Andalusite : An Attractive Raw Material for its Excellent Thermal Shock Resistance

J. Poirier*,** , M.L. Bouchetou*,** , L. Colombel*,** , P. Hubert***

Andalusite, a natural aluminosilicate mineral provides high thermal shock resistance to refractory products. At high temperature (> 1200 °C), andalusite single crystal grains are transformed into a composite made of a 3:2 mullite single crystal with a capillary network filled with silica rich liquid. Because of the specific microstructure and the presence of the liquid phase, during thermal shocks, the mullitized andalusite crystals exhibit a behaviour typical of composite materials : microcracks are deflected by mullite/glass interfaces and stopped in glass zones. During a further heating, cracks generated by a thermal shock are healed. The composite microstructure of mullitized andalusite crystals seems to be a strong advantage in order to increase thermal shock resistance. It can explain the good behaviour of fired andalusite bricks regarding thermal cycling.

1 Introduction

Andalusite ($Al_2O_3{\cdot}SiO_2$) is a natural raw material that exhibits attractive properties for refractory products : high refractoriness, low thermal conductivity, low thermal expansion, good chemical stability and interesting mechanical properties at high temperatures. The microstructural transformation of andalusite into mullite starts at 1200 °C and leads to a composite mullite-glassy siliceous phase with a unique microstructure that shows excellent thermal shock resistance. This property is a key parameter for many advanced applications where thermal shock resistance is required. In fired refractories, the transformation of andalusite into mullite is achieved in the production furnace and only a very small amount of residual andalusite is detected. In unfired refractories, this transformation occurs partly during the use of the refractory product. The purpose of this paper is to evaluate the thermal shock performance of andalusite and mullitized andalusite raw materials and of andausite based bricks.

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2 Andalusite and its Transformation into a Mullite Glass Composite

During heating, andalusite is converted into 3:2 mullite ($3\ Al_2O_3 \cdot 2\ SiO_2$) and silica rich glass. Complete transformation leads to about 80 % mullite and 20 % glass. Mullitized andalusite grains exhibit specific microstructure characteristics. During heating, the grain shape and the bulk chemistry are retained ; a single crystal grain is converted into a composite made of a 3:2 mullite single crystal with a capillary network filled with glass1 (Fig. 1). Mullite is topotactically oriented in relation with the host crystal with its c axis parallel to the c axis of the initial andalusite [2, 3, 4]. The glass filled capillaries form highly interconnected tubes with diameter in the micrometer range and are elongated along the c axis common to the neo-

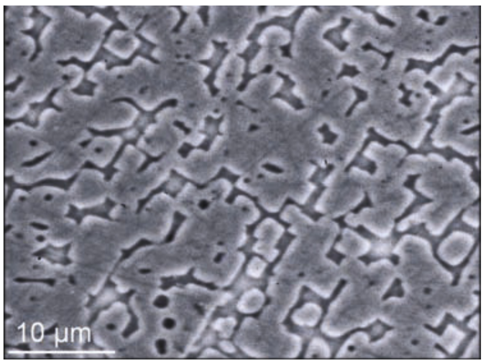

Fig. 1 Mullite-glass composite formed by heating an andalusite crystal at 1600 °C. Backscattered electrons SEM micrograph on polished section approximately parallel to the (001) plane of the initial andalusite crystal

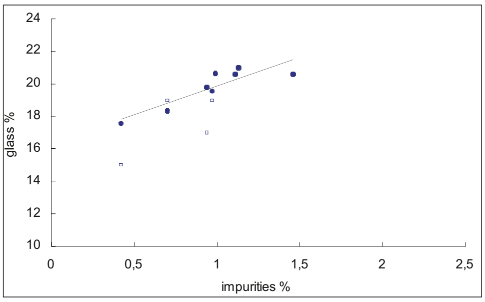

Fig. 2 Influence of the minor mineral proportion on the rate of glass (mass-%)

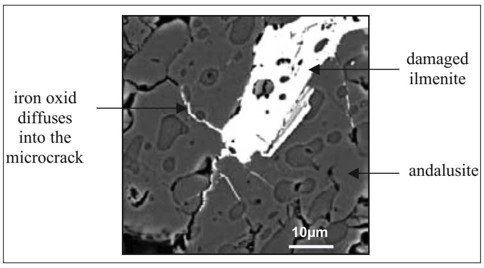

Fig. 3 Ilmenite after firing at 1200 °C (SEM backscattered electrons micrograph)

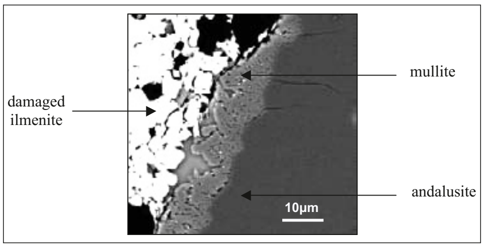

Fig. 4 After firing at 1300 °C mullite begins to crystallise near the damaged ilmenite (SEM backscattered electrons micrograph)

formed mullite and the parent andalusite crystal. The glass is silica rich and its composition differs only slightly from that of the eutectic liquid in the pure $Al_2O_3 \cdot SiO_2$ system : SiO_2 ~ 91 % and Al_2O_3 ~ 9 % [5]. This glass contains iron (Fe_2O_3 ~ 1-3 %), potassium (K_2O ~ 1-3 %) and other elements with amounts below 1% initially inside the minor impurity phases included in andalusite (Table 1). The nature and the amount of the included or attached minerals influence the rate of glass (Fig. 2)

As in the binary Al_2O_3–SiO_2 system, the lowest eutectic occurs at 1587 °C, mullitization of andalusite below that temperature was classically considered to be a solid state reaction leading to a great number of mullite needles oriented in relation with the host crystal [3, 4, 5, 6].

The presence of a liquid locally generated by low temperature melting of included and associated minerals also plays an important role on the transformation of andalusite into mullite [7]. The nature and the amount of these minerals have an influence on the kinetics of mullitization. The minor minerals, mainly ilmenite and micas are located on the surface of the grains and in the chiastolitic cruciform pattern of the andalusite grain. They supply iron and alkalis, and therefore local melting may occur at low temperature. As the amounts of iron oxide and alkalis increase, the amount of the liquid phase increases too and therefore atomic diffusion is promoted. Two parameters related to the liquid phase may affect the kinetics : the amount of liquid and its viscosity, which both depend on the amount of minor minerals in the initial andalusite. The minor minerals attached or included in the andalusite grains react when the temperature increases. Ilmenite ($FeTiO_3$) starts to melt at 600 °C and releases iron oxide which diffuses into microcracks (Fig. 3). Micas begin to damage at 1000 °C ; at about 1200 °C, the micas have melted and the liquid generates fine mullite crystals and quartz turns into cristobalite at about 1300 °C. The liquid phase promotes atomic diffusion and mullitization through dissolution precipitation mechanisms (Fig. 4). Therefore, the presence of minor minerals triggers mullitization

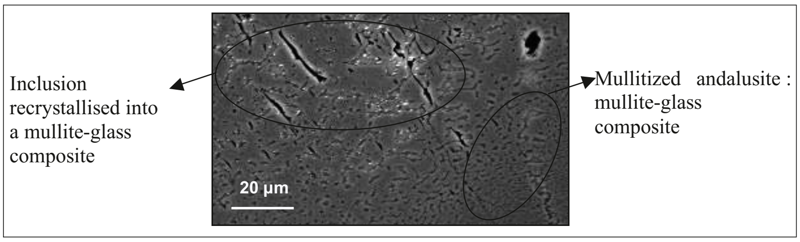

Fig. 5 After firing, both andalusite and minor minerals lead to a mullite-glass composite (SEM backscattered electrons micrograph)

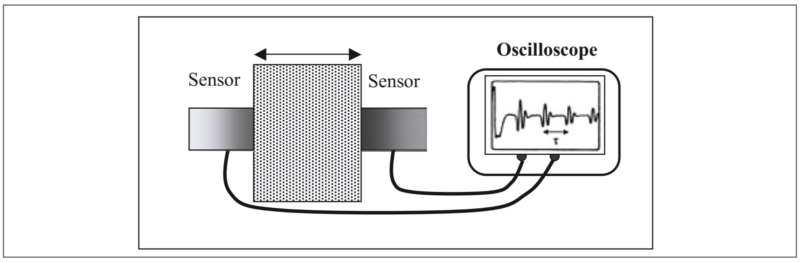

Fig. 6 The transmission mode method

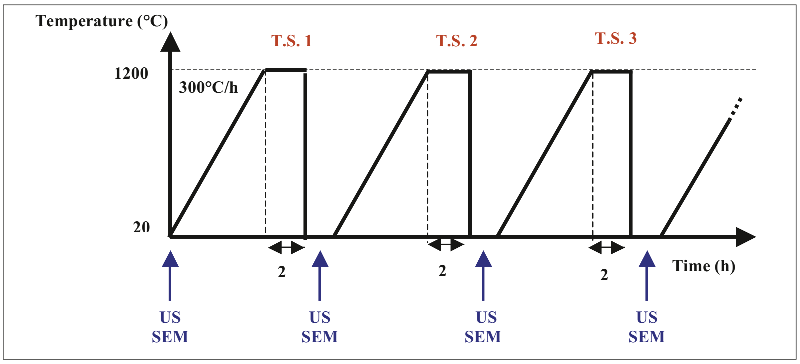

Fig. 7 Experimental procedure applied for thermal shock study on andalusite and mullitized andalusite crystals

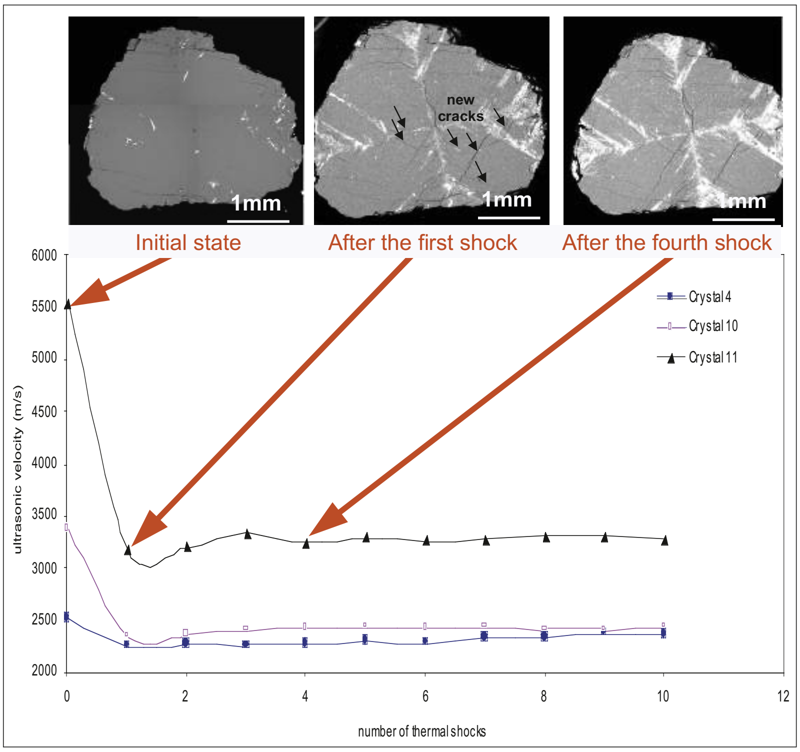

Fig. 8. Evolution of the velocity of ultrasonic waves for 3 representative crystals of andalusite after 10 successive thermal shocks

through a dissolution-precipitation mechanism. After firing, both andalusite and minor minerals lead to a mullite-glass composite (Fig. 5).

3 The Evaluation of the Thermal Shock Performance of Andalusite and Mullitized Andalusite Raw Materials

3.1 Methodology and Experimental Procedure

With an ultrasonic method, it is possible to determine Young's modulus which is an adequate characteristic to study the thermal shock and the thermo-elastic behaviour of andalusite and mullitized andalusite raw materials. The velocity of the propagation of the ultrasonic waves depends on several parameters: mineralogical phases, porosity, cracks network, chemical composition. In an infinite and isotropic medium, two kinds of waves may propagate with different velocity:

- Longitudinal waves (tensile-compressive waves) due to the movement of the elemental particles of the medium parallel to the direction of the propagation;
- Transverse waves (shearing waves) due to the movement of the elemental particles perpendicular to the direction of the propagation.

There is a relation between the velocity of the longitudinal waves, the velocity of the transverse waves and the modulus of elasticity [8].

The velocity of the longitudinal waves is:

(1)

The velocity of the transverse waves is:

(2)

where E is the modulus of elasticity, G is Coulomb's modulus, is Poison's ratio and is the bulk density.

When the transverse lengths are lower than the wavelength, the waves propagate in the "long bar mode". The velocity of the longitudinal waves is:

(3)

and the velocity of the torsion waves is:

(4)

where is a form factor (=1 for a circular section).

There is a direct relation between E, V and ρ. Therefore, in this paper, the elastic characteristics of refractories will be presented in terms of ultrasonic velocity, which is the measured parameter, in order to calculate the modulus of elasticity. The ultrasonic system is a SOFRANEL EPOCH equipment using two kinds of sensors: M106 (2 MHz) or X1020 (100 MHz). The choice of the frequency of the sensors depends on the material. The method of measurement is the transmission mode method (Fig. 6). The sample, with two parallel faces, is coupled to the sensors with grease. The generator transmits a periodic pulse to a sensor, which generates an ultrasonic wave in the sample. Another sensor receives the wave transmitted by the sample. The signal observed on the oscilloscope consists of a sequence of echoes. The time between two successive echoes corresponds to the time required for the ultrasonic wave to go through the sample. As thickness L of the sample is known, time t is measured, ultrasonic velocity V is calculated:

(5)

The thermal shock resistance of andalusite and mullitized andalusite crystals has been studied. Large well-formed crystals of andalusite (5…8 mm diameter) were carefully selected. Mullitized andalusite crystals were prepared by firing andalusite crystals up to 1500 °C with a 900 °C/h slope and a six-hours dwell time at maximum temperature. XRD has shown that there is not any residual andalusite after this heat treatment. The crystals were cut perpendicularly to their c-axis and one face (001) was polished.

The thermal shock resistance of andalusite or mullitized andalusite single crystals has been studied between 1200 °C and room temperature. 1200°C has been chosen because at

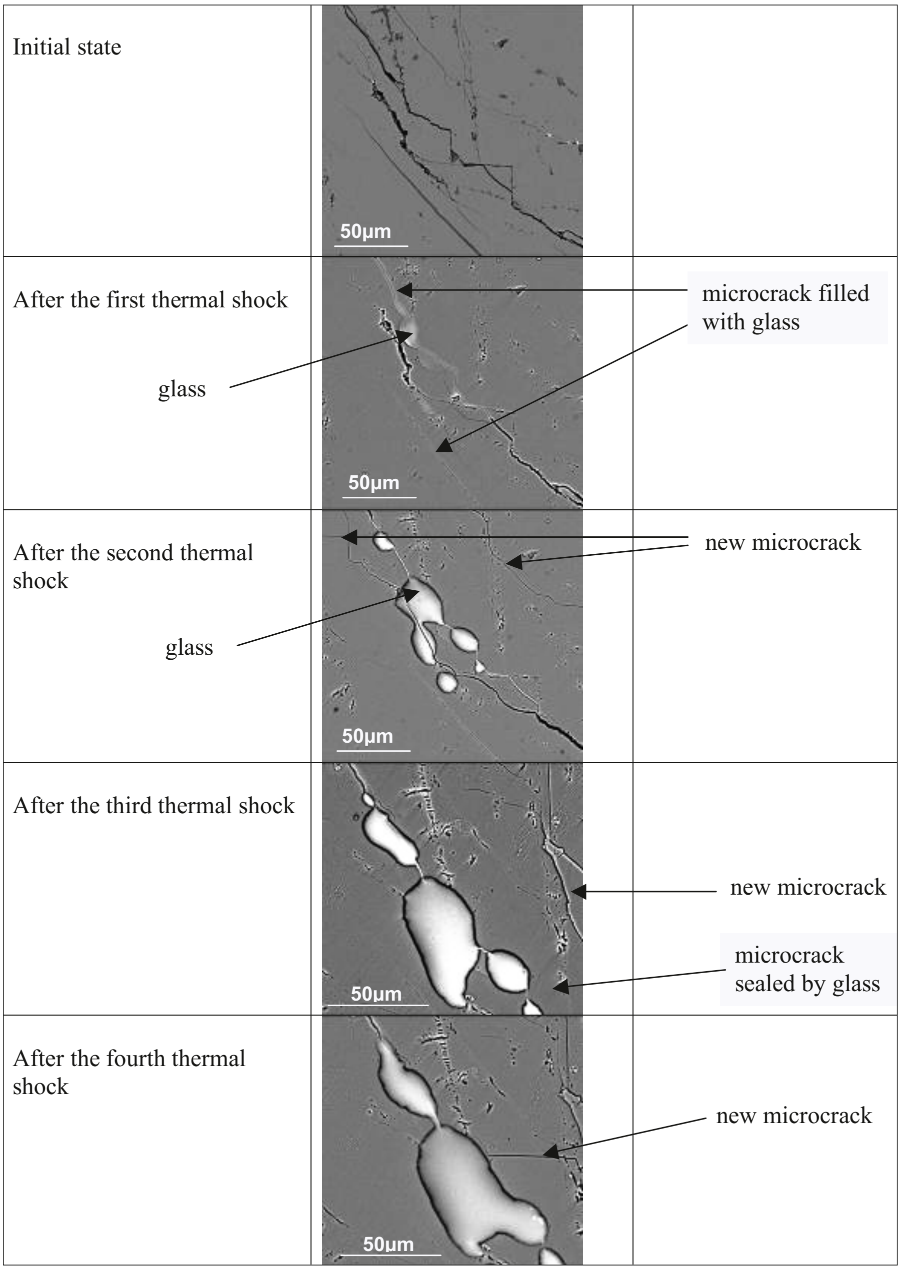

Fig. 9 Backscattered electron image of the initial aspect of andalusite crystal and the aspect of the crystal after thermal shocks

this temperature, the associated minerals melt providing a liquid phase and mullitization just begin to occur.

The polished grains are put into an electric furnace and heated at 1200 °C (at a heating rate of 300 °C/h). After two hours heating to homogenise temperature in the crystal, the samples are submitted to thermal shocks in the air. In order to increase quench, each aggregate was rapidly extracted from the furnace and its polished face put on a cooled polished cooper plate. Quenching time from 1200 °C to 20 °C was less than five seconds. Fig. 7 shows the experimental procedure of the successive thermal shocks. Prior to testing and after each quench, the velocity of propagation of ultrasonic waves, perpendicular to the c axis was measured with Sofranel EPOCH equipment and the polished face was examined by scanning electronic microscope (SEM) using secondary or backscattered electron imaging. Backscattering electron imaging with a high contrast has proved to be much more effective for the observation of microstructures.

3.2 The Study of the Thermal Shock Resistance of Andalusite Crystals

Fig. 8 shows the evolution of the velocity of ultrasonic waves for three representative crystals of andalusite after ten successive thermal shocks. The first thermal shock is the most damageable. After the other thermal shocks, ultrasonic velocity and the modulus of elasticity are then found to be stable. The initial andalusite contains some inclusions and exhibits an initial network of cracks, even before the first thermal shock. As andalusite is a natural mineral from a low-grade metamorphic rock, it can contain inclusions of associated minerals trapped (micas, chlorite…) or released (quartz) during the crystal growth. The initial cracks result from opening of the (110) cleavage planes. Cracks on the edge are also due to crushing during mineral processing.

After the first thermal shock (one cycle), the surface has already changed considerably:

- The amount of cracks has increased;
- A white new phase appears, located in geometrical figures;
- Large cracks appear.

This is the reason why ultrasonic velocity decreases. There is no micro-structural relation between the initial cracks (before the first thermal shock) and the cracks created by thermal shocks. The new cracks are generated by the successive thermal shocks which contribute to the advanced thermal shock performance.

They may develop:

- With the same orientation. The orthogonal cracks are in fact the traces of andalusite cleavages;
- Or without any relation to the cracks created during the previous thermal shock.

After 4 cycles, the pattern observed after 1 cycle remains. We only see an increase in the surface of the white phase which is a glass resulting from the melting of associated minerals. The associated mineral inclusions are located in a particular area of the crystal called chiastolite. The chiastolite is revealed by the melting of these inclusions.

If we look at andalusite crystals after each cycle at higher magnification, we observe interesting changes (Fig. 9)

- The initial cracks of the crystals are partly sealed by a glass as soon as the first cycle has been completed.
- But in the same time, new cracks appear elsewhere.
- Cracking and sealing can occur during each cycle. Coalescence of droplets at the surface reveals that more glass is expelled cycle after cycle.

SEM micrographs reveal that during two hours heating at 1200 °C before each thermal shock, a silica-rich vitreous phase appears which may fill, by capillarity, the network of cracks created by the thermal shocks. This melting phase, due to alkalis and iron oxides contained in minor mineral inclusions (quartz, phyllosilicates, ilmenite) of andalusite grains cures the existing cracks and stops the new cracks which are generated by the next thermal shock (Fig. 10).

Simultaneously, the mullitization of andalusite begins at 1200 °C, through a dissolution – precipitation mechanism. Mullite develops in andalusite from defect-rich zones and participates in the cure of the network of cracks (Fig. 11). Two "antagonistic" phenomena occur simultaneously: the heating allows the formation of a liquid phase, which cures some micro cracks and may increase Young's modulus. But the thermal shocks generate small cracks, which may decrease Young's modulus. The result is a stable Young's modulus. Consequently, andalusite provides excellent thermal shock resistance. There is a relation between ultrasonic elasticity properties and the evolution of microstructures: cracks are deflected or healed by glass-mullite zones.

3.3 The Study of the Thermal Shock Resistance of Mullitized Andalusite Crystals

The initial aspect of mullitized crystals is presented in Fig. 12 and 13. In these crystals, the number of initial cracks is limited and originates with the cooling down of the initial firing at 1500 °C.

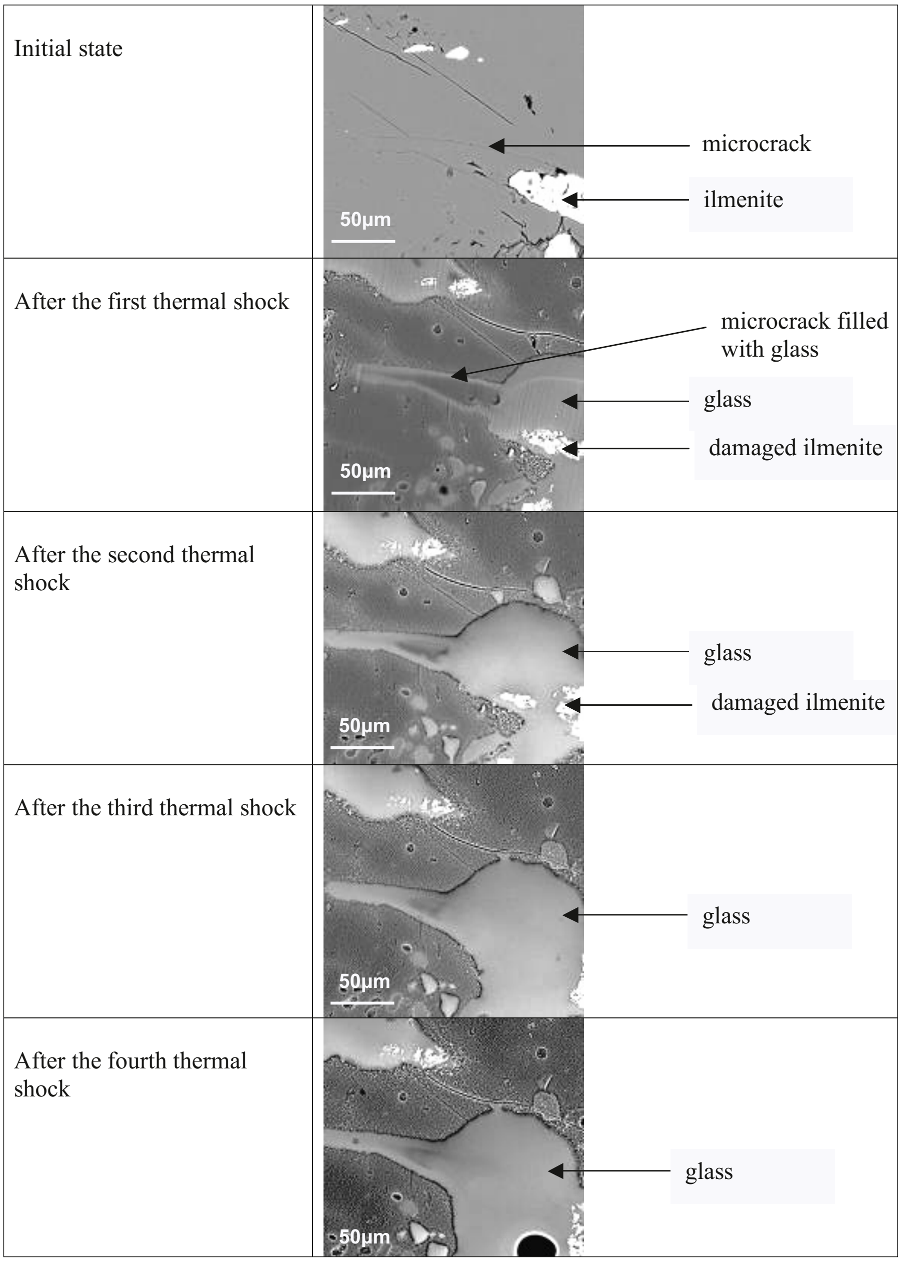

Fig. 10 Backscattered electron image of the initial aspect of andalusite crystal and the aspect of the crystal after thermal shocks (formation of a molten vitreous phase which fills the network of cracks)

Fig. 14 shows the evolution of the velocity of ultrasonic waves for 3 representative crystals of mullitized andalusite after four successive thermal shocks.

As for andalusite crystals, it is also observed a sealing of these initial cracks after one cycle (Fig. 15).

This observation confirms previous results [7]. We can notice that the silica glass is expelled from the crystal and precipitation of iron oxides occurs in the glass.

Table 1 Semi quantitative composition of glass in mullitized grains (EDS analysis, wt%)

	Sample 1	Sample 2
SiO_2	81,55	82,05
Al_2O_3	15,34	14,38
TiO_2	0,10	0,23
Fe_2O_3	0,93	10,6
MgO	--	--
Na_2O	0,80	0,88
K_2O	1,26	1,37

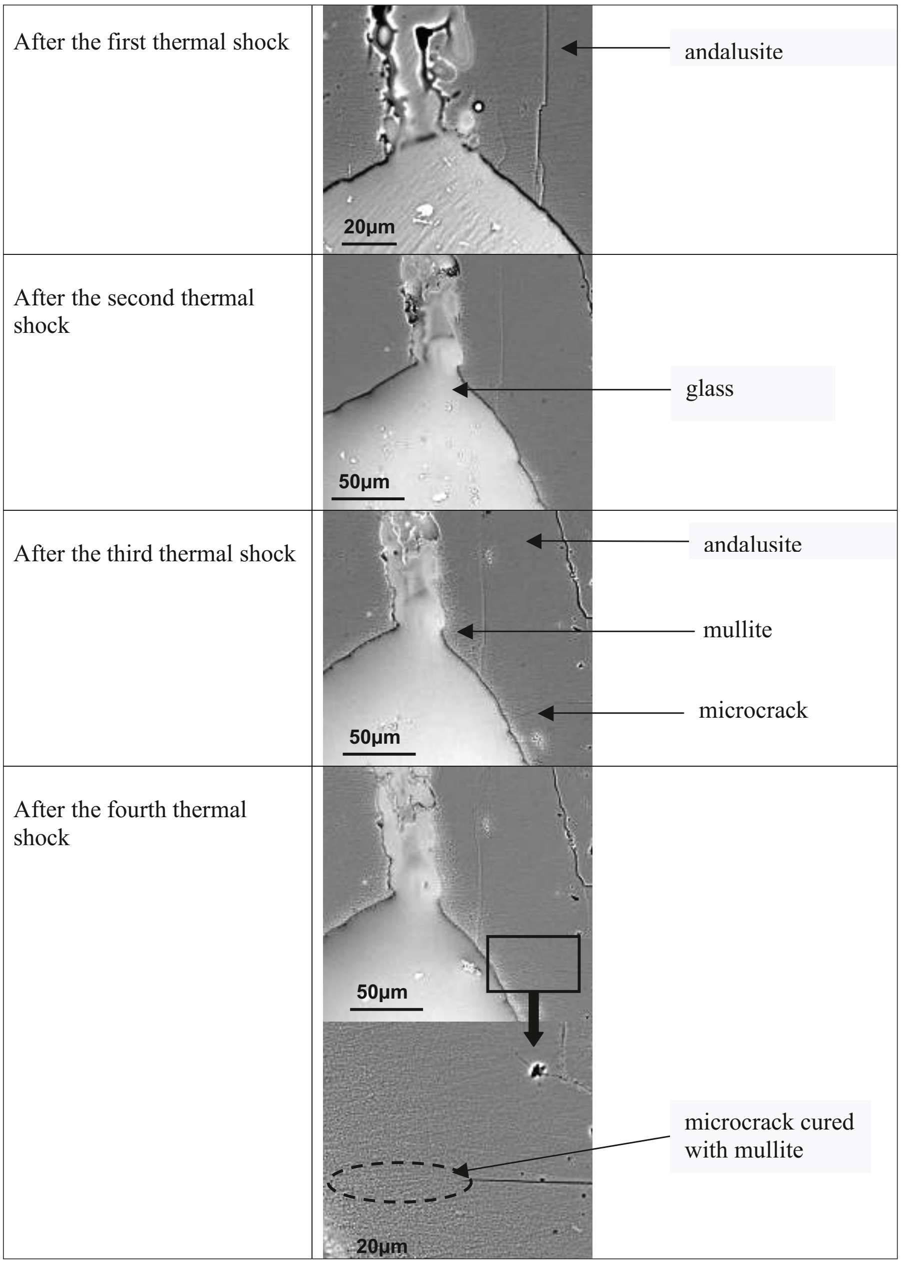

Fig. 11 Backscattered electron image of the andalusite crystal after thermal shocks (curing of a crack with mullite)

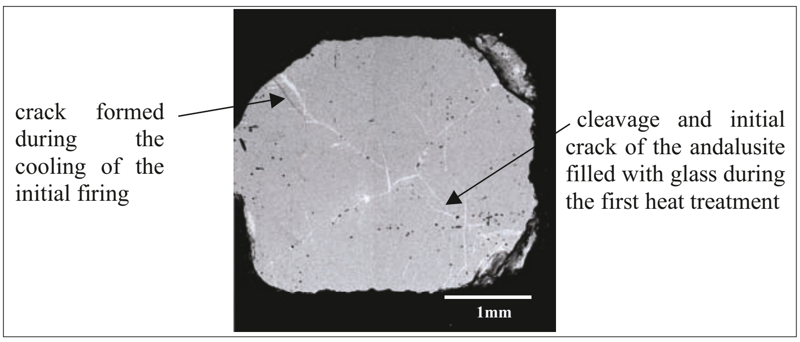

Fig. 12 Polished section of a mullitized andalusite grain (backscattered electrons SEM micrograph)

3.4 Comparison of the Thermal Shock Resistance of Andalusite and Mullitized Andalusite

As we can see in Fig.16:

- The initial velocity values are much more dispersed for andalusite crystals than for mullitized andalusite;
- The initial velocity is a combination of initial cracking and purity of the crystal. The crystal that has a large chiastolite and few cracks shows the highest US velocity. If we look at the evolution of the ultrasonic velocity as function of the thermal shock cycles, we can observe a strong difference between andalusite and mullitized andalusite (Fig. 17).
- For andalusite, the decrease in the velocity occurs from the first cycle and is stable afterwards. This decrease depends on the initial state of the crystal. The crystal that shows the highest initial velocity shows also the sharpest drop;
- For mullitized andalusite, ultrasonic velocity does not decrease increases slightly. The behaviour is also stable for the next cycles. Homogeneity of the behaviour of mullitized andalusite is confirmed.

Ultrasonic velocity measurements and microstructure study lead to several conclusions:

- The behaviour of andalusite crystals under thermal shocks depends on the initial state of the crystal (amount of associated mineral and amount of cracks);
- Cleavages of andalusite seem to move during thermal shocks and could contribute to decreasing fracture energy;
- If the firing temperature is high enough, the melting of associated minerals provides a recovery of the cracks initiated by the first thermal shock and consequently decreases the damage;
- Cycle after cycle, the mullitization of andalusite occurs even at 1200 °C and is concentrated in the stressed areas;
- Transformation into mullite of andalusite crystals during firing improves their behaviour under thermal shock because it homogenizes the mi-

Table 2 Composition of the tested brick

Raw material	Max. grain size	Amount / mass-%
Andalusite	≤ 4mm	73
Alumina fillers	Dust	15
Calcined alumina		5
High alumina ball clay		7
Phosphoric acid 75 %		+ 2,5
Water		+ 2,5

Table 3 Mineral phases of the tested brick (Rietveld method)

Phase name	Unfired brick / %	Fired brick / mass-%
Mullite 3:2	0	91
Andalusite	70	0
Quartz	2	0
Corundum	20	1
Kaolinite	6	0
Others	2	0
Amorphous phase	0	8

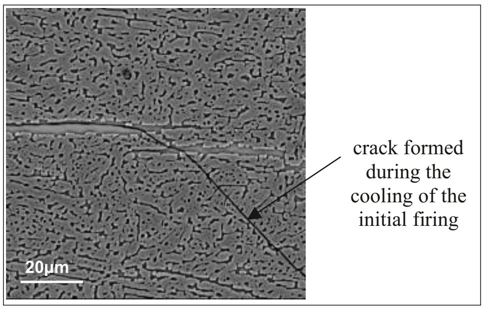

Fig. 13 Polished section of a mullitized andalusite grain (backscattered electrons SEM micrograph)

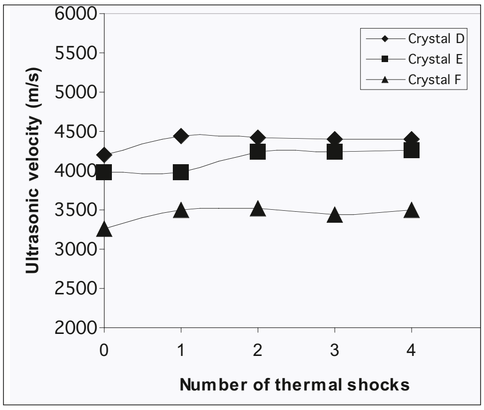

Fig. 14 Evolution of ultrasonic velocity mullitized andalusite crystals

crostructure of the initial crystal (building up of a unique mullite-silica glass network, sealing of cracks, melting of associated minerals).

4 The Evaluation of the Thermal Shock Performance of Andalusite and Mullitized Andalusite Based Bricks - Application to Steel Ladles

4.1 Methodology and Experimental Procedure

Andalusite based refractory products are used satisfactorily in applications where thermal shock resistance is required.

- In fired refractories, the transformation of andalusite into mullite is achieved in the production furnace and only a very small amount of residual andalusite is detected.
- In unfired refractories, this transformation occurs partly during the use of the refractory product.

In iron and steel ladles, fired or unfired andalusite based bricks are applied for bottom working linings. Consequently, it is useful to study the evolution of the thermal shock resistance with the mullitisation process in order to determine the most well-adapted type of bricks for such an application. The formula of the bricks was designed in order to obtain enough mechanical resistance after drying (300 °C) to be able to drill cylinders (Ø = 50 mm, h = 50 mm) in the brick (Tab. 2). The same formula was fired at 1550 °C during 8 h (slope = 100 °C/h) in order to obtain a complete mullitisation. The size of bricks is L = 230 mm, l = 114 mm, H = 64 mm. A cylinder of each type of brick (unfired and fired) was introduced with an hydraulic piston in a vertical furnace maintained at 1550 °C. The average heating up is 50 °C/min on the surface and ≈23 °C/min inside the cylinder. The holding time at maximum temperature (1510 °C inside the cylinder) is 2 min. Then, the hydraulic pressure in the piston is released and the sample stopped in an area of the furnace where the temperature reaches only 1000 °C . As soon as the minimum temperature is obtained (970 °C inside the cylinder), a new cycle starts (Fig. 18). This thermal cycle is closed to the thermal shock of

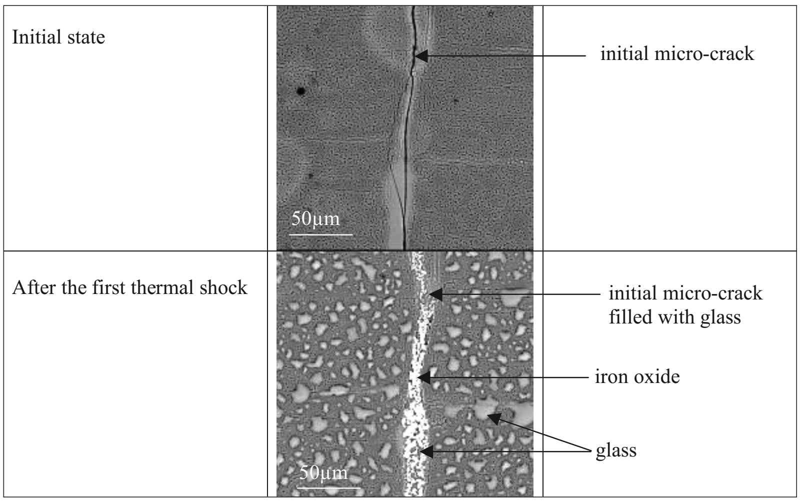

Fig. 15 Backscattered electrons image of a mullitized andalusite crystal

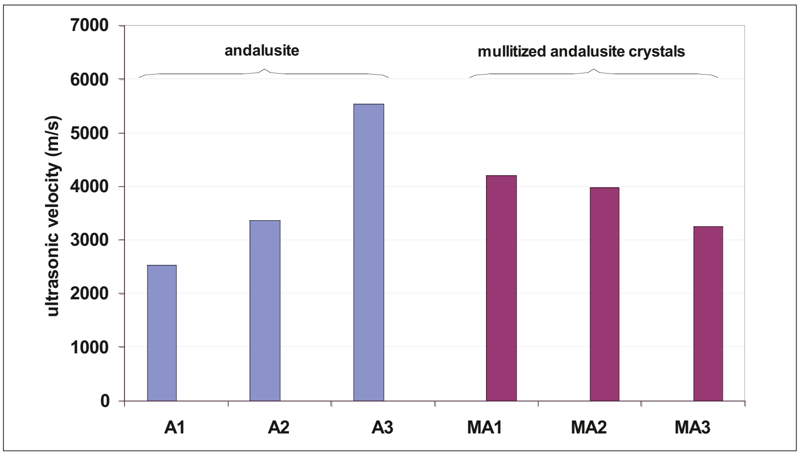

Fig. 16 Initial ultrasonic velocity of andalusite (A1,A2,A3) and mullitized andalusite crystals (MA1,MA2,MA3)

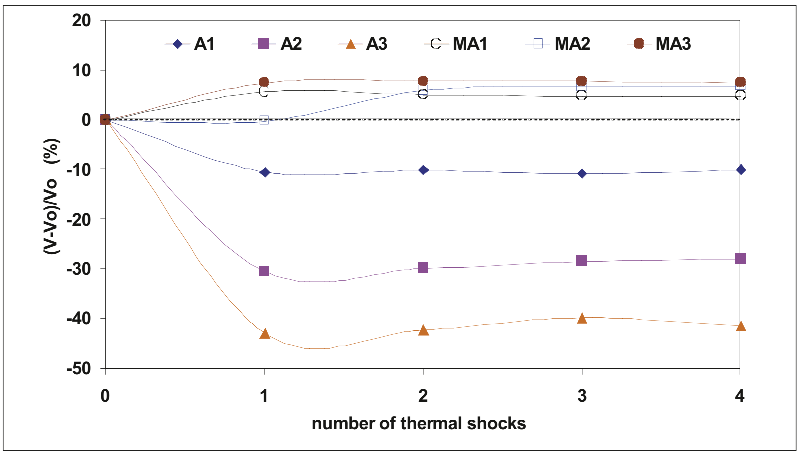

Fig. 17 Evolution of ultrasonic velocity of andalusite (A1,A2,A3) and mullitized andalusite crystals (MA1, MA2, MA3) – Vo initial velocity

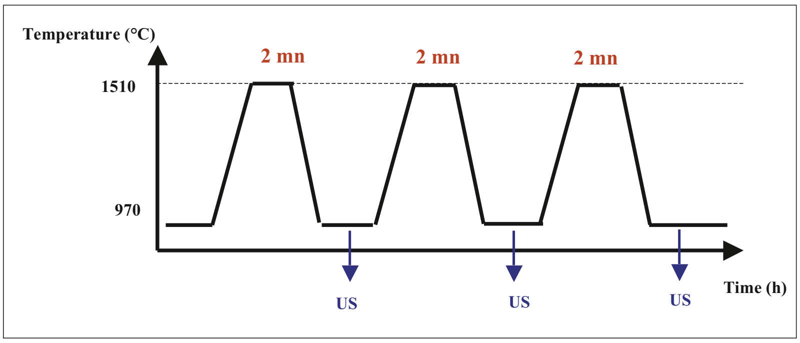

Fig. 18 Experimental procedure applied for thermal shock study on andalusite bricks

the steel ladle refractory lining. The cooling down has been estimated to 220-250 °C/min at the surface and 100-115 °C/min inside the cylinder. Ultrasonic velocity was measured on cylinders after 1 cycle, 15 cycles and 30 cycles for unfired bricks and after 1 cycle and 30 cycles for fired bricks.

4.2 Results and Discussion

4.2.1 Mineralogy of Fired and Unfired Bricks and the Initial Ultrasonic Velocity

The mineralogy determined by X-Ray diffraction (Rietveld method – TOPAS software) is presented in Tab. 3. In the fired brick, mullitisation of andalusite is achieved (no residual andalusite), most of the glass produced by kaolinite mullitisation has reacted with corundum of the matrix to produce a secondary mullite. Cristobalite is not detectable.

The unfired brick (UB) shows more dispersion of the ultrasonic velocity than the fired brick (FB). Even in a given unfired brick, we can notice a dispersion between cylinders (a,b,c) (figure 19). The heterogeneity of the unfired brick has a significant influence on velocity measurement after thermal shocks.

4.2.2 Variation of ultrasonic velocity (v- v_0/v_0) in function of the number of cycles

Because damaging of andalusite crystals was maximum after the first cycle, we measured the US after 1 cycle. 30 cycles is considered as a standard for many refractory applications. An intermediate number of cycles enables us to better observe the influence of andalusite mullitisation in unfired samples. As we can see in Fig. 20, there is a slight improvement of the unfired brick behaviour when the number of cycles increases but dispersion is very high. The first cycle is the most damaging while we can find less damage after 30 cycles (positive variation of velocity). For fired bricks, the behaviour is more stable and no significant increase in damage is detected, even after 30 cycles. The quantitative analysis of the mineral phases shows that even after 1 cycle, mullite level of unfired bricks reaches 46 % due to the time to reach maximum temperature (Fig. 21). After 30 cycles, the mullite rate of an unfired brick does not reach that of a fired brick, the amorphous phase is lower (≈5 % instead of 6–8 %) and corundum slightly higher (3–5 % instead of 1 %), cristobalite and quartz have not totally disappeared. In this case, total dwell time at 1510 °C reaches 1hour while the fired brick was fired at 1550 °C during 5 hours.

The fired brick is stabilized with no significant change in the mineral composition after 30 cycles. We noticed only a slight increase of mullite content and decrease of amorphous phase.

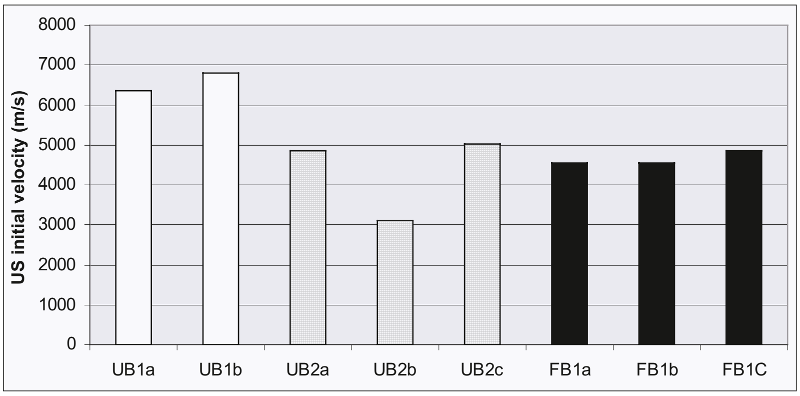

Fig. 19 Initial ultrasonic velocity of unfired bricks (UB1a, UB1b, UB2a, UB2b, UB2c) and fired bricks (FB1a, FB1b, FB1c)

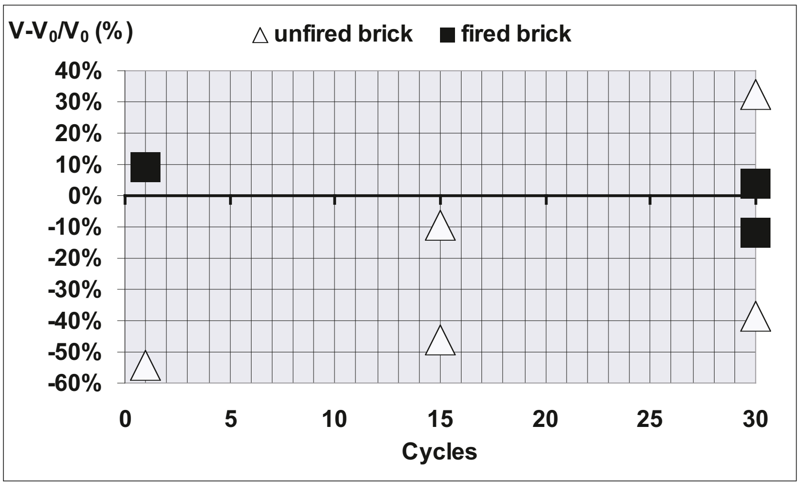

Fig. 20 Evolution of ultrasonic velocity for unfired and fired bricks depending on thermal cycles

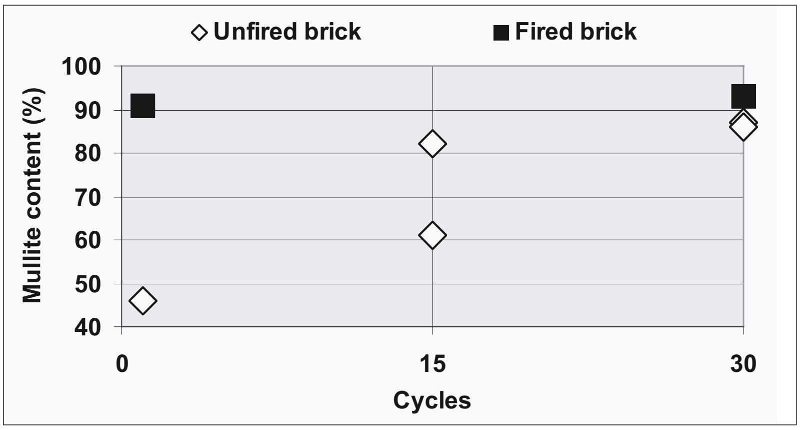

Fig. 21 Mullite content in function of number of cycles

4.2.3. Microstructure of unfired and fired bricks

Even after 30 cycles, the andalusite fired brick shows a homogeneous structure with some pores. A linear open porosity occurs around mullitised crystals but this porosity is not continuous (Fig. 22a). The contact between the matrix and the mullitised andalusite grain observed at a higher magnification, shows a bond between this matrix and the grain (Fig. 22b). The primary mullite (M1) formed from the mullitisation is interconnected to the secondary mullite grains (M2) produced by the mullitisation of the matrix. The secondary mullite can be recognized because of the occurrence of remaining corundum globules (C). The amorphous phases formed from andalusite mullitisation (G1) or located in the matrix (G2) appears completely trapped in the mullite network. The interconnection of the mullite reinforces the mechanical strength and homogenises the expansion behaviour of the brick. The amorphous phase trapped in the matrix and in the grains absorbs the stress during the cooling down and provides sealing of cracks.

This particular microstructure explains the very good thermal shock resistance of andalusite fired bricks and has been already observed in an andalusite based low cement castable after firing at 1500 °C. When andalusite mullitisation occurs during thermal cycling, we can observe an evolution of the microstructure, but damaging with cracks still occurs whatever the mullitisation rate (Fig.

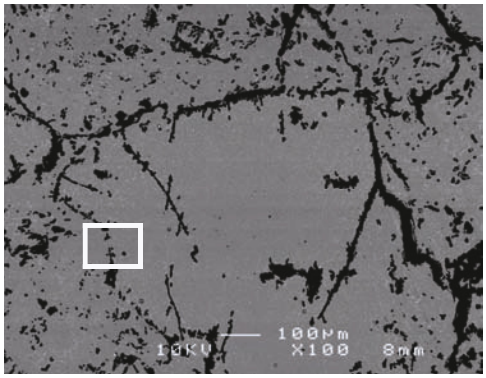

Fig. 22 a. General view of a mullitised andalusite crystal in the fired brick

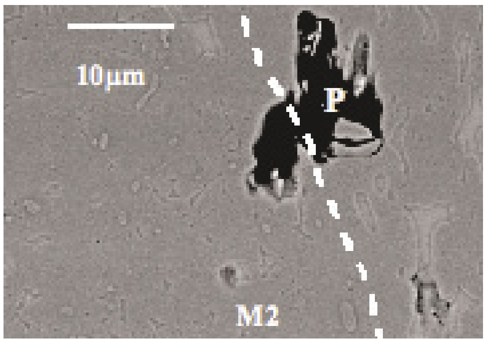

Fig. 22 b Backscattered electron image of the microstructure of an andalusite fired brick after 30 thermal shocks

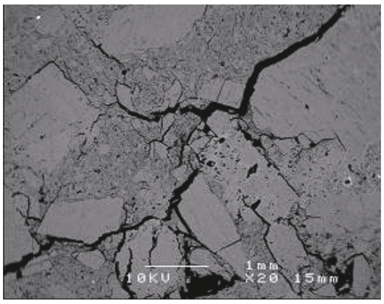

Fig. 23 a Unfired brick after 1 cycle Andalusite content: 46 %

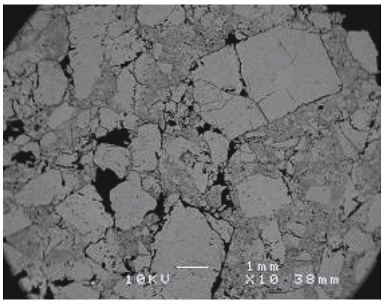

Fig. 23 b Unfired brick after 15 cycles Andalusite content: 25 %

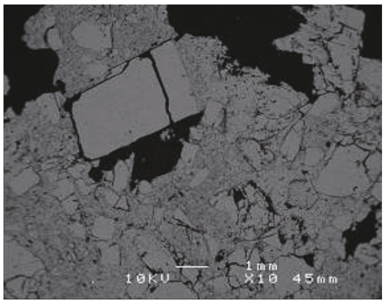

Fig. 23 c Unfired brick after 30 cycles Andalusite content: 1 %

23 a, b, c). An increase of the pore size and a decrease of dramatic failures (big cracks) are observed. We still observe trans granular cracks and a dense network of intra granular cracks even when mullitisation is achieved. The cracks at the edge of the grains are not systematic when mullitisation is achieved and similar contact between matrix and grains can be found in fired bricks.
The study of the microstructure confirms the results of the ultrasonic measurements:

- an unfired brick shows a brittle behaviour while a fired brick shows an elasto-plastic behaviour,
- the behaviour during thermal cycling is more heterogeneous and uncertain for an unfired brick than for a fired brick.

5 Conclusion

By firing natural andalusite grains as starting material, a 3 Al_2O_3· 2 SiO_2 mullite is formed by a dissolution precipitation mechanism involving silica rich liquids issued by low temperature melting of impurities. Andalusite single crystal grains are transformed into a composite made of mullite single crystal with a capillary network filled with silica rich glass. The behaviour of andalusite and mullitized crystals under thermal shocks has been studied between 1200 °C and room temperature. Damaging of andalusite crystals occurs mainly during the first thermal shock with a move of the cleavages and generation of cracks. During the short dwell time at 1200 °C between each thermal shock, the melting of associated mineral and mullitisation occurs. The liquid phase limits the effect of the thermal shock because it enables crack recovery. The crack healing process seems to occur as early as the first thermal shock for mullitised andalusite crystals. The composite microstructure of mullitized andalusite crystals seems to improve thermal shock resistance. The influence of thermal cycling has been studied on unfired or fired andalusite based bricks with the same composition.
The main damaging effect of the first thermal cycle has been shown on the unfired andalusite based bricks. The successive dwell times at high temperature enable a partial recovery of the microstructure whatever the initial state of the brick (fired or unfired). After 30 cycles, both materials are still operational. However, the andalusite fired bricks, thanks to the composite microstructure of mullitised andalusite grains, shows a significant advantage towards unfired bricks in terms of homogeneity and reproducibility of the behaviour towards thermal cycling. The typical microstructure of andalusite fired bricks can partly explain their good performance during heating-cooling cycles of iron and steel ladles. Therefore, andalusite made refractories are well suited for a thermal cycling use. These results offer new possibilities for the development of refractories using andalusite raw materials with optimized microstructure.

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