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Investigations on the impact strength of constructional high-strength Weldox steel at lowered temperature

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ABSTRACT

Purpose: The paper presents the results of investigations concerning the impact strength of thick steel plates at lowered temperature obtained by industrial smelting of micro-alloyed steel of the type S1100QL (Weldox 1100) and S1300QL (Weldox 1300) with a yield strength of 1100-1300 MPa.

Design/methodology/approach: The main methods used for these researches were the impact test Charpy V at lower temperatures, and metallographic observations. The tested samples at lower temperature have also been analyzed fractographically.

Findings: The influence of the chemical composition and technology of production on the structure and mechanical properties of the investigated kinds of steels have been determined, as well as their ductility temperature of transition into the brittle state.

Research limitations/implications: A large dispersion of intermetallic precipitated phases restricted considerably the possibility of their metallographic identification. This latter one will be done in the next stage of basic investigations.

Practical implications: A wide range of practical applications of Weldox 1100 and Weldox 1300 sheet plates is warranted by both their high impact strength, especially at lower temperatures, and lower ductility transition temperature.

Originality/value: It has been found that the degree of refinement of the martensitic structure and dispersion of secondary precipitations, mainly carbides and niobium nitrocarbides affect considerably the change of the impact strength within the investigated range of temperature from ambient temperature to minus 150°C.

Keywords: Metallic alloys; High strength micro-alloyed steel; Mechanical properties; Notched impact toughness; Ductility transition temperature.

PROPERTIES

1. Introduction

Structures of high dimensions like, drilling-rig platforms, bridges, containers, hulls, cranes and others, operating in changing load conditions and at low temperatures, require the application of new kinds of steel with a high yield strength, a possibly low ductility transition temperature (T_t) to the brittle state, a good technological weldability, as well as reasonable costs [1-4]. These properties are characteristic for the more and more generally used constructional micro-alloyed steels containing up to 0.25% wt. carbon, about 1.5% wt. manganese and microadditions of Nb, V, Ti and B, known as high strength low alloy (HSLA) or high strengthening steels (HSS) [5-7]. The growing requirements result in the introduction of new kinds of steel sheets of the type S1100QL (Weldox 1100) and S1300QL (Weldox 1300) with a yield strength in the range of 1100-1300MPa [8].

Simultaneously with the implementation of new metallurgical technologies of steel and the thermo-mechanical treatment, permitting to obtain final products in the form of high-strength tubes and plates without reducing their plastic properties, particularly at lower temperatures, new technologies and welding materials are applied [9-13]. An increase of the strength of fine-grained micro-alloyed Weldox steels depends on the effect of the structural mechanism of strengthening, particularly solution strengthening of intersticially alloying elements, the adjustment of the grain size, precipitation strengthening of dispersive secondary phases and phase transformation [14-15]. The size reduction of the grains in these steels ensures the formation of fine nuclei of crystallization in the metallurgical process as well as further changes in the presence of nitrides or carbonitrides (ALN, VN, V(CN), as applied for instance in the case of specially killed fine-grained steel [16].

The effect of microadditions in solid state steels depends on their state in the given conditions of the thermo-mechanical treatment. Dispersive particles of the interstitial phases of nitrides or carbo-nitrides precipitated on dislocations and grain boundary hamper the motion of the grain boundary of recrystallized austenite, slow down the recovery or dynamic recrystallization in the course of hot plastic deformation. After the completion of hot plastic deformation they hamper the rate of statical or metadynamical recrystallization. Thus, they permit to obtain products with a fine-grained structure and ensure an intensive precipitation strengthening of the steel.

The contribution of the respective metallic microadditions in the strengthening of Weldox steel and a depression of the ductility transition temperature in the brittle state is not equivalent, although they constitute with carbon and nitrogen isomorphic interstitial MX phases. Various phases of this type differ in their temperature stability, so that they require the accommodation of the thermo-mechanical treatment to the temperature stability of these phases and kinetics of their dissolution (or precipitation) in austenite. Depending on the availability of elements and destination of the steel several micro-additives are introduced, ensuring the required sequence of precipitation of MX phases, which restrict the growth of the austenite grain within the range of temperature of plastic treatment.

The achievement of high-strength properties of Weldox steel with a good toughness at lower temperature depends, therefore, not only on the introduction of the respective micro-additives into the basic steel, but also in the accommodation of the parameters of the thermo-mechanical treatment, particularly the temperature of hot plastic deformation to the kind and stability of the obtained interstitial MX phases due to the introduction of micro-additives [17].

Thus, the aim of the investigations is to determine the influence of the chemical composition and technology of production on the structure, as well as the mechanical properties of thick steel plates of constructional microalloyed types Weldox 1100 and Weldox 1300, and, what is most important, to assess their resistance to brittle fracture by determining their transition temperature during the impact Charpy-V test.

2. Experimental procedure

Investigations were carried out on high-resistant microalloy constructional Weldox steels, type S1100QL and S1300QL, resulting from industrial smelting in the Swedish firm SSAB (Oxelösund). The chemical composition of the investigated steels is to be seen in Table 1.

The provided samples consisted of steel sheet chaffs with a thickness of 10 mm (Weldox 1100) and 8 mm (Weldox 1300). The steel sheets had been hot-rolled by means of the AccuRollTech ensuring precise dimensional tolerances [8]. The mechanical properties were determined applying static tensile test measurements of the hardness and impact test at low temperature from $20^{o}C$ to $-150^{o}C$.

Static tensile tests were carried out on a testing machine Instron 1115 in the load range up to 400kN. For this purpose flat samples, sized 10x25x90 mm were used (Weldox 1100), taken from steel sheet transversal to the direction of rolling, as well as rod-shaped samples with a diameter of 7 mm and length of 50 mm, cut out from steel sheets parallelly and perpendicularly to the rolling direction.

The ductility temperature of transition into the brittle state was determined basing on impact tests making use of Charpy's method, applying standard samples (10x10x55 mm) (Weldox 1100) and notched samples type U2 size 10x7.5x55 mm (Weldox 1300). The impact test was carried out on of Charpy pendulum machine type Psd 300/150, using a container for freezing the samples in a solution of liquid nitrogen with ethyl alcohol. Lower freezing temperatures were achieved in a mixture of liquid nitrogen with kerosene ether.

Microscopic examinations of Weldox steels were performed on longitudinal microsections, mechanically ground and chemically etched in 5% solution of nitrogen acid in ethyl alcohol. Metallographic observations of the structure and nonmetallic inclusions were performed in a metallographic microscope Leica MEF 4A, with a magnification of 1000x.

Fractographic tests of the fracture after the impact test were carried out in a scanning electron microscope DSM 940 produced by Opton with a resolving power of 100A at a voltage of 62 kV in the range of magnification of up to 2000 times.

3. Experimental results and discussion

The structures of the investigated Weldox steels in their delivery state after thermo-mechanical treatment have been presented on micro-photographs (Fig 1 and 2). Weldox 1100 displayed a homogeneous finally dispersed needle-shaped tempered lathy martensite structure (Fig.1) with a hardness of about 44 HRC. Observations of the structure of Weldox 1300 proved that in the cross-section of the steel sheet there occurs a homogeneous martensitic - bainitic structure with trace amounts of ferritic grains (Fig.2)

Table 1.
Chemical composition of the investigated Weldox steels

Grade of steel	Chemical composition in mass %														
	C	Si	Mn	P_{max}	S_{max}	B	Nb	Cr	V	Cu	Ti	Al	Mo	Ni	N
S1100QL	0.21	0.5	1.4	0.02	0.005	0.005	0.04	0.8	0.08	0.1	0.02	0.02	0.7	3.0	0.01
S1300QL	0.22	0.22	0.91	0.006	0.005	0.005	0.03	0.48	0.19	0.08	0.03	0.05	0.37	1.25	0.01

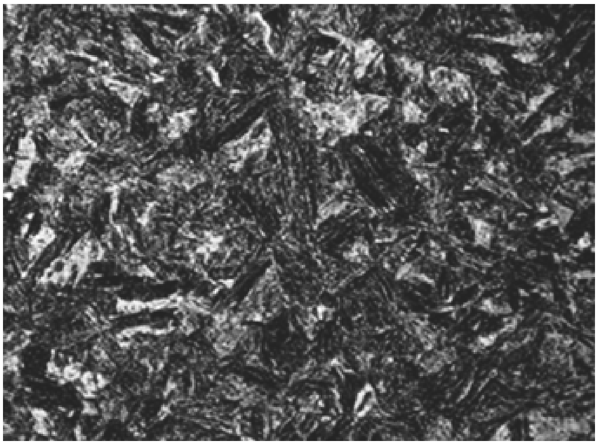

Fig. 1. Tempered martensite structure of Weldox 1100 steel in the delivered state; Etching Nital; Mag. 1000x

Fig. 2. Martensitic-bainitic structure of Weldox 1300 steel in the delivered state; Etching Nital; Mag. 1000x

It has been found that the micro-hardness of martensitic-bainitic regions amounts to 380-447 $HV_{0,02}$ and of the ferritic grains to about 90 $HV_{0,02}$. Weldox steel 1300 displays also a small amount of non-metallic spot inclusions, mainly oxides and non-deformable globular silicates with low standard indices.

The results of mechanical investigations of Weldox 1100 and Weldox 1300 steels have been gathered in Tables 2 and 3. It has been found that Weldox 1100 displays a high strength R_m of about 1400 MPa with a satisfactory plasticity (A about 10%) and hardness (about 44HRC) (Table 2).

Table 2.
Mechanical properties of Weldox 1100 steel

Kind of sample	Mechanical properties					
	$\overline{R}_{p0,2}$ MPa	$\overline{R}_m$ MPa	$\overline{A}$ %	$\overline{Z}$ %	$\overline{HB}$	$\overline{KCV}_{+20}$ J/cm^2
TD	1125	1410	10.3	36.4	430	208

TD - samples cut out from steel sheet transversal to rolling direction (RD)

Weldox 1300 is also characterized by good mechanical properties, independent of the kind of samples, oriented longitudinaly or transversely to the rolling direction (RD) of the sheets (Table 3). The coefficient of mechanical anisotropy of the investigated steel amounts to about 0,99 at a hardness of the steel sheet about 48 HRC.

Table 3.
Mechanical properties of Weldox 1300 steel

Kind of sample	Mechanical properties					
	$\overline{R}_{p0,2}$ MPa	$\overline{R}_m$ MPa	$\overline{A}_5$ %	$\overline{Z}$ %	$\overline{HRC}$	$\overline{KCU2}_{+20}$ J/cm^2
RD (rolling direction)	1369	1505	15	63	48.5	139
TD (transversal direction)	1363	1493	12	55		

RD-samples cutting out longways (lengthwise) to RD

The high strength properties of the investigated steels result from the fine-dispersive structure formed in metallurgical processes and the thermo-mechanical treatment. The final structural state of the analyzed steels and their mechanical properties result from the proper choice of micro-alloy additions and properly chosen parameters of thermo-mechanical treatment, viz. the heating temperature for the rolling of steels (ca, 1200°C), the scheme of rolling and the final temperature of this operation (about 950°C), as well as the accelerated rate of cooling after rolling from 870 °C to ambient temperature.

The results of the investigations on the impact strength of both kinds of Weldox steel at temperatures of 20°C to -150°C have been gathered in Table 4 and 5 and in Figs. 3 and 4. It has been found that the investigated kinds of Weldox steel are characterized by high values of impact strength both at room temperature and lower temperatures. It has also been found that the energy absorbed by fracturing and the impact toughness of steel actually decrease with the drop of the testing temperature, but in neither of these cases any distinct sudden transition from ductility to brittleness have been detected.

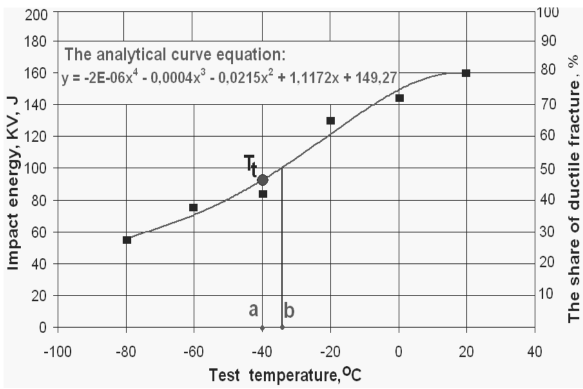

Fig. 3. Determination of the ductility transition temperature of Weldox 1100 steel basing of the inflexion point (a) and 50% of the fraction of ductile fracture (b)

The temperature of transition from the ductile to the brittle state (T_t) of Weldox 1100 determined basing on the criterion of the inflexion point of the curve KCV = f(T) amounts to about -40 °C (Fig.3).

An identical temperature has been confirmed in compliance with the criterion of the constant fraction of impact strength at room temperature, i.e. 50% KV_{20}. However, according to the criterion of 50% ductile fracture it has been found that T_t of the tested steel amounts to about -35°C.

In order to assess the ductility transition temperature of Weldox 1300 the obtained values of absorbed energy in the investigated range of temperature has been expressed analytically by a polynomial function (Fig.4).

Table 4.
Impact strength of Weldox 1100 Steel

N°	Test temperature °C	Impact energy KV, J	Impact value[1] KCV, J/cm²
1	20	167.1	208.2
2	0	137.5	171.7
3	-20	144.5	180.6
4	-40	87	108.8
5	-60	74.8	93.5
6	-80	55.5	70

[1)] samples cutting out transversal to RD

Table 5.
Impact strength of Weldox 1300 Steel

N°	Test temperature °C	Impact energy KU2, J	Impact value[1] KCU2, J/cm²
1	20	83.2	138.7
2	0	74.5	124.3
3	-20	74.7	124.1
4	-40	73.2	122.1
5	-60	72.4	120.3
6	-80	68.2	113.7
7	-120	66.0	109.9
8	-150	62.6	104

[1)] samples cutting out transversal to RD

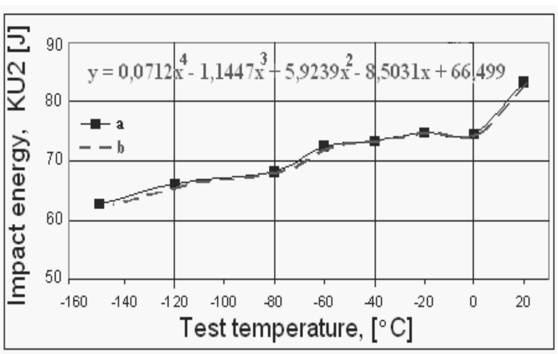

Fig. 4. Impact energy versus the impact strength test temperature of Weldox 1300 steel; a) experimental curve,b) analytical curve

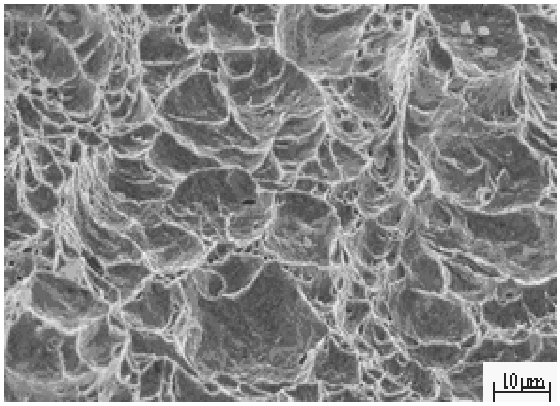

Fig. 5. Transcrystalline ductile fracture of Weldox 1100 steel, impact test temperature: -20ºC, Mag. 1000x

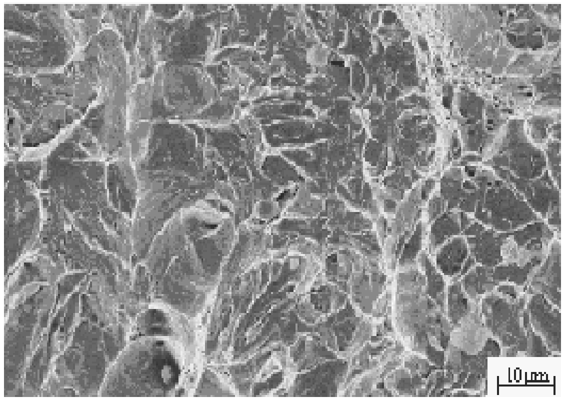

Fig. 6. Mixed fracture of Weldox 1100 steel; transcrystalline cleavage fracture with a share of ductile fractures and small particles of the intermetallic phases, impact test temperature: -40ºC, Mag. 1000x

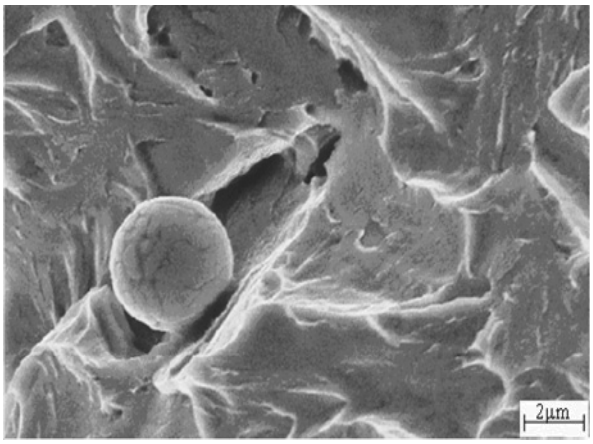

Fig. 7. Transcrystalline cleavage fracture of Weldox 1100 steel with a spherical particle of the intermetallic phase; higher magnification of the cleavage surface shown in Fig.6, impact test temperature: -40ºC, Mag. 5000x

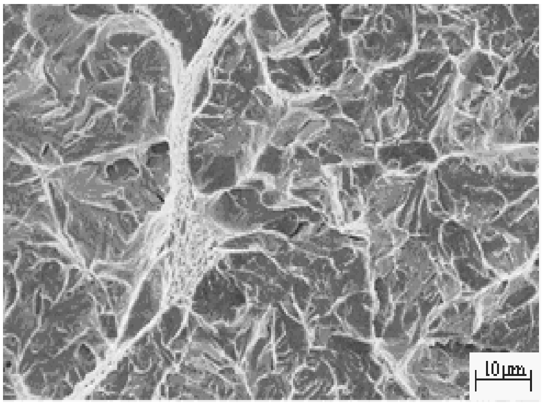

Fig. 8. Transcrystalline cleavage fracture of Weldox 1100 steel with traces of ductile areas, impact test temperature: -60ºC, Mag. 1000x

The correlation index R for the selected function is 0.98. The value of ductility transition temperature of Weldox 1300, assessed basing on the criterion of the flex point of the analytical curve and the fractographical criterion, amounts to about -60 ºC.

The results of fractographic investigations have been presented on microphotos (Figs. 5-11). Transcrystalline ductile fractures could be observed in samples of Weldox 1100 in the impact temperature range of 20ºC to -20ºC (Fig.5). At lower temperatures of -40ºC to -80ºC a transcrystalline cleavage fracture has been detected with traces of ductile surfaces (Figs. 6-8). On the fracture surfaces there are also small spherical particles, probably of calcium aluminate ($CaO-Al_2O_3$) (Figs. 6-7). These particles are probably not plastically deformed during the thermo-mechanical treatment like sulphides (MnS). Due to their size (diameter about 4-5μm), exceeding considerably oxide inclusions, such as Al_2O_3 and nitrides (TiN), they have an harmful effect on the fatigue strength of the material. This effect depends not only on the presence of inclusions but also on their size, shape and coefficient of thermal expansion. It may by supposed that irregular inclusions with sharp edges lead to a larger concentration of stresses than those with a regular shape.

In samples of Weldox 1300 after the impact test within the temperature range of 20ºC to -40ºC transcrystalline ductile fractures with a small share of cleavage fracture are to be observed (Fig.9). At lower temperature, however, transcrystalline mixed fractures with varying plastically deformed areas and areas characteristical for cleavage-brittle fracture do appear.

After the fractures of the samples at -120ºC to -150ºC brittle fracture dominate, with distinct cleavage planes and traces of ductile areas. The cleavage-brittle fracture displays numerous faults in the form of “rivers”, as well as short elevations or cavings called “tongues” [4]. In the craters of plastically deformed areas there are some spherical precipitations of the interstitial phases, probably carbides or nitrocarbides (Figs.10 and 11).

The microfractographic analysis of the investigated steels displayed zones of the material with the most critical state of stress, conditioning the occurrence of brittle fracture surfaces, and thus provided indispensable complementary data for an accurate determination of the transition temperature to the brittle state. The character of fractures over the whole of the temperature range of the impact test confirms the high values of notch impact toughness of the investigated type of steels.

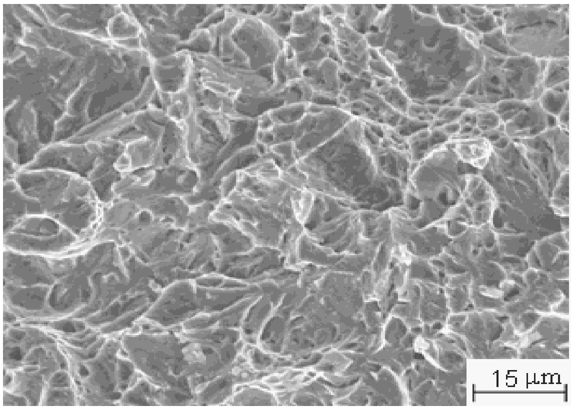

Fig. 9. Transcrystalline ductile fracture of Weldox 1300 steel with a small share of cleavage fracture, impact test temperature: -40ºC, Mag. 1000x

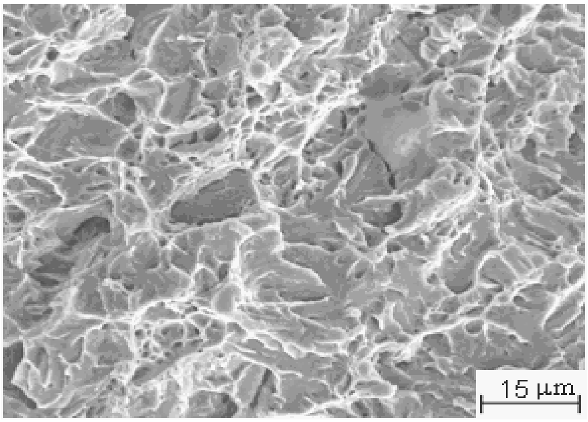

Fig. 10. Transcrystalline mixed fracture of Weldox 1300 steel, with intercrystalline microfractures, impact test temperature: -120ºC, Mag. 1000x

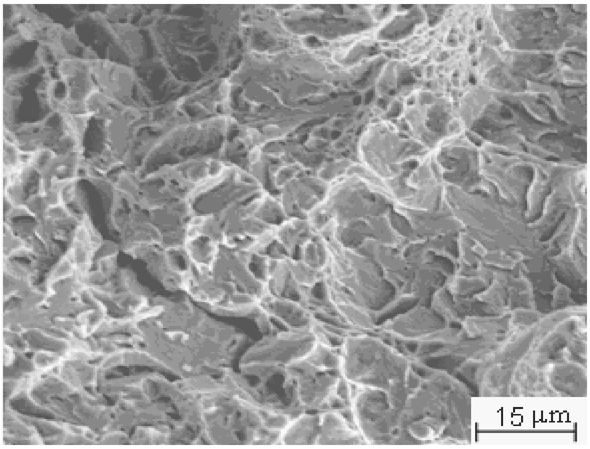

Fig. 11. Mixed fracture of Weldox 1300 steel with a share of ductile surfaces and microfractures at the grain boundaries, impact test temperature: -150ºC, Mag. 1000x

4. Conclusions

The obtained results of investigations lead to the following conclusions:

- Weldox 1100 and Weldox 1300 sheets supplied from industrial processess of thermo-mechanical treatment are characterized by a homogeneous fine-dispersial tempered martensite structure (Weldox 1100) or by martensitic - bainitic structure (Weldox 1300) with a high dispersion of martensite needles and a small share of ferrite grains.
- The obtained structure ensures high strength properties of the investigated steel sheets (R_m ca. 1400-1500 MPa) connected with a satisfactory plasticity (A ca. 10-15%) and favourable mechanical anisotropic index (ca. 0.99).
- The impact toughness of the steel sheets decreases with the test temperature from KCV ca. 210 kJ/cm^2 to about 70 J/cm^2 (Weldox 1100) and KCU2 from ca. 140 J/cm^2 to about 100 J/cm^2 (Weldox 1300), respectively at ambient temperature and lower temperature in the range -80ºC to -150ºC.
- Weldox 1100 sheets display a ductility transition temperature of -20ºC to -40ºC, whereas in the case of Weldox 1300 this temperature amounts to about -60ºC, depending on the assumed criterion of testing.
- The fractographic analysis of the investigated steels revealed, mainly in the craters of ductile areas, the presence of spheroidical precipitations of interstitial phases with a maximum size of about 2 µm requiring a future phase identification.

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