Journal
of Achievements in Materials and Manufacturing Engineering

VOLUME 35
ISSUE 2
August
2009

Effect of heat treatment on mechanical properties of H11 tool steel

S.Z. Qamar*
Mechanical and Industrial Engineering Department,
Sultan Qaboos University, Al Khoudh 123, Box 33, Oman
* Corresponding author: E-mail address: sayyad@squ.edu.om

Received 27.01.2009; published in revised form 01.08.2009

Materials

ABSTRACT

Purpose: AISI H11 is a special alloy steel, categorized as chromium tool steel. Because of its high toughness and hardness, it is well suited for hot work applications involving very high loads. Typical applications are hot-work forging and extrusion dies, helicopter rotor blades, etc. For longer life and higher design accuracy, properties of this type of tool steel can be improved by various types of heat treatment. Current work reports and analyzes results of mechanical testing performed on variously heat treated H11 steel samples, to arrive at an optimum heat treatment strategy for hot work applications.

Design/methodology/approach: Tensile and impact test specimens were fabricated using precision milling and EDM. These samples were subjected to various heat treatment sequences, consisting of annealing, hardening, air and oil quenching, and tempering at different temperatures. Heat treated samples were then mechanically tested for hardness (Rockwell), impact toughness (Charpy), and tensile properties (yield strength, ultimate strength, ductility).

Findings: Mechanical testing of H11 samples revealed that with increasing temper temperatures: (a) hardness first increases to a maximum and then gradually decreases; (b) impact toughness first decreases to a minimum and then increases; (c) yield strength first decreases, then increases, and then increases again; (d) ultimate strength first increases to a maximum and then steadily decreases; and (e) ductility (% elongation) gradually decreases till 600ºC, and then increases rather sharply.

Practical implications: Though a very promising candidate for hot-work applications, H11 steel is not commonly used for die and tool making. Results of this study can provide die designers and users in the metalworking industry with good guidelines to select proper heat treatment strategies to use H11 steel for various applications.

Originality/value: Very little information is available in published literature about mechanical properties of H11 steel, especially after different types of heat treatment. Results from this study can fill some of this gap.

Keywords: Tool steel; Heat treatment; Hardening; Quenching; Tempering; Mechanical properties

Reference to this paper should be given in the following way:
S.Z. Qamar, Effect of heat treatment on mechanical properties of H11 tool steel, Journal of Achievements in Materials and Manufacturing Engineering 35/2 (2009) 115-120.

1. Introduction

High-quality steels used to make tools for metal cutting and metal forming operations are known as tool steels. These are usually complex high-alloy steels, containing relatively large amounts of tungsten, molybdenum, vanadium, or chromium. Such alloy contents make these steels suitable for applications requiring high-strength, high-toughness and high-hardness [1].

One of the higher-grade tool steels that can be used in various hot and cold-work manufacturing processes is AISI H11 steel. It has relatively low-carbon and high-chromium contents compared to other tool steels, and is therefore categorized as a hot-work chromium steel (H10-H19 category). The standard composition range is shown in Table 1 [2]. It possesses high toughness, high strength, and good ductility. It is therefore aptly suited for the manufacturing of some special tools, including aircraft landing gears and helicopter rotor blades and shafts [3-5]. It is the highest shear strength tool steel presently available, but is unfortunately near extinction as a hot-work steel [6]. It can be used in high-stress environments such as hot-forging, hot-extrusion, die-casting, etc. During these manufacturing operations, various damage mechanisms act simultaneously to produce cumulative damage to the tool and cause increasing deviations from the original tool geometry due to wear, micro-chipping, heat-checking, or breaking of the tool or a part of the tool [7,8]. For better tool performance, material of the tool must be improved by changing its properties. The two most relevant properties are toughness and hardness; toughness prevents instantaneous fracture of the tool or tool edges [9], and hardness must be sufficiently high to avoid local plastic deformation so that tool geometry remains unchanged [10,11]. Toughness and hardness can be inter-dependent, and a good combination can be achieved by judicious heat treatment [12].

2. Experimental work

Standard tensile and Charpy V-notch impact specimens were made from H11 steel in collaboration with a precision machining facility, using EDM wire cutting and high speed machining. Samples were subjected to different heat treatment sequences: annealing, hardening, air or oil quenching, and single or double tempering at five different temperatures: 450°C, 500°C, 550°C, 600°C, 650°C. Heat treated specimens were mechanically tested for tensile properties, impact toughness, and hardness.

2.1. Heat treatment

Heat treatment was carried out in line with the standard procedure outlined below [13,14]. Three sets of specimens were prepared in this way: (a) air cooled and single tempered, (b) air cooled and double tempered, and (c) oil quenched and double tempered.

Annealing

To remove any preexisting anomalies of material properties, all samples were first subjected to a careful annealing cycle:

- Preheating to 200°C; hold for 15 min.
- Slow (stepwise) heating to 850°C; 200 → 400 → 600 → 850°C; hold for 15 min at each step.
- Holding for 2 hr at 850°C.
- Slow cooling; shutoff furnace and leave samples inside until cooled to 480°C.
- Brisk cooling; open furnace door, cool to room temperature.

Austenitizing (Hardening)

- Heat the furnace to 260°C; load samples into the furnace.
- Slow (stepwise) heating to preheat temperature; 260 → 460 → 660 → 815°C; hold for 15 min at 815°C.
- Slow (stepwise) heating from preheat temperature to austenitizing temperature; 815 → 915 → 1010°C; hold for 30 min at 1010°C.

Quenching

- After holding for 30 minutes, shut off the furnace and open the furnace door to allow the samples to cool inside the furnace until red heat is gone.
- Take out the samples and air-cool to 65˚C in still air.
- In the case of oil quenching, take out the samples which are at the austenitizing temperature, submerge in oil bath, and oil-quench to room temperature.

Tempering

- Set the furnace to the desired tempering temperature; this should be already done while the samples are being quenched.
- Load the samples inside the furnace immediately after they reach 65˚C (or room temperature for oil-quenched samples); hold for 2 hours.
- Remove samples from the furnace and allow them to cool to room temperature in still air.
- For double tempering, cool samples for at least one hour; place them in furnace steadied at the same tempering temperature as before; hold for 2 hr; remove from furnace; air cool to room temperature.

2.2. Mechanical testing

Heat-treated samples (different heat treatment sequences) were tested for various mechanical properties. For hardness testing, oxide layers etc formed during heat treatment were removed by stage-wise grinding. Average *HRC* readings were determined by taking five hardness readings at different positions on the samples, using a digital Rockwell hardness tester. Impact energy (*CVN*) was recorded using the Charpy impact tester. For tensile properties, standard tensile specimens were loaded into a 600-kN universal testing machine hooked up to a data logger. Load-elongation data were recorded and converted into stress-strain graphs. Yield strength (σ_Y), ultimate (tensile) strength (σ_U), and ductility (% elongation) were determined from these graphs, reported values being average of three readings. All testing was done in accordance with ASTM standard test procedures [15-17].

Table 1.
Composition of AISI H11 steel [2]

Element	C	Mn	Si	Cr	Ni	Mo	V	Cu	P	S
Weight %	0.33-0.43	0.20-0.50	0.80-1.20	4.75-5.50	< 0.3	1.10-1.60	0.3-0.6	< 0.25	< 0.03	< 0.03

3. Results and discussion

As described above, samples were subjected to three types of heat treatment sequences: air-cooled and single-tempered (air single), air-cooled and double-tempered (air double), and oil-quenched and double tempered (oil double). Variation of mechanical properties of H11 steel after these heat treatments is presented below in a graphic format. All mechanical testing was performed at room temperature.

3.1. Hardness

Variation of hardness against tempering temperature for each heat treatment sequence (air double, oil double, and air single) is shown in Fig. 1. As tempering temperature increases, hardness first increases to a maximum and then gradually decreases. For all three heat treatments, maximum hardness is obtained for samples tempered at 500°C, highest value being 50 HRC for single-tempered air-cooled specimens. Curves for the three cases are quite close to each other, indicating that difference in heat treatment sequence does not have a significant effect on hardness. It is a general observation for normal steels that hardness decreases with higher tempering temperatures. However, the increasing-decreasing trend seen here for H11 steel is in line with typical behavior of high-strength hot-work tool steels, especially H-category steels [18].

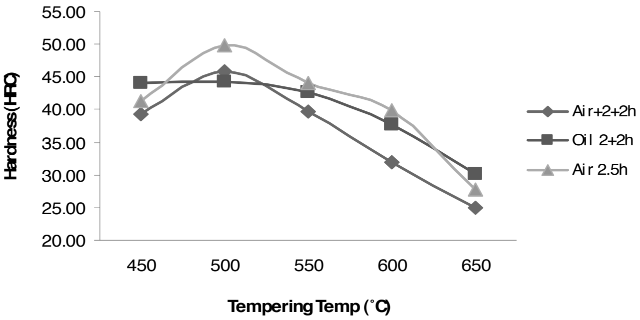

Fig. 1. Variation of hardness against tempering temperature for different heat treatments

3.2. Impact strength

Figure 2 presents the variation of impact strength (*CVN*) against tempering temperature for each heat treatment sequence. With an increase in tempering temperature, impact strength first decreases to a minimum and then increases. Minimum *CVN* occurs for samples tempered between 500°C and 550°C. At lower tempering temperatures, all three curves are quite close to each other, but the difference in impact values for the three sets becomes more significant at higher temper temperatures. Single-tempered air-cooled samples generally exhibit the lowest impact energies. The mirror behavior (as compared with hardness) of decreasing-increasing impact energy is also compatible with general trends observed for H-class tool steels [19]. Decrease of *CVN* values after 600°C for oil quenched samples may be an experimental error, as toughness should increase at higher temper temperatures.

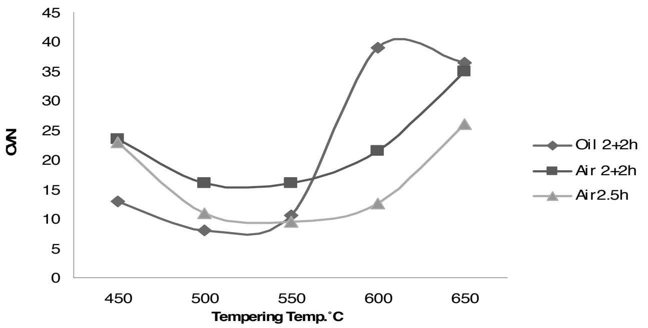

Fig. 2. Variation of impact toughness against tempering temperature for different heat treatments

3.3. Yield strength

Tensile tests were performed on samples subjected to each of the heat treatment sequences: five tempering temperatures for each heat treatment type: air double, oil double, and air single. Stress-strain graphs were plotted for each sample to extract tensile characteristics, Fig. 3 showing a typical curve. Each reported property is an average of three values obtained from graphs of three samples that were similarly heat treated. Figure 4 shows the variation of yield strength (σ_Y) against tempering temperature for the three sets. It is interesting to note that yield strength first decreases (from 450°C to 500°C), then increases (from 500°C to 550°C) before starting to gradually decrease for higher tempering temperatures. Double-tempered oil-quenched samples exhibit the highest yield strengths, followed by double-tempered air-cooled ones. In the medium temper-temperature range, maximum yield strength of 1400 MPa for oil-double samples occurs for tempering at 550°C. Generally, there is a significant effect of heat treatment type on yield strength values, the three curves showing a notable offset from each other.

3.4. Ultimate strength

Graphs demonstrating the variation of ultimate tensile strength (σU) against tempering temperature for the three heat treatment schemes are presented in Fig. 5. Ultimate strength first increases to a maximum and then keeps on decreasing as temper temperature increases. The three curves are almost overlapping each other, indicating that there is only a marginal effect due to the difference in the heat treatment sequence. Maximum tensile strength of about 2100 MPa occurs at tempering of 500°C for the oil-quenched double-tempered samples. It should be noted that ultimate strength variation has almost the same pattern as hardness variation. This confirms that there is an almost direct relationship between hardness and strength, just as for most of the other steels.

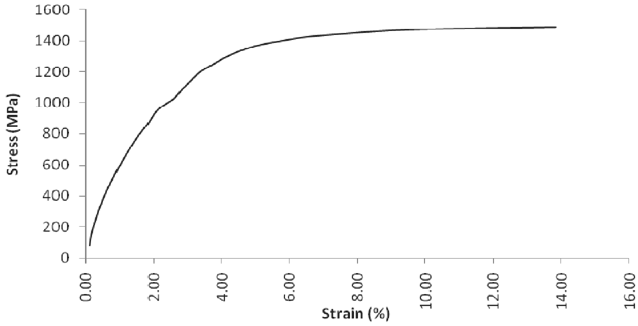

Fig. 3. Stress-strain curve for one of the air-cooled double-tempered samples (Air-Double 600ºC)

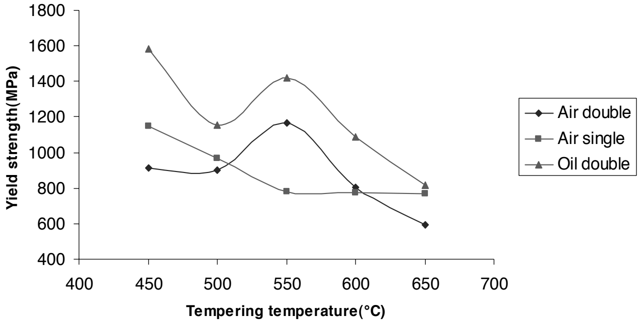

Fig. 4. Variation of yield strength against tempering temperature for different heat treatments

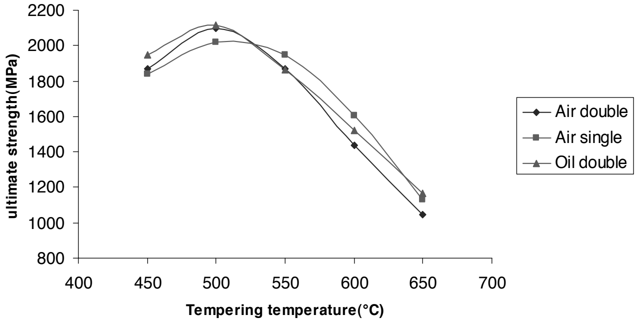

Fig. 5. Variation of ultimate strength against tempering temperature for different heat treatments

3.5. Ductility

Graphs portraying the variation of ductility (represented here as percent elongation) against tempering temperature for each heat treatment sequence are shown in Fig. 6. Ductility steadily decreases as tempering temperature increases up to 600°C, and then starts to increase rather sharply. Lowest ductility value of about 12% is obtained for air-cooled single-tempered samples tempered at 600°C. This decreasing-increasing trend of ductility variation is also typical of tool steels of this class.

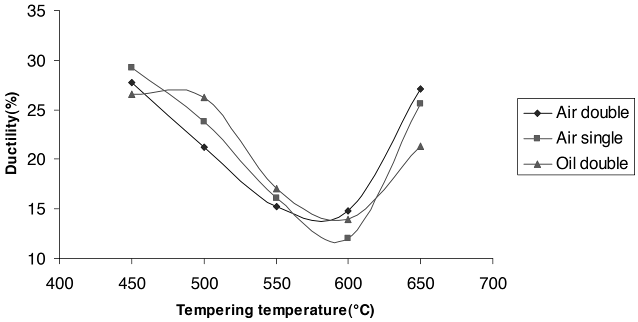

Fig. 6. Variation of ductility against tempering temperature for different heat treatments

3.6. Combined hardness and toughness

As described earlier, H11 steel is suitable for applications where high mechanical and thermal fatigue coexist. A combination of superior hardness (to maintain a high degree of dimensional accuracy) and good toughness (to avoid fracture failure) is therefore a basic requirement. Variation patterns need to be studied very closely to decide what optimum heat treatment strategy should be adopted to yield reasonably high hardness together with good toughness. That is why variation of hardness and toughness with temper temperature is plotted side by side in Fig. 7 for the three heat treatment schemes. As expected, hardness and toughness exhibit a mirror behavior; if the hardness curve is decreasing-increasing, the toughness curve shows an increasing-decreasing pattern.

3.7. Optimum heat treatment strategy

At a cursory glance, the best combination of high-hardness and high-toughness appears to be at the tempering temperature of 600°C for double-tempered oil-quenched samples. However, this tempering would produce the lowest ductility (Fig. 6), leading to the undesirable combination of low formability and possible manufacturing defects such as cracks. Also, tempering at 600°C would lead to very low yield strength (Fig. 4) and ultimate strength (Fig. 5). This can possibly result in excessive plastic deformation leading to die failures such as tongue deflection, shape and dimensional inaccuracy, and wear on the die land [20].

If tempering is done at 550°C, it would produce much higher hardness, highest yield strength, much better tensile strength, and a significant improvement in ductility. Toughness for this tempering would be rather low. However, we should bear in mind that H11 tool steel is best suited for hot metalworking. It is a well-established fact [18,19] that toughness of tool steels increases with increasing working temperatures. The actual toughness of the steel would thus be much higher than the value recorded during room-temperature tests. On the other hand, hardness decreases with increasing operating temperatures. High hardness is therefore much more critical than high toughness in the case of hot-work tool steels. In the light of all of the above observations, the optimum heat treatment strategy for H11 steel appears to oil-quenching and double-tempering at 550°C.

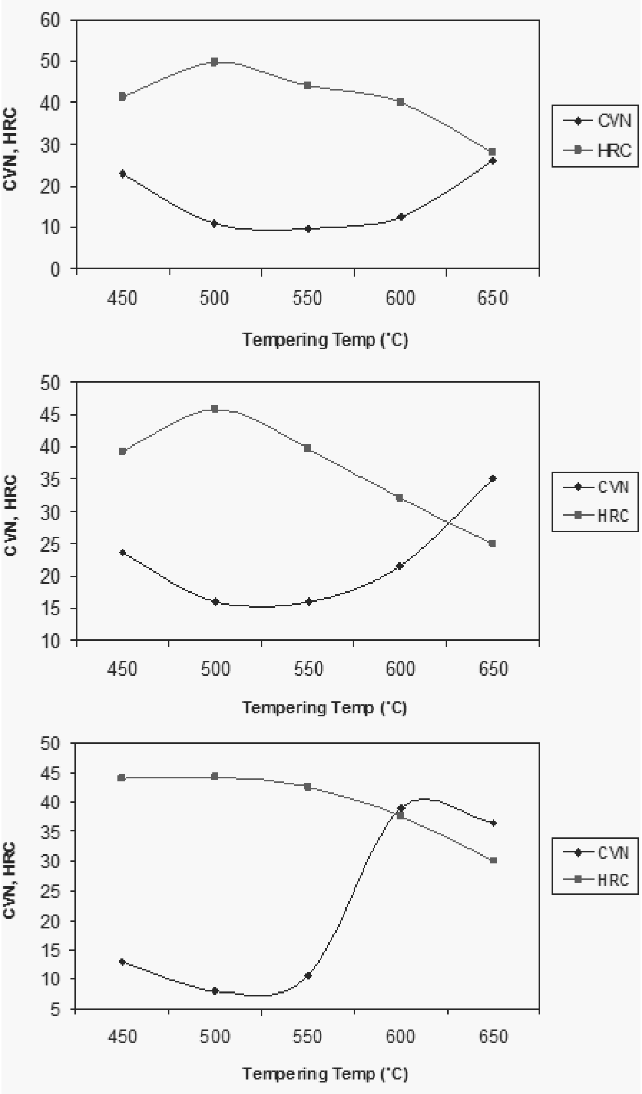

Fig. 7. Variation of toughness and hardness against tempering temperature for the three heat treatments (Air-Cooled, Single Tempering; Air-Cooled, Double Tempering and Oil-Quenched, Double Tempering)

4. Conclusions

H11 is a special high-alloy tool steel, belonging to the hot-work chromium tool-steel category. Because of its good toughness and hardness, it can be used in applications of extreme loads such as hot-work forging, extrusion, and die-casting dies, helicopter rotor blades and shafts, etc. Proper heat treatment of H11 steel can increase the working life of dies and tools, and can yield better dimensional accuracy. Experimental work done for the current study consists of:

- High-precision fabrication of large number of tensile and Charpy impact test specimens from H11 steel.
- Heat treatment of these samples according to various schemes, consisting of annealing, hardening/austenitizing, air and oil quenching, and single and double tempering at different temperatures (450°C, 500°C, 550°C, 600°C, 650°C).
- Room-temperature mechanical testing of heat treated samples for Rockwell hardness (HRC), tensile properties (yield strength, tensile strength, ductility), and impact toughness (CVN).

In line with general behavior of high-strength hot-work tool steels, testing of the H11 samples revealed that with increasing temper temperatures:

- Hardness first increases to a maximum and then gradually decreases.
- Impact toughness first decreases to a minimum and then increases, confirming that hardness and toughness behave in a mirror-opposite fashion.
- Yield strength first decreases, then increases, and then gradually increases again.
- Ultimate (tensile) strength first increases to a maximum and then steadily decreases.
- Ductility (expressed as percent elongation) gradually decreases till 600°C, and then increases rather sharply.

Initially, it looks as if the best combination of hardness and toughness can be achieved by double-tempering at 600°C. However, a more in-depth evaluation of the test results reveals that the optimum heat treatment strategy would be oil-quenching and double-tempering at around 550°C (for a judicious combination of hardness, toughness, yield strength, ultimate strength, and ductility).

References

[1] J. Kaszynski, R. Breitler, How the Steelmaking Process Influences the Properties of Hot Work Die Steels, Technical Paper - Society of Manufacturing Engineers CM02-216 (2002) 1-12.

[2] ASM International, ASM Handbook Volume 1: Properties and Selection - Nonferrous Alloys and Special Purpose Materials, 10th edition, American Society for Metals, Metals Park, Ohio, 1990.

[3] J.R. Davis ASM Specialty Handbook: Tool Materials, ASM International, Materials Park, Ohio, 1995.

[4] G.A. Roberts, G. Krauss, . Kennedy, Tool Steels, 5th edition, American Society for Metals, Metals Park, Ohio, 1998.

[5] J. Szumera, The Tool Steel Guide, Industrial Press, New York, 2003.

[6] W.E. Bryson, Heat Treatment, Selection, and Application of Tool Steels, 2nd edition, Hanser Gardner Publications, Cincinati, 2005.

[7] B. Fnides, M.A. Yallese, H. Aouici, Hard Turning of Hot Work Steel AISI H11: Evaluation of Cutting Pressures, Resulting Force and Temperature, Mechanic 72/4 (2008) 59-63.

[8] Da Klobčar, Ja Tušek, Bb Taljat, Thermal Fatigue of Materials for Die-Casting Tooling, Materials Science and Engineering A 472 (2008) 198-207.

[9] G. Cornacchia, M. Gelfi, M. Faccoli, R. Roberti, Influence of Aging on Microstructure and Toughness of Die-Casting Die Steels, International Journal of Microstructure and Materials Properties 3 (2008) 195-205.

[10] M. Pellizzari, M. Zadra, A. Molinari, Tribological Properties of Surface Engineered Hot Work Tool Steel for Aluminum Extrusion Dies, Surface Engineering 23/3 (2007) 165-168.

[11] Oa Barrau, Ca Boher, Rb Gras, Fa Rezai-Aria, Analysis of the Friction and Wear Behavior of Hot Work Tool Steel for Forging, Wear 255 (2003) 1444-1454.

[12] D. Nolan, V. Leskovsek, M. Jenko, Estimation of Fracture Toughness of Nitride Compound Layers on Tool Steel by Application of Vickers Indentation Method, Surface and Coating Technology 201 (2006) 182-188.

[13] GE Totten (ed) Steel Heat Treatment Handbook; Vol 1: Metallurgy and Technologies; Vol 2: Equipment and Process Design, 2nd edition, 2007, CRC Press, Boca Raton.

[14] ASM International, ASM Handbook Volume 4: Heat Treating, American Society for Metals, Metals Park, Ohio, 1991.

[15] ASTM E18, Standard Test Method for Rockwell Hardness of Metallic Materials, American Society of Testing and Materials, 2008.

[16] ASTM E23, Standard Test Method for Notched Bar Impact Testing of Metallic Materials, American Society of Testing and Materials, 2007.

[17] ASTM E8, Standard Test Method for Tension Testing of Metallic Materials, American Society of Testing and Materials, 2008.

[18] S.Z. Qamar, A.K. Sheikh, A.F.M Arif, A CVN-KIC Correlation for H13 Tool Steels, International Journal of Materials and Product Technology 33/4 (2008) 421-432.

[19] S.Z. Qamar, A.K. Sheikh, A.F.M Arif, T. Parif, Regression-Based CVN-KIC Models for Hot Work Tool Steels, Materials Science and Engineering A 430 (2006) 208-215.

[20] A.F.M. Arif, A.K. Sheikh, S.Z. Qamar, K.M. al-Fuhaid, A Study of Die Failure Mechanisms in Aluminum Extrusion, Journal of Materials Processing Technology 134/3 (2003) 318-328.