

The standard processing window of alloyed ADI materials

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Abstract

In present paper the effect of austempering conditions and alloying elements on the microstructure, mechanical properties and processing window of Cu and Cu + Ni alloyed austempered ductile irons has been studied. A new concept of “standard” processing window was suggested as an alternative to the well-known “microstructure” processing window. This concept is based on the ability to achieve mechanical properties required by different standards, namely ASTM, ISO and EN. The results obtained show that alloying with Cu + Ni produced ductile grades of ADI, while alloying with Cu grades of higher strength. The standard processing window depends on the austempering parameters and alloying elements, as well as standard used. The ISO and EN standards give a larger standard processing window compared to the ASTM. It was also shown, that from the engineering point of view, determination of a standard processing window gives great advantage compared to the microstructure processing window where special methods and procedures have to be used.

Key words: austempered ductile iron, microstructure, mechanical properties, standard processing window

1. Introduction

In recent years, there has been great interest in the processing and developing of austempered ductile irons (ADI). ADI materials possess a unique microstructure of ausferrite, produced by the heat treatment (austempering) of ductile irons. The ausferrite is a mixture of ausferritic ferrite and carbon enriched retained austenite [1, 2]. Due to this unique microstructure, the ADI materials have remarkable combination of high strength, ductility and toughness together with good wear, fatigue resistance and machinability [3]. Consequently, ADI materials are used increasingly in many wear resistant and tough engineering components in different sectors including automotive, trucks, construction, earthmoving, agricultural, railway and military [4].

It is well established by several authors [1, 2, 4] that during the austempering, the ADI undergoes a two stage transformation process. In the first stage, the austenite (γ) transforms into mixture of ausfer-

ritic ferrite (α) and carbon enriched retained austenite (γ_{HC}), a product named – ausferrite. If the casting is held at the austempering temperature too long, then the carbon enriched retained austenite (γ_{HC}) further decomposes into ferrite (α) and carbides [1]. The occurrence of carbides in the microstructure makes the material brittle and therefore, that reaction should be avoided [5]. Hence, the optimum mechanical properties of ADI material can be achieved upon completion of the first reaction, but before the second reaction starts, i.e. inside processing window.

Previous studies have shown that alloying elements influenced the isothermal temperature and the initiation time and completion of the austempering reaction, and thereby affording a larger processing window and ease off control of the reaction. The influence of copper and nickel is of interest in this respect. Copper delays nucleation of ferrite plates around graphite nodules and favours formation of plate-like morphology [6]. Furthermore, Cu suppresses the formation of carbides in the microstructure [7]. Presence of nickel

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Table 1. Chemical composition of as-cast material (mass %)

Material	C	Si	Mn	Cu	Ni	Mg	P	S
DI Cu	3.64	2.49	0.30	0.46	–	0.066	0.014	0.014
DI Cu + Ni	3.48	2.19	0.26	1.57	1.51	0.060	0.020	0.012

reduces the transformation speed and lowers the temperature of the isothermal reaction [8]. The synergetic effect of Cu and Ni on suppressing the nucleation and early growth of ferrite plates and thus expanding the time for isothermal reaction is especially important [8].

The quantitative determination of a processing window has attracted great interest in previous years [2, 4, 9–13]. The best known criterion of processing window determination is that proposed by Elliott and Bayati [2, 13]. The beginning of the processing window represents a point when the unreacted austenite volume decreases to 3 % (value obtained using quantitative metallography), while the end of window is correlated to a decrease of reacted (carbon enriched) retained austenite volume (V_γ) to 90 % of its maximum (where V_γ was determined by X-ray diffraction). The processing window determined in this way might be called a "microstructure" processing window, as it is defined by microstructural features. Mechanical properties of ADI material produced in microstructure processing window have to satisfy ASTM A897M:1990 standard. However, there are three ADI standards used currently worldwide: ASTM A897M-06 (first edition from 1990), EN 1564:1997 and ISO 17804:2005 [14]. As those standards vary in some details regarding the number of grades and minimal requirements of ultimate tensile strength and elongation for different grades, so the processing window will differ and depend on the standard used. Therefore, the processing window defined in this way might be referred to as "standard" processing window. This concept of a standard processing window is of great importance for manufacturing engineering, since it determines the possibility for production of high-quality ADI materials in large amounts by utilizing the most cost-efficient austempering parameters.

In view of this, the influence of Cu and Ni on the microstructure, mechanical properties and processing window has been studied and the standard processing window according to ASTM, EN and ISO standards established.

2. Experimental procedure

Chemical composition of the ductile irons (DI) alloyed with Cu and Cu + Ni in as-cast condition is given in Table 1. Selected alloys have been produced

in commercial foundry and cast into the standard 25.4 mm (1 inch) Y block sand moulds. The samples for mechanical testing were machined from the lower parts of Y blocks in order to avoid any segregation or porosity. After machining, the samples were heat treated to produce an ADI material. The samples were austenitized at 900 °C for 2 h in a protective atmosphere of argon and then rapidly quenched in a salt bath at an austempering temperature of 300, 350 and 400 °C and held for 1, 2, 3, 4 and 6 h.

Conventional metallographic preparation technique (mechanical grinding and polishing followed by etching with nital) was applied prior to light microscopy (LM) examinations of samples cut from Charpy impact specimens. For microstructural characterization, a "Leitz-Orthoplan" metallographic microscope was used, while fractured surfaces were studied on JEOL JSM 6460LV scanning electron microscope operated at 25 kV. The volume fraction of retained austenite (V_γ) in ADI material was determined by the X-ray diffraction technique using "Siemens D 500" diffractometer with nickel filtered Cu $K\alpha$ radiation. For all samples, mechanical properties, namely: tensile properties (R_m – ultimate tensile strength, $R_{p0.2\%}$ – proof strength, A_5 – elongation, EN 10002), impact energy (K_0 – unnotched samples, EN 10045) and Vickers hardness (HV10, ISO 6507) were determined.

3. Results and discussion

3.1. As-cast material

The light micrographs of the ductile iron microstructure, polished and etched, are given in Figs. 1 and 2, respectively. The spheroidization of graphite in all specimens was more than 90 %, with average graphite volume fraction of 11 %, nodule size of 40 to 55 μm and nodule count of 50 to 80 per mm^2 (Fig. 1). The as-cast microstructure of ductile iron alloyed with Cu was main pearlitic with up to 10 % of ferrite (Fig. 2a), whereas ductile iron alloyed with Cu + Ni was fully pearlitic (Fig. 2b).

The mechanical properties of as-cast material are given in Table 2. The pearlitic matrix had the most significant influence on mechanical properties resulting in higher strength of ductile iron (DI) Cu + Ni over DI alloyed only with Cu, as microstructure of DI Cu + Ni is fully pearlitic. The as-cast microstruc-

Table 2. Mechanical properties of as-cast material

Material	R_m (MPa)	$R_{p0.2\%}$ (MPa)	A_5 (%)	K_0 (J)	HV10	EN 1563:1997
DI Cu	770	514	4.9	21.4	270	EN-GJS-700-2
DI Cu + Ni	880	677	3.2	20.5	296	EN-GJS-800-2

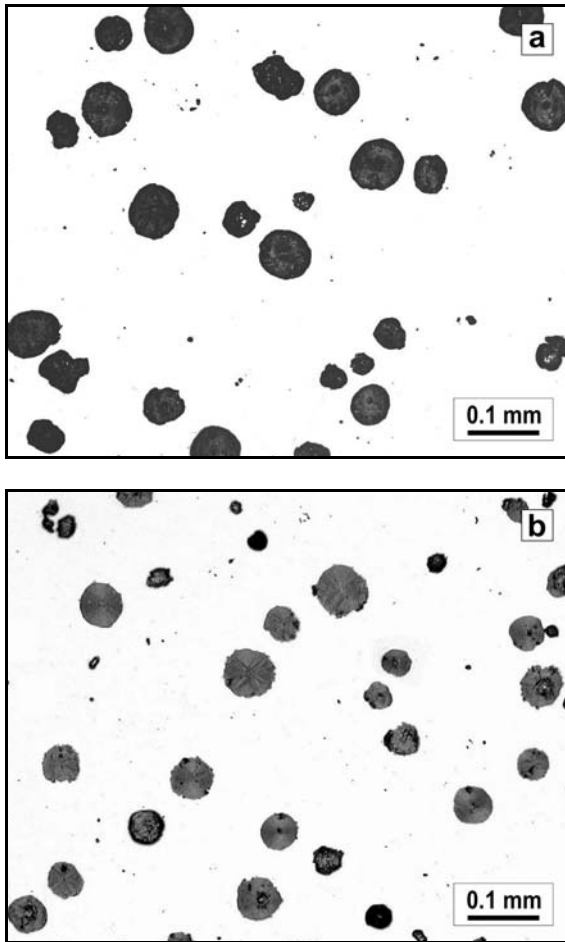


Fig. 1. Microstructure of ductile iron (polished surface):
a) DI Cu, b) DI Cu + Ni.

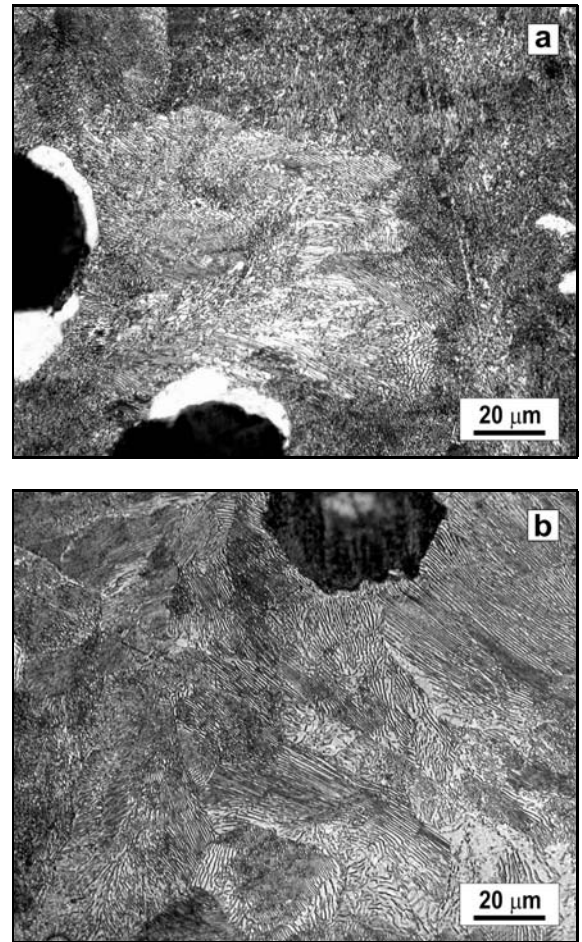


Fig. 2. Microstructure of ductile iron (etched surface):
a) DI Cu, b) DI Cu + Ni.

ture influences the fracture mode of ductile irons. The ductile iron alloyed with Cu has a transgranular brittle fracture with small amount of ductile fracture around graphite nodules (Fig. 3a). The ductile regions are correlated with the presence of ferrite in amount less than 10 %. In case of ductile iron alloyed with Cu and Ni, the fracture surface is fully brittle (Fig. 3b), corresponding to fully pearlitic matrix microstructure.

3.2 Microstructure of ADI

The influence of austempering temperature on microstructure morphology of ADI material alloyed with Cu is shown in Fig. 4. The microstructure is fully aus-

ferritic consisting of mixture of ausferritic ferrite and carbon enriched retained austenite. However, increasing the transformation temperature changes the ausferritic morphology, from needle-like (Fig. 4a) to more plate-like (Fig. 4c). At lower temperatures, undercooling is larger leading to a slow diffusion rate of carbon [15]. Consequently, nucleation of ferrite plates is favourable, while their growth is delayed. In these conditions, the resultant microstructure consists of a fine but dense ferrite plates of acicular morphology [8, 15]. At higher austempering temperatures the carbon diffusion rate is higher and faster, promoting growth of ferrite plates, which will be larger and coarse in nature [8, 16]. These microstructure differences at lower and

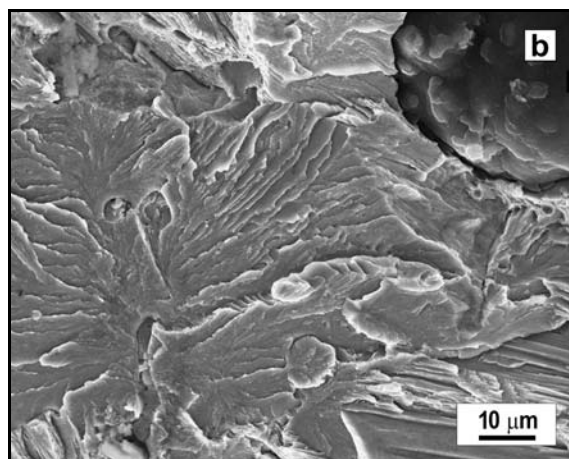
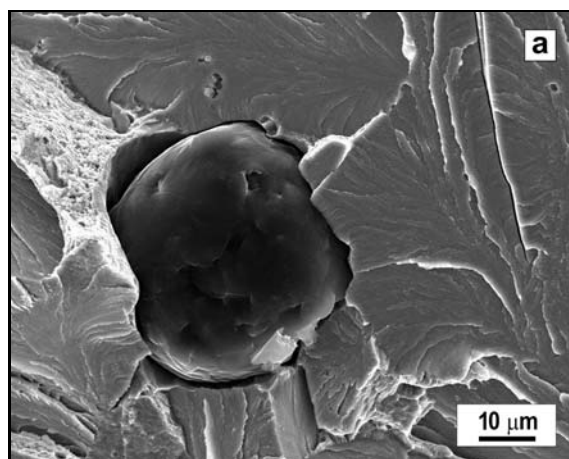


Fig. 3. Fracture mode of ductile iron: a) DI Cu, b) DI Cu + Ni.

higher austempering temperatures are clearly visible in Fig. 4a to 4c.

The time of transformation also has great influence on ausferrite microstructure (Fig. 5). The saturation of austenite with carbon is insufficient at short austempering time and lower temperature. Hence, austenite is not stabilized and its transformation to martensite upon cooling to room temperature occurs [12]. In the case of ADI alloyed with Cu, martensite was observed only after austempering at 300 °C for 1 h (Fig. 5a). The longer time and higher temperature of austempering promote the start of stage II of isothermal reaction resulting in decomposition of carbon enriched retained austenite (γ_{HC}) into ferrite (α) and carbides (i.e. bainite) [4]. This kind of behaviour for ADI Cu is observed at austempering temperature of 400 °C for 4 and 6 h of transformation (Fig. 5b). The absence of austenite for these austempering parameters was confirmed by X-ray measurements of retained austenite volume fraction (V_γ), Table 3.

The influence of austempering temperature on aus-

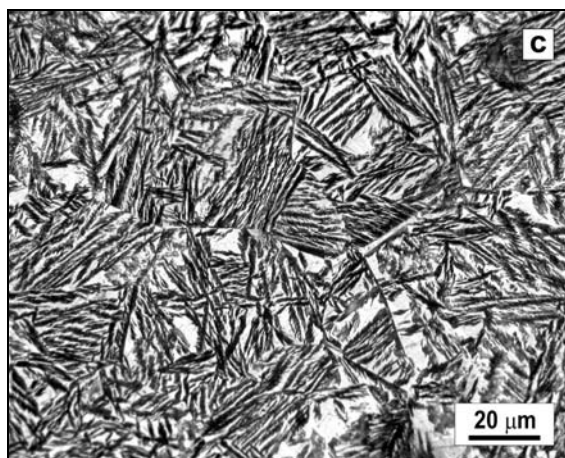
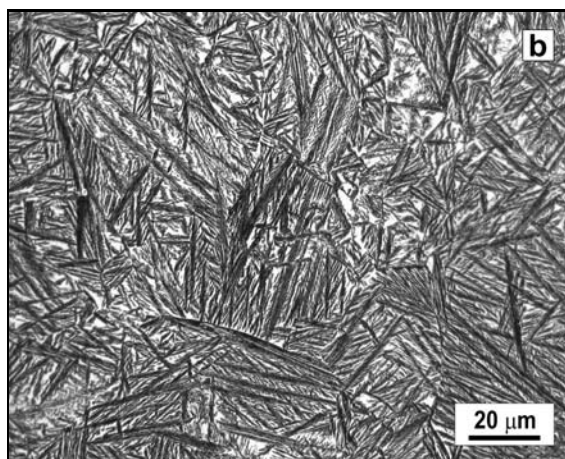
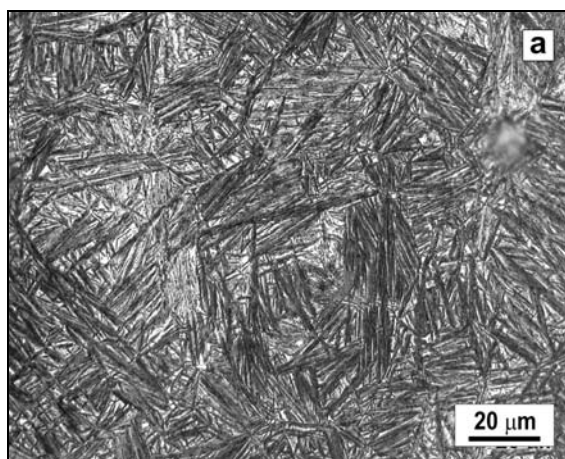


Fig. 4. Influence of austempering temperature on microstructure of ADI Cu: a) 300 °C/2 h – fine needles of acicular ausferrite, b) 350 °C/2 h – acicular ausferrite, c) 400 °C/2 h – plate-like morphology of ausferrite.

ferrite morphology of ADI alloyed with Cu + Ni (Fig. 6) is similar to the case of ADI alloyed with Cu. Increase in temperature of austempering change the acicular morphology of ausferritic ferrite at 300 °C (Fig. 6a) to plate-like appearance at 350 °C (Fig. 6b),

Table 3. Mechanical properties of ADI alloyed with Cu

Austempering										
Temp. (°C)	Time (h)	R_m (MPa)	$R_{p0.2\%}$ (MPa)	A_5 (%)	K_0 (J)	HV10	V_γ (%)	ASTM A897M-06	EN 1564:1997	ISO 17804:2005
300	1	1427	1315	1.4 ^A	52.6	452	6.8	–	EN-GJS-1400-1	JS/1400-1
	2	1428	1346	3.4	59.7	451	7.1	1400/1100/02	EN-GJS-1400-1	JS/1400-1
	3	1445	1342	3.7	76.9	378	11.0	1400/1100/02	EN-GJS-1400-1	JS/1400-1
	4	1481	1391	3.1	71.5	406	8.7	1400/1100/02	EN-GJS-1400-1	JS/1400-1
	6	1412	1345	2.7	69.4	436	8.7	1400/1100/02	EN-GJS-1400-1	JS/1400-1
350	1	1158	1026	4.7 ^{AEI}	85.6	402	13.9	–	–	–
	2	1112	998	7.9	106.1	373	16.6	1050/750/07	EN-GJS-1000-5	JS/1050-6
	3	1109	993	7.1	105.1	350	16.4	1050/750/07	EN-GJS-1000-5	JS/1050-6
	4	1205	1121	5.9	100.8	391	12.3	1200/850/04	EN-GJS-1000-5	JS/1200-3
	6	1160	1066	5.3 ^{AI}	91.6	420	11.8	–	EN-GJS-1000-5	–
400	1	977	760	6.3 ^{AEI}	86.3 ^A	345	14.9	–	–	–
	2	984	834	7.1 ^{AEI}	89.4 ^A	344	15.5	–	–	–
	3	987	820	6.2 ^{AEI}	56.5 ^A	327	13.7	–	–	–
	4	1007	804	4.5 ^{AEI}	23.0 ^A	332	0.0	–	–	–
	6	1019	884	2.0 ^{AEI}	20.4 ^A	364	0.0	–	–	–

^A mechanical property is below minimal value required by standard ASTM A897M-06

^E mechanical property is below minimal value required by standard EN 1564:1997

^I mechanical property is below minimal value required by standard ISO 17804:2005

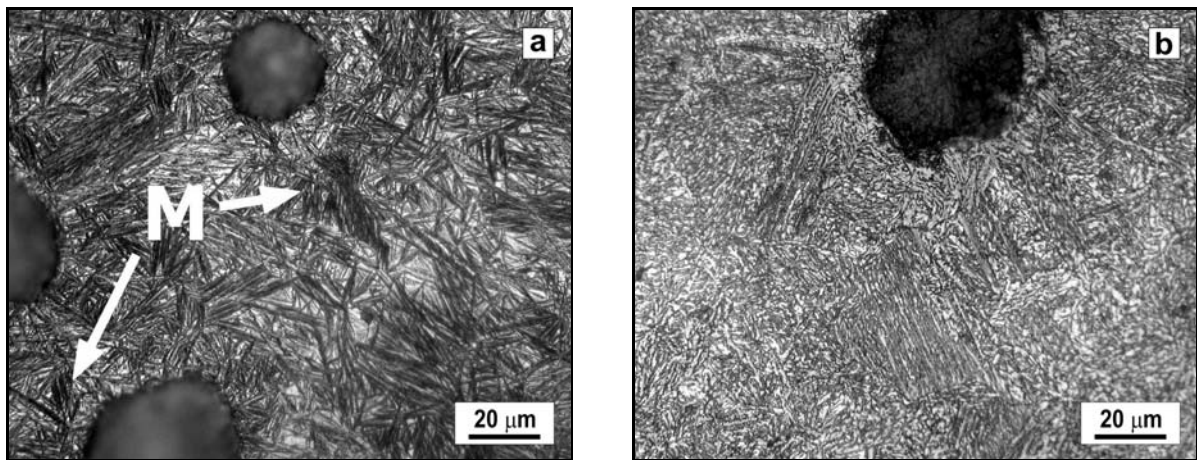


Fig. 5. Influence of austempering time on microstructure of ADI Cu: a) 300°C/1 h – occurrence of martensite (M) in ausferrite, b) 400°C/4 h – bainite: ferrite and carbides.

and finally to coarse ausferrite morphology at 400°C (Fig. 6c).

However, if the microstructure morphology of ADI Cu + Ni and ADI Cu is compared side by side, it might be seen that ADI Cu + Ni at the same austempering temperature has shorter, wider and more space apart ausferritic ferrite plates than ADI Cu. This morphology change is due to alloying elements. The synergetic effect of Cu and Ni manifests itself by suppressing ferritic plates nucleation [8] and in lowering the temperature of isothermal transformation [11, 16]. Furthermore, alloying austempered ductile iron with Cu + Ni

delays the transformation kinetics of austenite [10, 17], shifting the maximum of retained austenite to longer times [18].

The austempering time was sufficient to stabilize the austenite at all temperatures for ADI Cu + Ni, as martensite was not observed. The time has a larger influence on morphology of ausferrite in case of ADI Cu + Ni compared to ADI Cu, since Cu and Ni promotes carbon diffusion during longer times and hence produces a plate-like appearance of ausferrite [19]. This morphology change is visible in Fig. 7a,b. The decomposition of ausferrite to ferrite and carbides (i.e. bain-

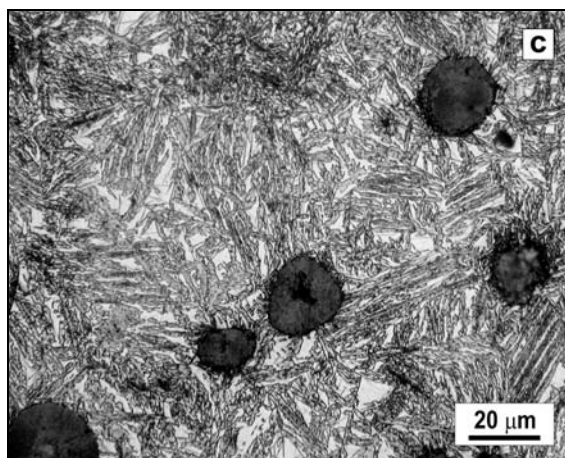
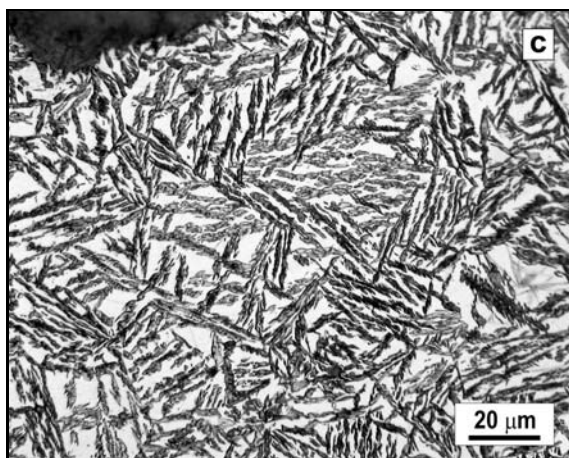
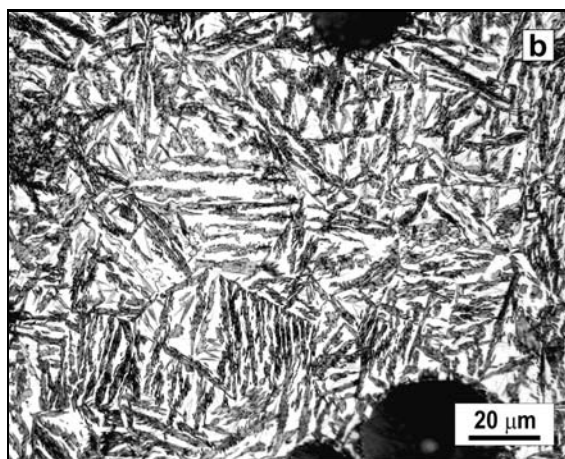
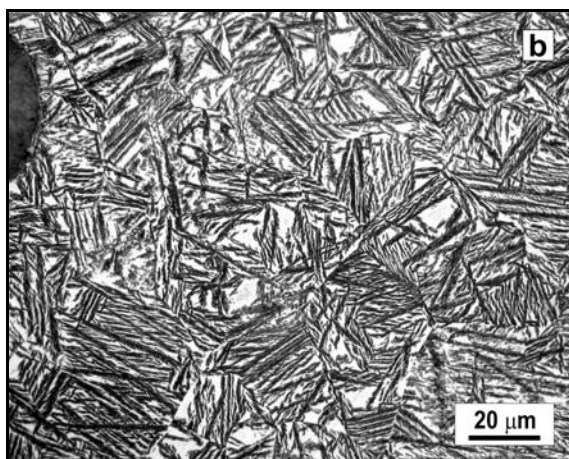
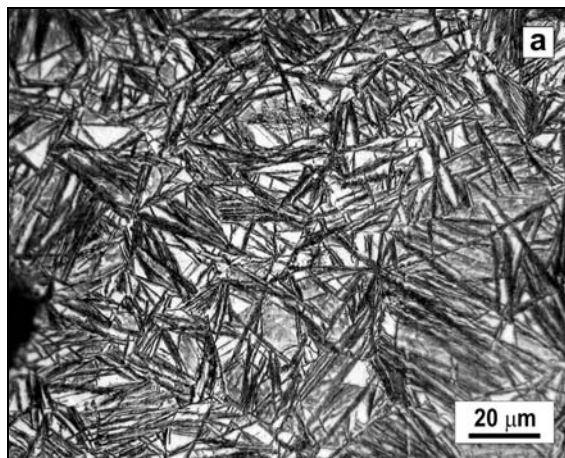
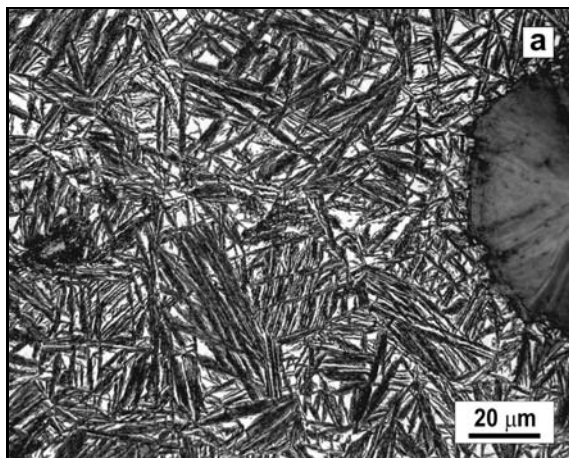


Fig. 6. Influence of austempering temperature on microstructure of ADI Cu + Ni: a) 300°C/3 h – acicular ausferrite, b) 350°C/3 h – plate-like morphology of ausferrite, c) 400°C/3 h – coarse plate-like morphology of ausferrite.

Fig. 7. Influence of austempering time on microstructure of ADI Cu + Ni: a) 350°C/1 h – acicular ausferrite, b) 350°C/6 h – plate-like morphology of ausferrite, c) 400°C/6 h – some carbon enriched retained austenite start to decompose into ferrite and carbides (bainite).

ite) was observed at longer austempering time and higher temperature (400°C/6 h), Fig. 7c. Again, compared to ADI Cu where the appearance of bainite is observed at 400°C/4 h, the presence of Cu and Ni delayed decomposition to longer time (6 h).

3.3. Retained austenite

The volume fraction of retained austenite (V_{γ}) for ADI alloyed with Cu and Cu + Ni is given in

Table 4. Mechanical properties of ADI alloyed with Cu + Ni

Austempering										
Temp. (°C)	Time (h)	R_m (MPa)	$R_{p0.2\%}$ (MPa)	A_5 (%)	K_0 (J)	HV10	V_γ (%)	ASTM A897M-06	EN 1564:1997	ISO 17804:2005
300	1	1390	1180	3.5 ^A	52.6 ^A	454	8.4	–	EN-GJS-1200-2	JS/1200-3
	2	1354	1176	4.5	59.7 ^A	414	10.8	–	EN-GJS-1200-2	JS/1200-3
	3	1369	1159	5.5	76.9	384	16.3	1200/850/04	EN-GJS-1200-2	JS/1200-3
	4	1375	1182	5.6	71.5	424	16.0	1200/850/04	EN-GJS-1200-2	JS/1200-3
	6	1325	1205	3.4 ^A	69.4	462	7.0	–	EN-GJS-1200-2	JS/1200-3
350	1	1111	824	5.4 ^{AI}	46.1 ^A	415	6.6	–	EN-GJS-1000-5	–
	2	1109	931	10.0	90.2 ^{AI}	383	14.9	1050/750/07	EN-GJS-1000-5	JS/1050-6
	3	1070	901	11.1	122.1	308	18.9	1050/750/07	EN-GJS-1000-5	JS/1050-6
	4	1043	892	10.1	106.1	351	15.2	900/650/09	EN-GJS-1000-5	JS/900-8
	6	1042	822	6.1 ^{AI}	50.3 ^A	380	14.2	–	EN-GJS-1000-5	–
400	1	973	642 ^A	10.6	100.2	308	19.7	–	EN-GJS-800-8	JS/900-8
	2	989	708	10.9	94.3 ^A	322	19.9	–	EN-GJS-800-8	JS/900-8
	3	950	677	7.7 ^{AEI}	82.5 ^A	344	15.9	–	–	–
	4	986	723	7.1 ^{AEI}	78.4 ^A	361	15.3	–	–	–
	6	959	695	5.6 ^{AEI}	57.8 ^A	438	3.5	–	–	–

^A mechanical property is below minimal value required by standard ASTM A897M-06

^E mechanical property is below minimal value required by standard EN 1564:1997

^I mechanical property is below minimal value required by standard ISO 17804:2005

Tables 3 and 4, respectively. The two ADI materials have the same trend of the retained austenite volume change with austempering time and temperature. With the increase of austempering time, the value of retained austenite first increases to a maximum (or plateau) after which it gradually decreases. This trend is clearly connected with the two stage transformation process. During short austempering times, the first stage of the transformation is not fully complete and a maximum of retained austenite is not achieved yet. Upon the completion of stage I, the retained austenite volume reaches a maximum. After that, the second stage begins and the retained austenite decreases as it starts to decompose into ferrite and carbides. The influence of austempering temperature is also evident in the increases of retained austenite volume fraction when temperature rises. At higher austempering temperature the diffusion of carbon is increased, growth of ausferritic ferrite plates is more favourable than nucleation and the resulting microstructure is coarse and more plate-like [8]. In these conditions, the higher volume of austenite can be enriched with carbon and stabilized, resulting in overall increase of retained austenite volume fraction (V_γ). Moreover, alloying austempered ductile iron with Cu + Ni delays the transformation kinetics of austenite [17], shifts the maximum of retained austenite to longer times [10] and promotes the increase of retained austenite volume fraction (V_γ) by lowering the transformation temperature (Table 4, V_γ).

3.4. Mechanical properties of ADI

The results of tensile, impact and hardness testing of ADIs, together with retained austenite volume fraction (V_γ) are given in Tables 3 and 4, for ADI alloyed with Cu and ADI alloyed with Cu + Ni, respectively.

The tensile strength (R_m) and the proof strength ($R_{p0.2\%}$) exhibit similar behaviour for ADI alloyed with Cu and for ADI alloyed with Cu + Ni. The highest values of strength are obtained at lower austempering temperatures, while strength decreases with further increase of austempering temperature. On the other hand, the change of austempering time (in given time interval from 1 to 6 h) has no significant influence on strength. From this kind of behaviour, it might be considered that ausferrite morphology (which changes with temperature) is a primary factor influencing strength, while amount of retained austenite (which changes with temperature and time) does not have a crucial influence. The higher strength can be correlated with a fine acicular appearance of ausferrite produced at lower austempering temperatures, while lower strengths are correlated with plate-like, coarse morphology. The addition of alloying elements influences strength through the influence on morphology of ausferrite. The Cu and Ni lower the transformation temperature, enabling more plate-like morphology of ausferrite and hence give ADIs of lower strength compared to ADI alloyed only with Cu (Tables 3 and 4).

The value of elongation, hardness and impact en-

ergy depend on austempering temperature, but also on austempering time (Tables 3 and 4). Furthermore, their values can be correlated with the change of amount of retained austenite. With the increase of retained austenite volume fraction, the elongation and impact energy increase up to the maximum or to the plateau. After that, with the further decrease of retained austenite volume fraction, elongation and impact energy decrease as well. Hardness has an opposite trend. The lowest hardness values are correlated with the maximum values of retained austenite, and vice versa. At short austempering times, martensite may form in the microstructure [20], while at longer times carbides are formed [5]. The presence of martensite or carbides in the microstructure, gives rise to brittleness of ADI materials, which in turn reduces elongation and impact energy, and increase hardness. Furthermore, values of elongation, impact energy and hardness are influenced by ausferrite morphology. The fine acicular appearance of ausferrite improves ductility, i.e. elongation and impact energy, while coarse morphology reduces ductility [21]. Morphology is influenced by alloying elements, hence the correlation between mechanical properties and austempering parameters is very complex and characteristic for any given ADI material.

3.5. Fracture mode of ADI

The characteristic fracture surfaces of un-notched impact specimens are shown in Figs. 8 and 9 for ADI alloyed with Cu and ADI alloyed with Cu + Ni, respectively. For both types of ADIs a three distinctive modes of fracture may be distinguished: i) fully ductile fracture, ii) mix-mode fracture, and iii) brittle fracture. Furthermore, the fracture mode might be correlated with values of impact test, i.e. to the retained austenite volume fraction and ausferrite morphology.

The fully ductile fracture with characteristic dimples is associated with higher austempering temperatures and high values of retained austenite (Figs. 8a and 9a). The mix mode of fracture is observed for specimens austempered at lower temperatures which have a reduced content of the retained austenite (Figs. 8b and 9b). The amount of brittle fracture, produced by quasi-cleavage mechanism, in those cases increases with the decrease of retained austenite. Especially negative effect on fracture mode, according to Sidjanin et al. [5], has a presence of carbides formed during stage II when ausferrite microstructure is transformed into mixture of ferrite and carbides, i.e. bainite. The fracture becomes fully brittle produced by quasi-cleavage mechanism (Figs. 8c and 9c). Comparing the fracture mode of two ADIs, a somewhat higher number of dimples is observed in the Cu + Ni alloy which are associated with the higher values of ductility (elongation and impact energy) and retained austenite

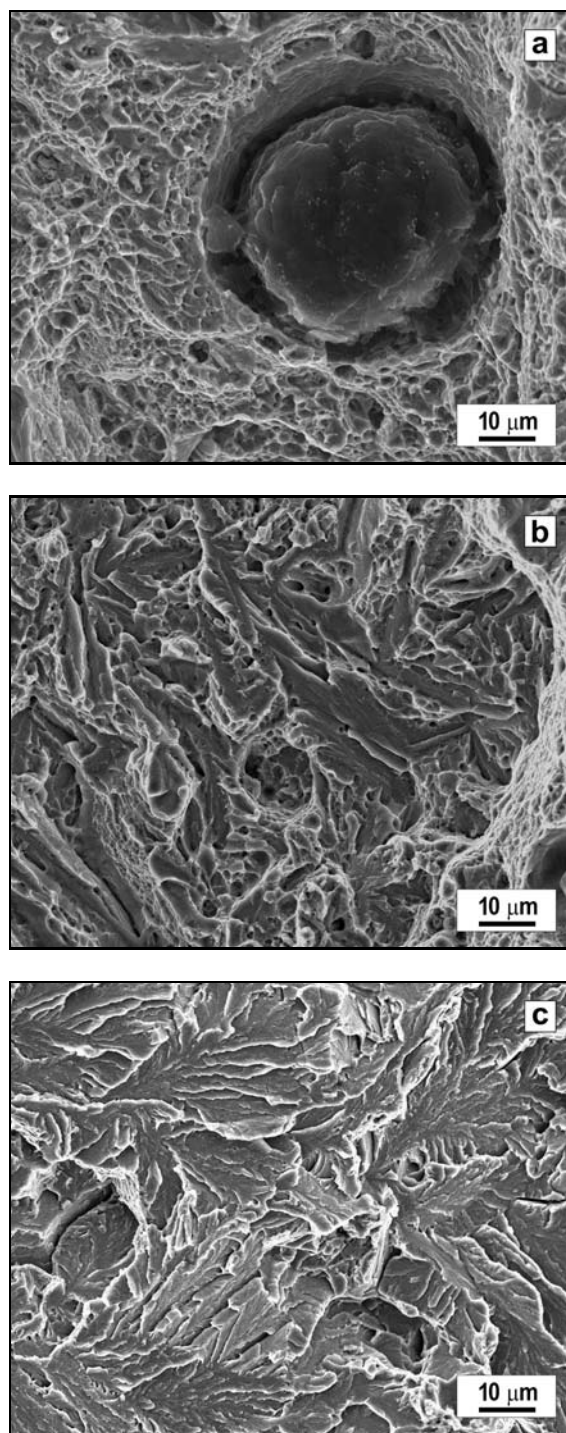


Fig. 8. Fracture mode of ADI Cu: a) 350°C/2 h – ductile fracture, b) 300°C/3 h – mix mode fracture, c) 400°C/4 h – brittle fracture.

volume fraction [22].

3.6. Standard processing window

The standard processing window was determined by comparing obtained mechanical properties with re-

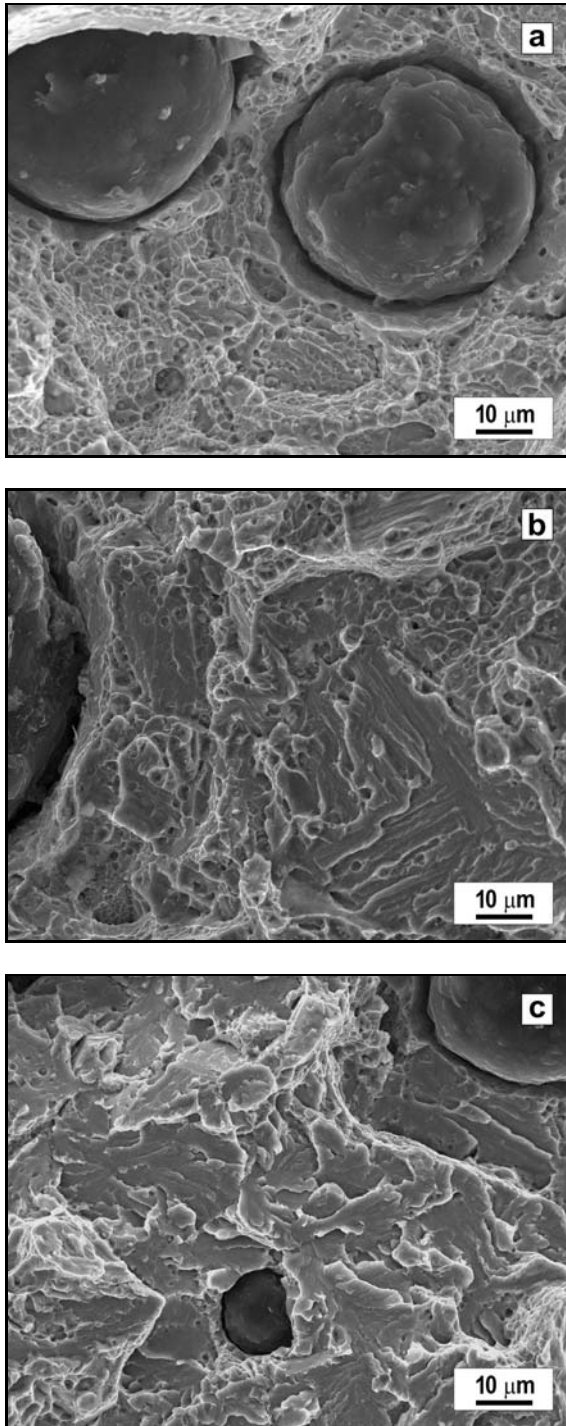


Fig. 9. Fracture mode of ADI Cu + Ni: a) 350°C/3 h – ductile fracture, b) 300°C/2 h – mix mode fracture, c) 400°C/6 h – brittle fracture.

quired minimal values given by the standard ASTM A897M-06, EN 1564:1997 and ISO 17804:2005 (Tables 3 and 4).

From given tables it can be noticed that alloying ductile iron with Cu and Cu + Ni influences the mechanical properties (grades of ADI), and therefore

the standard processing window. The standard grades of ADI Cu + Ni have a greater ductility, but lower strength. In addition, the standard processing window is in that case larger. The ADI Cu has a narrower processing window and standard grades are of higher strength and lower ductility.

When comparing standard processing windows defined by different standards (Tables 3 and 4) it can be observed that the processing window is narrower for the ASTM standard, as it requires higher values of mechanical properties, especially ductility. On the other hand, the EN and ISO standard provides larger processing windows, as the mechanical properties requirements are not so severe.

Overall, it might be asked: which standard should be used and which processing window is optimal? From a practical point of view, the EN standard and corresponding processing window are most favourable, as they provide the largest processing window and the required grades are easily achieved after short austempering times, resulting in production of quality ADI materials through the most cost-efficient austempering parameters. However, if high performance parts are required, then a processing window determined by ASTM standard should be used. For example (Table 4), to produce EN-GJS-1200-2 or ISO JS/1200-3 grade from the Cu + Ni alloyed ductile iron it is only necessary to hold part for 1 h at 300°C, while for similar ASTM 1200/850/04 grade it is necessary to hold it for 3 h at the same temperature.

As the primary goal in production is to achieve the required mechanical properties a determination of the standard processing window is more efficient than the microstructure processing window which can be costly in time and money because of the very sophisticated methods and procedures used. Furthermore, as microstructure processing window is based on the ASTM which is the most rigorous, so the microstructure requirements are most restricting, as well. If another standard is used (EN, ISO, or some other) as basis for determining the processing window, then another microstructure requirements have to be used. This also implies that EN and ISO grades could be achieved outside microstructure processing window as defined by Elliott and Bayati [2, 13].

The use of the standard processing window does not mean that the microstructure can be totally discarded, but only suggests that processing window is not a narrow or uniquely defined as microstructure only approach proposes.

At the end, it should be pointed out that mechanical properties of ADIs are only achieved through the adequate microstructure, which is in turn a function of chemical composition and austempering parameters, and that microstructure needs to be closely controlled.

4. Conclusions

The results obtained show that the processing window depends on the austempering parameters and alloying elements, as well as the appropriate standard. The EN and ISO standards give a larger standard processing window compared to ASTM standard.

The standard grades of ADI alloyed with Cu can be produced in following standard processing windows: for ASTM from 2 to 6 h at 300 °C and from 2 to 4 h at 350 °C; for EN from 1 to 6 h at 300 °C and from 2 to 6 h at 350 °C; for ISO from 1 to 6 h at 300 °C and from 2 to 4 h at 350 °C. At 400 °C, the processing window is closed for all standards. On the other hand, the standard processing windows for ADI alloyed with Cu + Ni are: for ASTM from 3 to 4 h at 300 °C and from 2 to 4 h at 350 °C, while at 400 °C window is closed; for EN from 1 to 6 h at 300 °C, from 1 to 6 h at 350 °C and from 1 to 2 h at 400 °C; for ISO from 1 to 6 h at 300 °C, from 2 to 4 h at 350 °C and from 1 to 2 h at 400 °C.

Alloying ductile iron with Cu + Ni produces grades of ADI that are more ductile, while alloying with Cu provides grades of higher strength.

From a production engineering approach, determination of standard processing window, suggested in this paper, has great advantage compared to microstructure processing window where the special methods and procedures have to be used. In addition, microstructure requirements do not need to be identical for different standards.

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