phosphorus in temper embrittlement [4]. Segregation of phosphorus leads to a reduction of cohesion in the microstructure and allows easy crack initiation, thus reducing toughness. For the alloys tested, a noticeable reduction of toughness occurred with 0.021% P although the impact bending values were still high enough to meet the demands of various customer specifications.

Also, ductility determined in tensile tests at room temperature was reduced with increasing phosphorus content. A content of 0.021% P was found to increase the yield strength by 100 MPa while it did not have a bearing on tensile strength. The effect on yield strength results from the integration of phosphorus atoms in the iron-solid solution and has already been described for engineering steel grades. Due to the different atom radii the crystal lattice is distorted and thus a hardening effect and an influence on yield strength is evoked.

The properties determined in creep tests such as creep strength and yield strength were significantly reduced by phosphorus (Fig. 2). This effect on the creep resistance can be explained by time-dependent grain boundary phosphorus segregation reducing toughness. Also it is known that phosphorus accelerates the velocity in primary and secondary creep regions as it facilitates the formation of coarse carbides that reduce creep resistance [5].

The influence of copper was determined for contents between 0.05% and 0.38%. Copper as a residual in steel H11 did not show any effect on the processing properties although this element is always mentioned in connection with defects during casting and hot-forming operations [6]. Obviously, the effects of

TABLE I Content of residuals in mass.% in hot-work tool steel X38CrMoV5-1 (H11, material-no. 1.2343) (all alloying elements within range of SEL)

Denomination of test material	P	Ni	Cu	Al	N
0.002 P	**0.002**	0.10	0.05	0.005	0.008
0.014 P	**0.014**	0.10	0.05	0.006	0.013
0.021 P	**0.021**	0.09	0.05	0.006	0.013
0.10 Ni	0.014	**0.10**	0.05	0.006	0.013
0.30 Ni	0.015	**0.30**	0.04	0.005	0.012
0.49 Ni	0.014	**0.49**	0.05	0.007	0.009
0.05 Cu	0.014	0.10	**0.05**	0.006	0.013
0.20 Cu	0.014	0.10	**0.20**	0.007	0.010
0.38 Cu	0.014	0.10	**0.38**	0.006	0.008
0.003 Al	0.013	0.29	0.19	**0.003**	0.011
0.015 Al	0.014	0.29	0.19	**0.009**	0.006
0.025 Al	0.012	0.30	0.18	**0.025**	0.012

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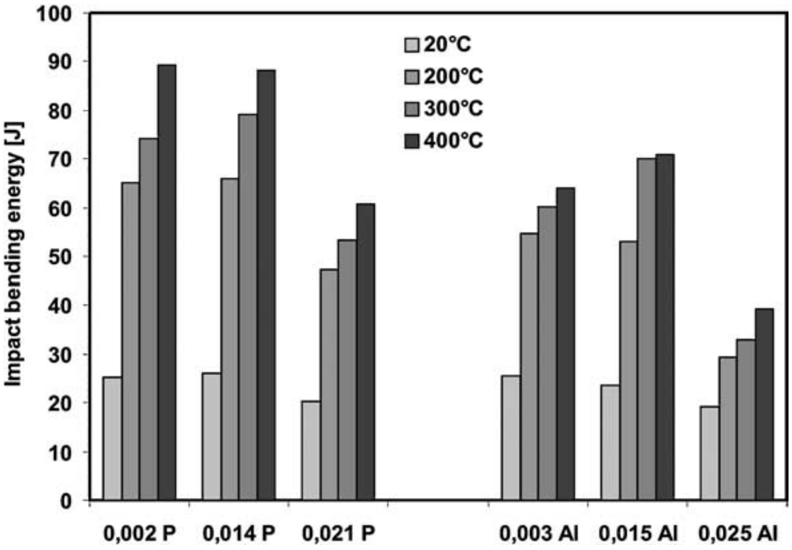

Figure 1 Influence of phosphorus and aluminum on notched-bar impact bending energy (Charpy-V notched specimens, hardness 45 HRC).

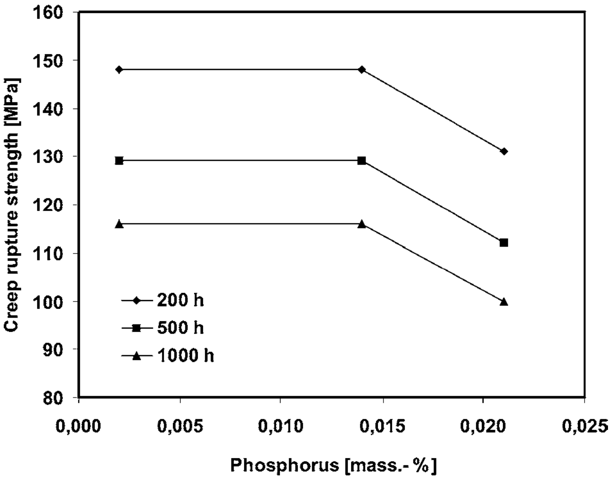

Figure 2 Creep strength at 600 °C in dependence of phosphorus content.

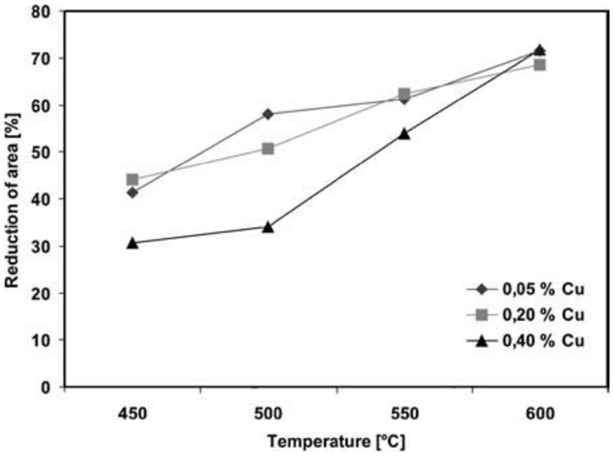

Figure 3 Reduction of area in tensile test at elevated temperature in dependence of copper content.

copper, which means enrichment at the scale-steel interface, penetration along the grain boundaries and causation of surface cracks, described for low alloyed steels with contents of up to 0.49% cannot be alienated to the hot-work tool steel investigated. Possibly the amount of copper contained was not high enough to deteriorate processing properties.

In contrast, high copper content of 0.38% impaired ductility tested in tensile tests at room temperature and at elevated temperatures between 450 °C and 550 °C (Fig. 3). One possible reason could be the precipitation of copper-rich phases that is known to take place at the temperature range cited and that might reduce ductility. However, this kind of precipitation was not effective enough to increase tensile strength likewise. Copper was also found to have a large degrading influence on the creep strength and time dependent yield strength at elevated temperatures. Possibly, the same mechanism was effective here.

Amounts of 0.10% to 0.49% nickel were also subject of the investigations. Nickel is one of the elements forming solid solutions together with iron. It features a low diffusion coefficient in Fe-Ni alloys and therefore reduces the critical cooling rate. Hence the through-hardenability of tool steels is improved and nickel generally is used as a valuable alloying element.

Of all the residuals investigated, nickel was the least harmful. It was found to broaden the solidification range and to impair continuous castability. Besides that, some minor negative influences on ductility in tensile tests at room temperature as well as on the properties in creep tests were ascertained.

Aluminum contents from 0.003% to 0.025% were investigated. The concurrent amounts of nitrogen were 0.005% to 0.013%, those of oxygen 8 ppm to 16 ppm. Aluminum was found to impair toughness and ductility to a large extent. The impact bending energy at all temperatures tested was severely reduced. At elevated temperature, the effect of aluminum on the toughness even was stronger than the effect of phosphorus (Fig. 1). Also, ductility in hot workability tests as well as in tensile tests was decreased.

Some specimens with low impact bending toughness were investigated by electron microscopy (REM, TEM). They displayed aluminum nitride precipitations (AlN) preferably situated on grain boundaries (Fig. 4) as well as a larger amount of aluminum oxide inclusions (Al_2O_3).

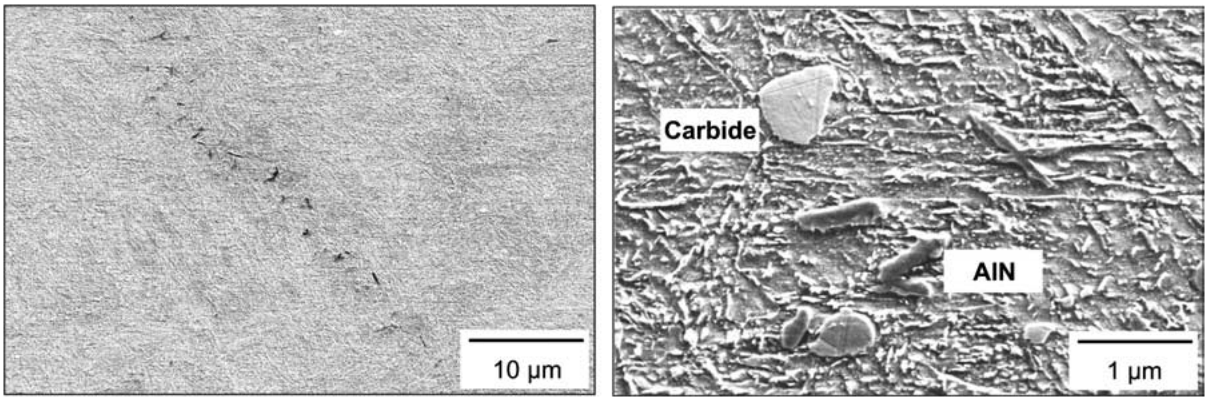

Figure 4 Precipitations of aluminum nitride (AlN) in test material with 0.025 mass.% Al.

The reduction of ductility in hot workability tests can be explained by a precipitation of embrittling aluminum nitrides in the temperature range from 1200 °C to 900 °C. The precipitates are formed at the γ grain boundaries, weakening the boundary region and encouraging intergranular failure [7]. For C-Mn steels, the product of soluble aluminum and total nitrogen contents is stated to be more than 3×10^{-4}, for example 0.060% Al and 0.005% N, for this to occur. Obviously in the hot-work tool steel investigated, the effect already turned up at 0.025% Al.

Both types of precipitations, i.e., nitrides and oxide inclusions, most likely are connected to the low toughness revealed by the alloy with high aluminum content. Besides of a reduction of aluminum it should therefore also be kept in mind to watch the oxygen and nitrogen contents.

With respect to the fields of application of hot-work tool steels, e.g., pressure die casting and metal extrusion, the impact of the residuals on the most important properties was evaluated (Table II). For hot-work tools under high load that generally imply the use of ESR-material ("premium grades"), the following recommendations from a mere scientific viewpoint can be made:

- Alloys containing the highest contents of residuals showed impact bending energies above the minimum limit stated for unnotched specimens in NADCA-(≥170 J) [8], VDG-(≥250 J) and DGM-specification (≥280 J). Also the impact bending energy of Charpy-V-notched specimens was well above the lower NADCA-limit (≥11 J). Hence all alloys are able to reach the toughness values demanded by current international standards. A limitation on this account is not required.
- As toughness and ductility are important properties for further improvement of the steel quality, it is desirable to restrict the amounts of phosphorus and aluminum to 0.015%. This could help in advancing life time of very high-loaded tools such as metal extrusion dies and die casting dies.
- As creep resistance is a key to improvement of service life, high copper contents should be avoided. A suggested limit for copper is 0.20%.
- Of the residuals investigated, nickel was the least harmful. Nevertheless, due to its influence on the steel processing properties, the maximum content is recommended to be 0.30%. This limit is of more importance to the steel producer than to the steel user.

On implementing the suggested upper limits of residuals to large-scale steel production some points will have to be taken into consideration. First, the limitations of copper and nickel most of all are closely connected

TABLE II Summary of influences of residuals on properties of steel H11

		Investigated element range			
Property	Parameter	P 0.002–0.021 (%)	Cu 0.05–0.38 (%)	Ni 0.10–0.49 (%)	Al 0.003–0.025 (%)
Solidification range	T_{liq}–T_{sol}	–	o	↑↑	–
Continuous castability	900 °C–T_{liq}	–	o	↓↓	–
Hot workability	900 °C–1150 °C	–	o	o	↓
Toughness	RT-400 °C	↓	o	o	↓↓
Tensile strength	RT	o	o	o	o
Yield strength		↑	o	o	o
Ductility		↓	↓	↓	↓
Tensile strength	450 °C–600 °C	o	o	o	↓
Ductility		o	↓	o	↓
Creep strength	500 °C–600 °C	↓↓	↓↓	↓	–
1%-yield strength (time dependent)	10 h – 1000 h	↓↓	↓↓	↓	–

o = no significant influence, ↓ = decrease, ↑ = increase, – = not tested.

to the availability of appropriate scrap and its costs. Furthermore, a limitation of aluminum could bear some technical problems in the steel production process as this element is used for desoxidation and is not easy to handle in the remelting process. Finally, the reduction of phosphorus also is connected aluminum careful scrap selection and the use of alloying additions with low phosphorus content. All of this is bound to have an influence on the price of the steels produced although the beneficial impacts on material properties are uncontradicted.

Acknowledgment

The authors would like to thank the European Community for Coal and Steel for financial support (project 7210.PA/175).

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Received 10 July
and accepted 29 July 2003