COMPARISON OF DIFFERENT CHARACTERISTICS OF MODERN HOT-WORK TOOL STEELS

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INTRODUCTION

Hot-work tool steels in operation are subjected to distinct mechanical forces and considerable changes in temperature. The complex effects of mechanical, thermal, and chemical factors on the tools in operation imply demanding requirements for hot-work tool steels. In recent years a number of investigations have been made as to how different alloying elements affect the material properties of hot-work tool steels [1, 2, 3]. Based on more profound knowledge in this field, new materials were developed and brought to market so that nowadays users have a wide range of material grades with differences in quality to choose from. In addition to changes in the composition of alloys a variety of processing techniques may also influence material quality [4, 5].

Application of carefully directed forming and tempering operations may result in specific material characteristics like isotropy of mechanical properties, formation of structure, as well as content, shape and distribution of non-metallic inclusions. Thus users face a great number of alternative materials to choose from. The material assessment for extrusion tools will serve as an example of a procedure for the systematic selection of the most suitable material and an investigation is to be made into the differences in quality between the respective materials. From a number of materials suitable for this purpose, disks of the same dimensional category were procured and subjected to tests relevant to the service life to be expected.

TEST PROCEDURE

For the investigation disks were procured from round bars of the respective steels, the dimensions were 320 mm in diameter, 30 mm thickness, the condition was soft annealed. The steels were grade 1.2343 and 1.2367 as well as three special grades, designated Special A, B, and C. The soft annealed samples were pickled to establish the degree of segregation in the materials, and in addition to that the annealed structure in the transverse direction was determined, shown in Fig. 1. For the testing of mechanical properties specimens for notched bar impact test, impact bending test, and tensile test to destruction were taken from the transitional area of the disks in a transverse orientation. Each of the sample blanks was tempered at the company producing that particular steel grade. Additional data as far as they are relevant for assessing the test results are presented together with these results.

TEST RESULTS

CHEMICAL COMPOSITION

The analysis of each of the supplied steel samples established its chemical composition as shown in Table 1. From the results of the analyses the ratios chromium /carbon, molybdenum/carbon, and vanadium/carbon were calculated and included in the table. The results indicate that Special A as well as Special C are variants of the original steel grade 1.2343 with lowered carbon content and simultaneously increased vanadium content. Hence there is a considerable change of the chromium/carbon ratio as well as a significantly changed vanadium/carbon ratio. Both changes are due to recommendations made after earlier tests, to change the ratio of carbide formers to carbon content in this steel [2, 3]. In the alloying variant Special A the molybdenum content is also higher than in 2343. Special B is a variant of steel 1.2367 resulting from an additional alloying of a higher cobalt content.

Table 1. Analyses of tested materials as measured

Designation	Composition of material									Ratio of carbide formers to carbon content		
	C	Si	Mn	P	S	Cr	Mo	V	Co	Cr/ C	Mo/ C	V/ C
1.2343	0.369	0.882	0.398	0.012	0.005	4.37	1.14	0.28	0.01	11.84	3.09	0.76
1.2367	0.374	0.335	0.327	0.017	0.004	4.37	3.07	0.55	< 0,01	11.68	8.21	1.47
Special A	0.345	0.38	0.331	0.015	0.006	4.74	1.96	0.56	< 0,01	13.74	5.68	1.62
Special B	0.355	0.39	0.35	0.026	0.005	4.22	2.89	0.5	2.58	11.89	8.14	1.41
Special C	0.321	0.308	0.24	0.019	0.005	4.33	1.27	0.41	< 0,01	13.49	3.96	1.28

PICKLING TEST

The pickling test makes existing block segregations visible. If segregations exist, the chemicals affect the material more or less strongly depending on their respective alloying composition, and the resulting effect becomes noticeable with changing surface brightness. The ground specimens were pickled as follows: 50% H2O plus 50% HCl (mixed to 37% content) at room temperature for 40 minutes. During this test no differences were visible in the degree of segregations in the materials. All disks showed a macroscopically homogeneous distribution of alloying elements across the entire surface.

ANNEALED STRUCTURE

The annealed structure was classified as suggested by the North American Die Casting Association (NADCA). Accordingly, steel grade 1.2343 was classified D1. This means it is acceptable, the carbide distribution, however, is not homogeneous. There are regions containing significantly fewer carbides. Moreover, string-like structures are apparent. The annealed structure of steel 1.2367 was classified B2 according to NADCA. The annealed structure shows a fine distribution of carbides, but they are not distributed homogeneously, as can be seen from slight difference in contrast Fig. 1b. The annealed structure of Special A was classified NADCA A1, which is equivalent to very good. Carbide distribution in Special B is somewhat coarser, that meant NADCA classification B1 in this case. Carbides in Special C are comparatively fine but have not been completely formed. Moreover, a slight irregularity of carbide distribution is evident from a needle-like matrix. The annealed structure of this steel was classified B1 – C1 according to NADCA. All annealed structures were studied and classified according to NADCA guidelines for longitudinal as well as transverse specimens, and the results have been compiled in Table 2.

Table 2. Results of structure classification according to NADCA guidelines

	Annealed structure according to NADCA	
Steel	Longitudinal sample	Transversal Sample
1.2343	D1	D1
1.2367	B2	A3
Special A	A1	A1
Special B	B1	B1
Special C	C1	B1

HEAT TREATMENT AND TEMPERED STRUCTURE

The structures observed in heat-treated samples are presented in Fig. 2 together with the parameters of heat treatment and final hardness measured. Already at first sight, pronounced differences are obvious. Material 1.2343 quenched from a temperature of 1010 ℃has a coarse grain with coarse, needle-like martensite structure. The other materials hardly differ from one another, for example Special C has the smallest austenite grain size. This steel was, however, hardened at the lowest austenitizing temperature. If hardness is compared after the last tempering process, which was at 570 ℃for all steels, the low-carbon steel variants show significantly higher tempering than the original steel 1.2343. The result corresponds to findings presented in other publications [3], according to which variants of hot-work tool steel X 40 Cr MoV 51 with lower carbon content have a lower secondary hardness, and in the technically important range of tempering temperatures these low-carbon steels have almost identical and occasionally even higher hardness than higher-carbon steels.

MECHANICAL, TECHNOLOGICAL PROPERTIES

All steels underwent tensile tests to destruction at room temperature, at 450 ℃ and at 550 ℃. Figure 3 shows the tensile strengths of all steels tested. There is hardly any difference between the tensile strengths of each steel, and existing deviations nearly correspond to the differences in hardness measured. As is to be expected, tensile strength and yield strength definitely decrease at higher test temperatures. This decrease of strength is more or less strongly developed with each material, so that at high test temperatures, for example at 550 ℃, the steels do show quite different results (Fig. 3).

Figure 4 presents the proportional decrease of tensile strength and yield strength and how they relate to the values at room temperature. It is obvious that above all Special A and Special C demonstrate a very favorable behavior. Tensile strength at room temperature as well as at raised temperatures depends on precipitated carbon content as well as on dissolved carbon content in the matrix. Both of these are influenced by the ratio of carbide forming elements to carbon in the steel. Therefore Fig. 5 shows tensile strength at different temperatures and its dependence on the ratio chromium/carbon, vanadium/carbon and molybdenum/carbon. Here is an indication that particularly with Special C a very favorable ratio of carbide formers to carbon has been achieved. It becomes evident that neither an increase of the ratio chromium/carbon nor one of the ratio vanadium/carbon, or molybdenum/carbon would be able to contribute to any further increase of tensile strength. A similar observation as for steel grades 2343 cannot be made for steel grades 2367 as the ratio chromium/carbon, molybdenum/carbon, and vanadium/carbon remained almost identical and only more cobalt was alloyed to the steel. This higher cobalt content does not result in any improvement of tensile strength at higher temperatures as can be seen from Fig. 4 when comparing steel 1.2367 with Special B.

The toughness of the respective steels was tested in notched rod impact tests and in impact bending tests. The notched rod impact tests were carried out according to DIN 50 115 (German Industrial Standard) on V-notched specimens with a pendulum impact-testing machine with 450 Joule impact load at room temperature. The impact bending tests were carried out according to DIN 50 115 and DGM guidelines with the same pendulum impact-testing machine. The mean results of six tests each are summarized in Fig. 6. Here it becomes evident once again that Special C generally has the most favorable toughness. The least favorable results are found with steel 1.2367, whilst the almost identical steel with a higher cobalt content has significantly better toughness. Also with respect to toughness, certain observations can be made about the influence of the ratio of carbide forming alloying elements to carbon (Fig. 7). Once more, optimal results are achieved with Special C, having a ratio chromium/carbon of about 13.5, a ratio vanadium/carbon of about 1.3 and a ratio molybdenum/carbon of about 4. Surely the stated influence of alloy composition can be further enhanced by different forging and/or tempering procedures. An interesting finding in this context is that with almost the same basic alloying compositions the ratio of carbide forming elements to carbon has such a very positive effect.

To enable a valid assessment of the overall properties of the steels the individual results were plotted on a radar chart (Fig. 8). The hardness and tensile strengths at 450 ℃and 550 ℃reflect the strengths of the steels. The impact bending load, the notch impact load and the reduction of area at 550 ℃are indicators for the toughness of each steel. The larger the area enclosed is, the better are the overall properties of the material. As was already to be concluded from the measured values, Special C has the largest enclosed area and thus exhibits the best overall properties. Special A also shows quite positive overall properties, whilst Special B has a less favorable result than original grade 1.2343 everything being considered. For material 1.2367 the results of this investigation were generally inadequate.

DISCUSSION OF TEST RESULTS

In order to improve the mechanical properties and in particular the toughness of hot-work tool steels there are two options of proceeding:

- changing forging and heat treatment
- changing the material.

Optimization of hot-work tool steels by alloying techniques as pursued by steel producers appears to be a very promising option, considering the results of this investigation. The ratio of carbide forming alloying elements to carbon content offers a possibility to control above all the carbide reaction in the steel. Carbon, chromium, molybdenum, and vanadium are responsible for the formation of carbides in hot-work tool steels containing these elements.

In the annealed condition the total carbon content of hot-work tool steels is available in the form of carbides. In the course of hardening and tempering, a large portion of carbon is dissolved and stored in the matrix where it influences the transformation behavior noticeably. Decreasing carbon content increases the $\mathrm{M_s}$ and $\mathrm{M_f}$ temperatures significantly, but its effect on $\mathrm{A_{c1b}}$ and $\mathrm{A_{c1e}}$ temperatures is negligible. With a higher ratio of carbide formers to carbon there is less hardenability. Lower carbon steels have a lower secondary hardness maximum [3]. Previous investigations have shown that further elevation of the tempering temperature, i.e. above the secondary hardness maximum, reduces these differences again [2]. As this levels off the steep drop in hardness when annealing lower carbon steels, the required operational hardness should be more easily achieved. In general, due to the restricted availability of carbon, lower carbide contents are found in the annealed condition as well as in the tempered condition. Because of this lower carbide content, toughness is improved. It has repeatedly been shown in earlier investigations that by lowering the carbon content in hot-work tool steels 1.2344 and 1.2343 hot-work strength, hot-work toughness, and creep strength can be improved simultaneously. Those laboratory tests have been confirmed by this investigation of hot-work tool steels as produced by the mill. At present the materials are being tested in the extrusion of aluminum sections. Operational results up to now suggest that the systematic selection of material presented here will optimize the service time of extrusion tools.

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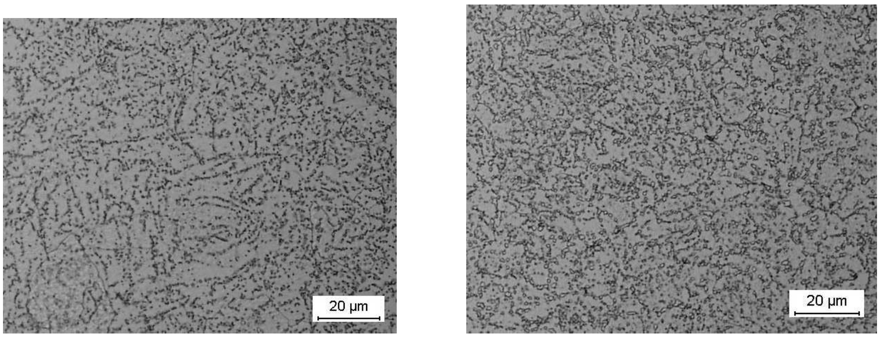
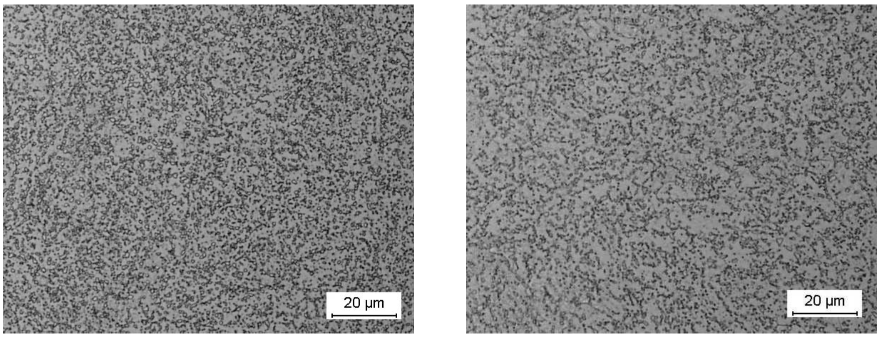
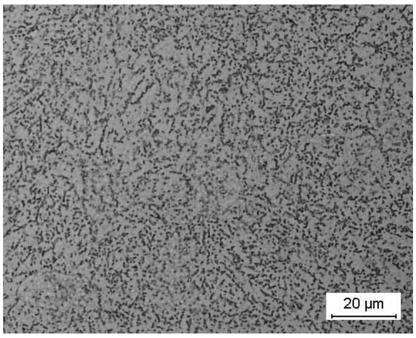


(a) 1.2343 (b) 1.2367

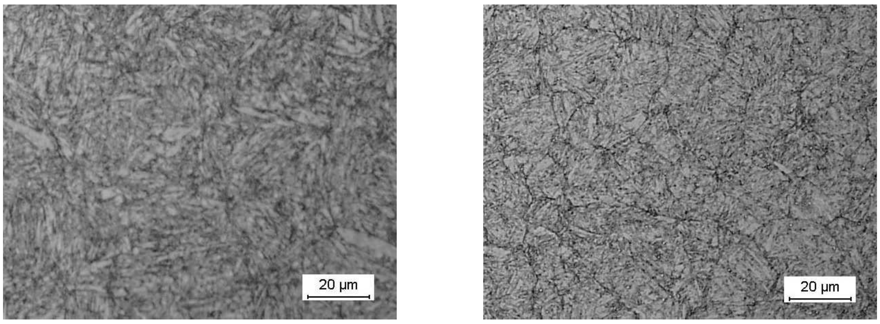


(c) Special A (d) Special B



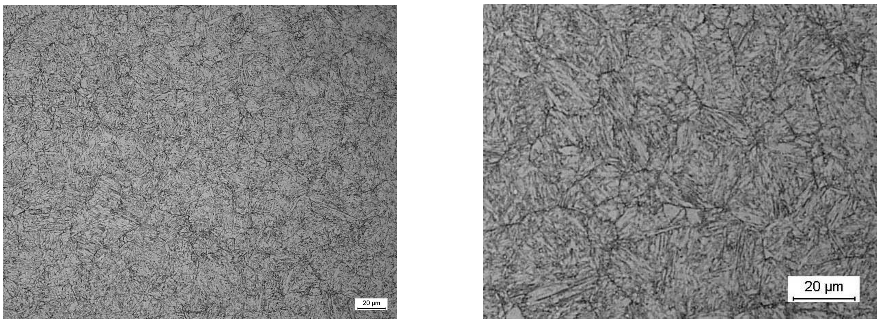
(e) Special C

Figure 1. Annealed microstructure of cross-sections of transverse cuts in the transitional region.



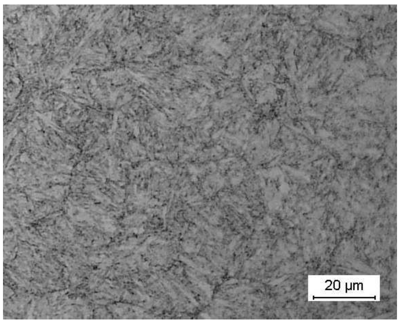
(a) 42 HRC, 1.2343
1010 ℃/ 45 min/ Polymer
620 ℃/ 610 ℃/ 570 ℃

(b) 44 HRC, 1.2367
1030 ℃/ 45 min/ Polymer
640 ℃/ 610 ℃/ 570 ℃



(c) 43 HRC, Special A
1010 ℃/ 45 min/ Polymer
640 ℃/ 580 ℃/ 570 ℃

(d) 42,5 HRC, Special B
1030 ℃/ 45 min/ Polymer
640 ℃/ 580 ℃/ 570 ℃



(e) 44 HRC, Special C , 1000 ℃/ 45 min/ Öl
625 ℃/ 580 ℃/ 570 ℃

Figure 2. Hardened and annealed structure of tested steels with data on heat treatment and final hardness measured HRC.

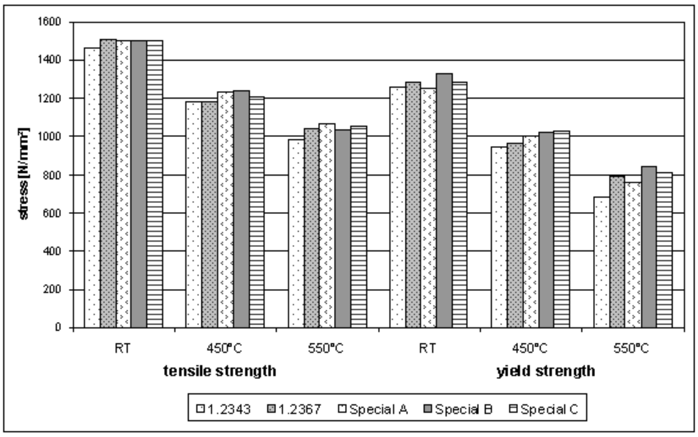


Figure 3. Survey of tensile strength values established in tensile tests at room temperature and at elevated temeratures.

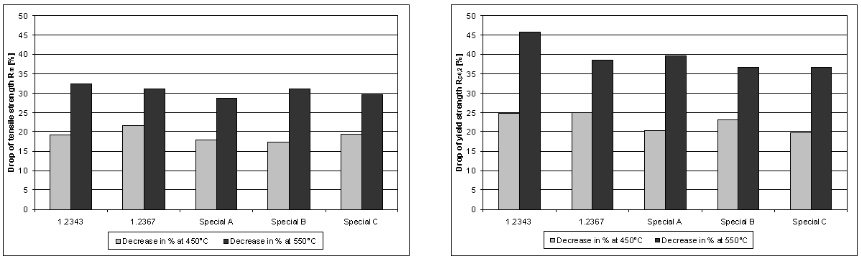


Figure 4. Drop of tensile strength at elevated temperatures as compared to tensil strength at room temperature.

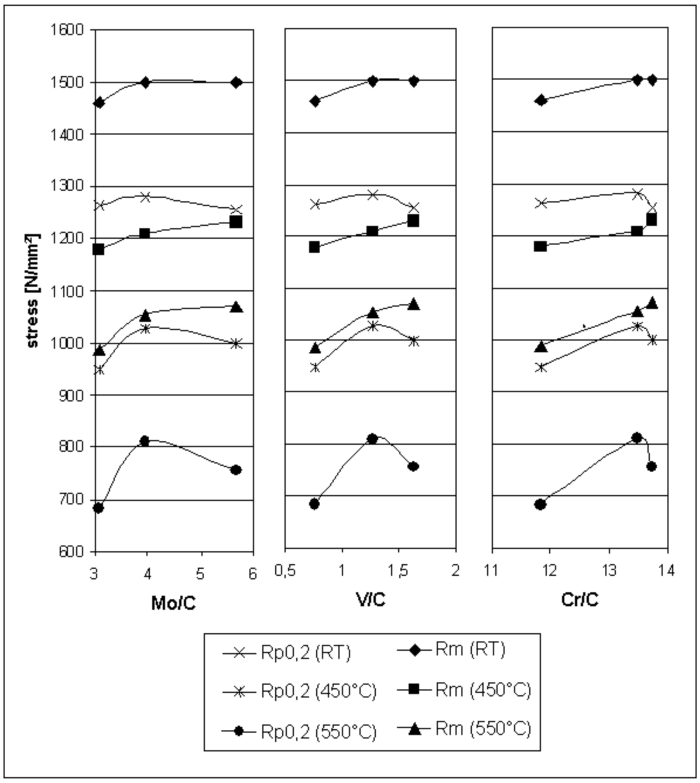


Figure 5. Effect of the ratio of carbide forming elements to carbon on material strength properties, based on steel grade 1.2343.

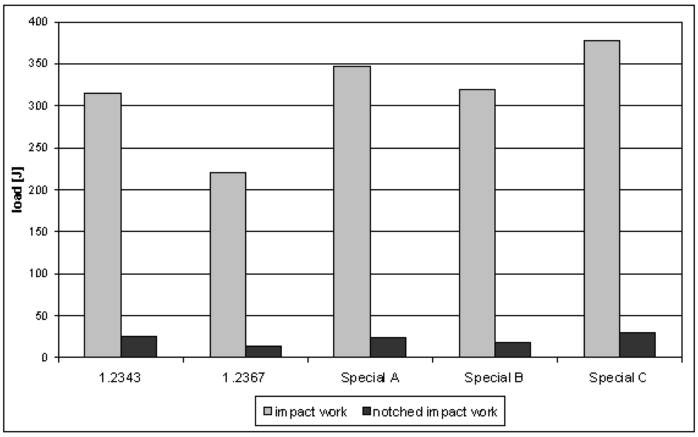


Figure 6. Toughness comparison of tested steels.

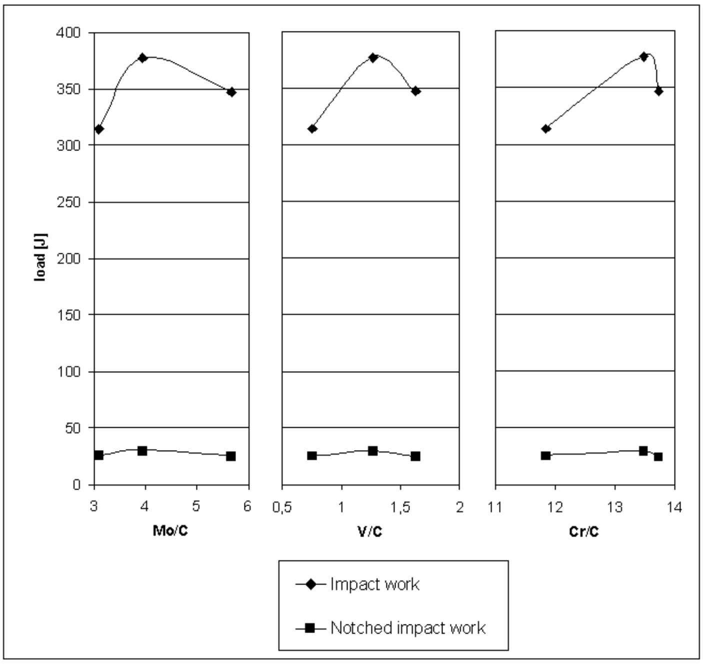


Figure 7. Influence of the ratio of carbide forming elements to carbon on toughness, based on steel grade 1.2343.

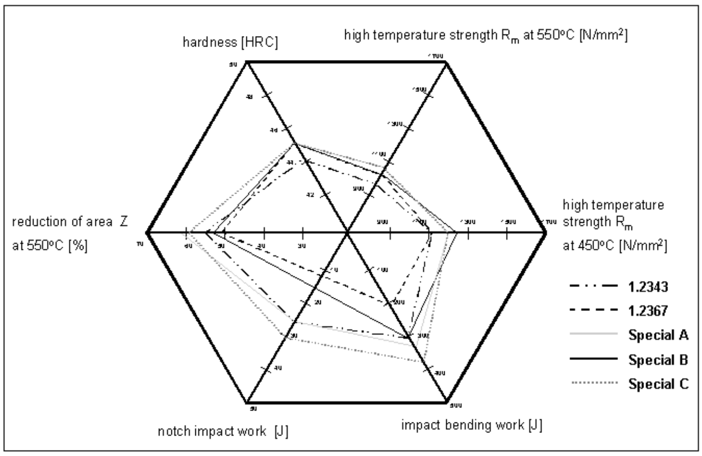


Figure 8. Assessment of the overall properties of tested steels.