Association of Metallurgical Engineers of Serbia
AMES

Scientific paper
UDC: 669.295

ALUMINOTHERMIC PRODUCTION OF TITANIUM ALLOYS (PART 1): SYNTHESIS OF TIO_2 AS INPUT MATERIAL

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Received 25.02.2014
Accepted 28.05.2014

Abstract

This article reports on the hydrometallurgical production of synthetic anatase from ilmenite. Mechanical activation followed by pressure leaching facilitates the leaching of ilmenite and the separation of titanium/iron by means of the synchronous hydrolysis of anatase. At 95% TiO_2, the produced synthetic anatase fulfills the requirements for the aluminothermic production of titanium alloys.

Keywords: ilmenite, mechanical activation, anatase process, pressure leaching

Introduction

Titanium is one of the ten most commonly found elements in the earth's crust, together with O, Si, Al, H, Na, Ca, Fe, Mg, and K. The most abundant titanium mineral, ilmenite ($FeTiO_3$), is, together with rutile (TiO_2), a mass commodity of high availability.

The first step in the production of titanium metal is to gain pure TiO_2 products from ore concentrates containing ilmenite or rutile. The beneficiation of ilmenites requires pyrometallurgical or chemical process steps to separate the iron content of approx. 30%. The beneficiation of rutile to TiO_2 concentrates is mostly done physically.

Several different ways of separating the iron from ilmenite are known, which differ in their technical complexity and energy requirements. The chemical process is made difficult by the low solubility of ilmenite in sulphuric acid. For the production of pure TiO_2 concentrates from ilmenites, the classic sulphate process with concentrated H_2SO_4 at < 220°C, yielding TiO_2 in pigment quality, is too complex [1]. As a result,

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apart from strictly pyrometallurgical processes [2-4], combinations of pyrometallurgical and hydrometallurgical processes [5-28] were developed for the production of synthetic TiO_2 concentrates. These concentrates can be used as raw material for the sulphate process as well as for the chloride process. For the production of titanium metal, the TiO_2 content of approx. 90% is insufficient.

One possibility for the direct hydrometallurgical beneficiation of ilmenites is the pre-treatment of ilmenite concentrates by means of mechanical activation. First investigations on the solubility of ilmenites were presented in 1968 by Gock in a study on the mechanical activation of titaniferous magnetite [29]. Since the 1990s, more studies on the solubility of ilmenites after mechanical activation using different mills for ultrafine grinding such as vertical ball mills (attritors), planetary ball mills and drum mills have been published. The focus of the investigations was on the structural changes of ilmenite. Technical applicability was not the intention [30-38]. Mechanical activation in general means exposing solids to high mechanical stress, which exceeds the enlargement of the surfaces and causes defects in the crystalline structure leading to an increase in the level of enthalpy of the crystalline system. In many cases, the increase in the enthalpy strongly influences the reaction behaviour. The influence on the dissolving and leaching activities of mineral compounds with low solubility is important for hydrometallurgical processes. The scientific background is summarized in a few monographs [39-42].

The mechanical activation of ilmenites for direct hydrometallurgical production of synthetic TiO_2 concentrates by means of the energetically efficient vibration milling method could be a new concept for the use of this material in aluminothermic titanium alloy production. However, TiO_2 contents of at least 95% TiO_2 are required.

In the following, we will report on the reaction kinetics of mechanically activated ilmenite during the hydrometallurgical production of synthetic TiO_2 concentrates with anatase structure as input material for aluminothermic titanium alloy production [43].

Experiments

The material used was commercial ilmenite concentrate with 30.02% Ti, 34.43% Fe, 0.76% Si, 0.42% Al, 0.02% Cr, <50 ppm Th, <50ppm U, 7 ppm Zr, <5 ppm P. The particle size was 100% <0.3 mm. The diffractometer analysis also showed content of hematite and quartz.

Mechanical activation took place in a full-scale eccentric vibratory mill [44-46] by Siebtechnik GmbH/Mühlheim Ruhr (ESM-656.0.5 ks), equipped with a 5 l satellite milling container for the treatment of smaller samples. With this setup it is possible to determine the energy requirements per ton of material input as well as the mill throughput for technical implementation. In order to determine the optimum activation conditions, parameter studies were carried out with mill feed quantities varying between 100 and 300 g per load and activation times ranging from 15 to 60 minutes. The amplitude or frequency of the mill was kept constant at 20 mm or 960 min^{-1}. Steel balls with a diameter of 30 mm were used.

The degree of activation was set as the ratio I/I_0 at lattice plane 104 of ilmenite after and before mechanical activation. Every degree of activation has a reproducible reaction kinetic behaviour.

The leaching tests were carried out in an agitator autoclave by Deutsch & Neumann GmbH, Berlin with a reaction volume of 2 L. The solvent used was diluted

H_2SO_4. Stirring occurred at 250 min^{-1} and the temperatures were between 100 and 150°C. Further parameters were the initial acid concentration (10-30% H_2SO_4), the leaching time (15-60 min), Fe addition (6-16%) and the solids content per litre (50-200 g/l). An ICP-OES (Vista-MPX, Varian, Australia) was used for analytical measurements. The solutions as well as the precipitation products (anatase and copperas) were analysed. In addition, X-ray diffraction patterns (Philips X´Pert PW 3040 MPD, Germany) and scanning electron microscope image (Zeiss DSM 982 Gemini, Germany) were taken.

Results

The most important parameters influencing the hydrometallurgical processing of mechanically activated ilmenite are described below.

Influence of mechanical activation

The determination of the degree of activation was based on the treatment duration of a 100 g specimen. The determined degree of activation for the performed milling tests as a function of the milling time is shown in Figure 1. It is obvious that the ilmenite structure is strongly strained by the mechanical activation. The same behaviour was also observed in the case of thermal treatment of ilmenite in a muffle furnace [29]. At > 800°C in the presence of oxygen, ilmenite converts into rutile and hematite. This process is proven by the measurements at lattice plane 104.

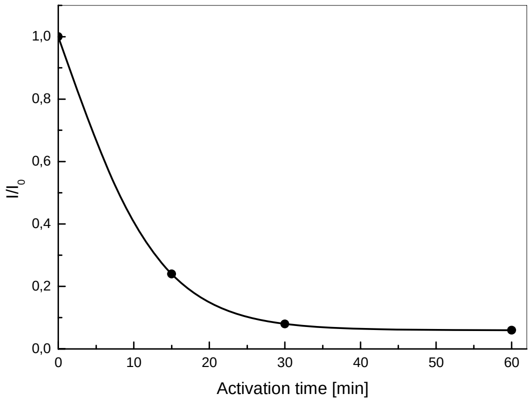

Fig. 1. Degree of activation I/I_0 of ilmenite as a function of the activation time measured at lattice plane 104 at 2θ=32.7°

The influence of the activation time on the TiO_2 extraction in the precipitation product is shown in figure 2. The leaching tests confirm the dependence on the degree of activation. A critical point is that after a mere 15 minutes of activation most of the ilmenite has been dissolved. This finding is extremely interesting from a technical point of view. The hydrolytic precipitation of anatase is influenced by an initial solution accelerated with increasing activation.

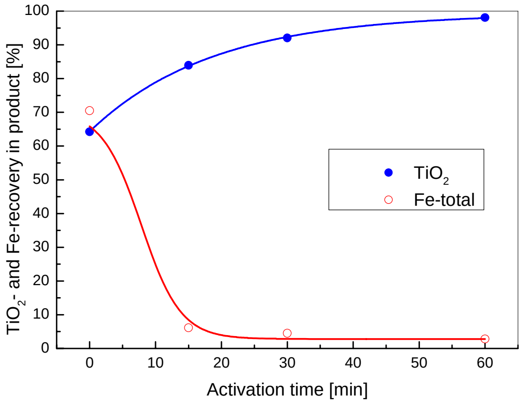

Fig. 2. Influence of the activation time of ilmenite on the precipitation of anatase; leaching temperature 150°C, solids content 50 g/l, leaching time 60 min, 30% H_2SO_4, 12% Fe-powder

Influence of temperature

At temperatures > 50°C and a pH value > 1.5 the hydrolysis from titanyl sulphate solutions to TiO_2 is triggered. In the investigated temperature range, the dissolution of ilmenite and the simultaneous precipitation of TiO_2 take place in parallel. If the hydrolysis conditions are less than perfect, a partial precipitation of TiO_2 will occur. The hydrolytic conditions are influenced positively, if the dissolution of ilmenite takes place at temperatures > 100°C under steam pressure in an autoclave.

The variation of the temperature in the range of 100-150°C yielded the reaction process shown in figure 3.

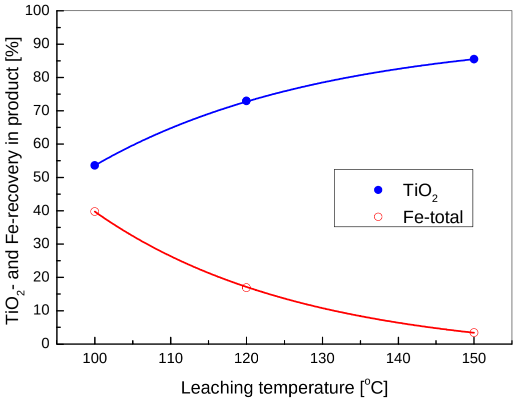

Fig. 3. Influence of the leaching temperature on the precipitation of anatase; solids content 50 g/l, 15 min eccentric vibratory milling, leaching time 60 min, 30% H_2SO_4, 6% Fe- powder

The curve for the total iron extraction in the product reflects the dissolution of the ilmenite. At a leaching temperature of 150°C and a leaching time of 60 minutes, approximately 86% of the ilmenite dissolves. Parallel to the dissolution of the iron, the titanium is being dissolved and the hydrolysis of the generated titanyl sulphate solution to anatase takes place following the almost complete dissolution of the ilmenite. At 150°C only traces of titanium remain in the solution. Under the same temperature conditions the amount of Fe powder, used as a reduction agent, was increased to 10%. Under these conditions, extraction was already largely achieved at a leaching temperature of 120°C. The TiO_2 extraction in the product is approx. 86% (see figure 4). The optimum reaction temperature is thus influenced by the amount of reduction agent. As proven in point: Influence of Fe-additive, the addition of Fe accelerates the initial reaction of the leaching.

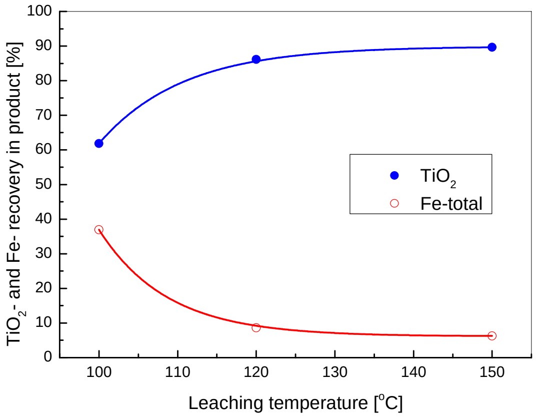

Fig. 4. Influence of the leaching temperature on the precipitation of anatase upon increasing the amount of reduction agent from 6 to 10% Fe-powder; solids content 50 g/L, 15 min eccentric vibratory milling, leaching time 60 min, 30% H_2SO_4

Influence of the initial acid concentration

The extraction of ilmenite using the sulphate process requires approximately 2 tonnes of concentrated sulphuric acid per tonne of ilmenite. The generated extraction cake is then leached with water. The content of free acid must guarantee a pH value < 1.5. As a consequence, the direct leaching of ilmenite performed here requires a solids/acid ratio of at least 1:2. Figure 5 shows the influence of the initial acid concentration on the solution of activated ilmenite using 10% acid. This corresponds to a solids/acid ratio of 1:2, and a 77% solution of ilmenite after a leaching time of 60 minutes. Increasing the initial acid concentration to 20%, this corresponds to a ratio of 1:4, the ilmenite almost completely dissolves. From a processing point of view, continuous operation requires keeping the acid in circulation and replacing the spent acid. It is in this way that the process acid always has a preparatory titanyl sulphate content.

As a consequence, it shows that the initial acid concentration has a direct influence on the rate of ilmenite dissolution. For technical dimensioning, the ratio of ilmenite to acid should be < 1:4. An excessively high amount of acid would complicate the hydrolytic conditions.

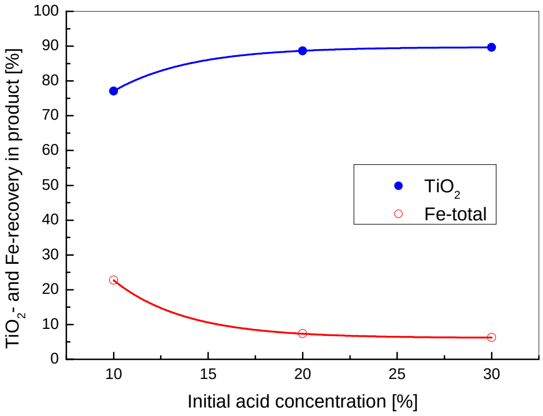

Fig. 5. Influence of the initial acid concentration on the precipitation of anatase; solids content 50 g/l, 15 min eccentric vibratory milling, leaching temperature 150°C, leaching time 60 min, 10% Fe-powder

Influence of the leaching time

The leaching time was varied in a range from 15 to 90 minutes. A general fact is that the dissolution of ilmenite takes place at a fast rate. Figure 6 shows the dissolution of ilmenite in a magnitude of approx. 64% (related to the dissolution of iron) at a leaching time of 30 minutes and a reaction temperature of 120°C.

When increasing the reaction temperature to 150°C, again, approx. 86% of the ilmenite dissolves after a leaching time of 30 minutes. Figure 6 also shows that the leaching time has a relatively low impact on the hydrolysis. After 60 minutes, approx. 93% of the anatase has precipitated and the Fe content in the anatase concentrate is reduced to < 6%. The generated product is a synthetic TiO_2 concentrate of relatively high purity.

If the temperature is lowered from 150°C to 120°C, it is impossible to produce a high-quality synthetic anatase concentrate.

Influence of the Fe-additive

As proven in point: Influence of temperature, regarding the influence of the leaching temperature, the addition of Fe influences the initial rate of the ilmenite dissolution. This correlation is shown in figures 3 and 4.

Figure 7 shows that after a leaching time of 60 minutes the influence of the Fe-additive is no longer identifiable.

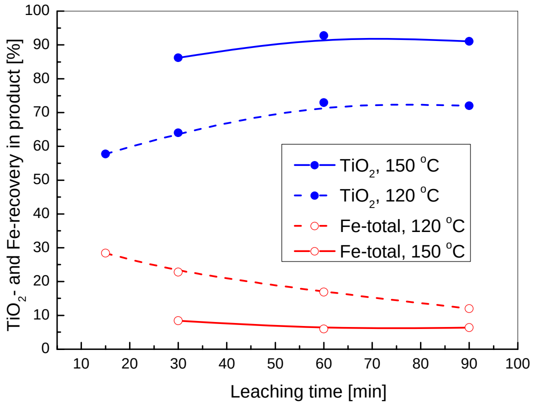

Fig. 6. Influence of the leaching time and the temperature on the precipitation of anatase; solids content 50 g/l, 15 min eccentric vibratory milling, 30% H_2SO_4*, 6% Fe-powder*

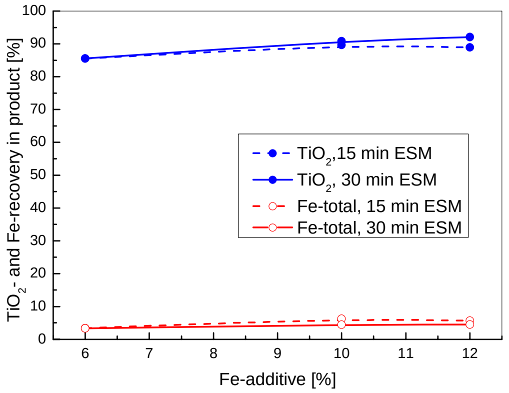

Fig. 7. Influence of the Fe-additive on the precipitation of anatase; leaching temperature 150°C, 15/30 min eccentric vibratory milling, solids content 50 g/L, leaching time 60 min, 30% H_2SO_4

Influence of the solids content

Solids content between 50 and 200 g/L were investigated (Figure 8). In order to show the influence of mechanical activation on the leaching with different solids contents of $FeTiO_3$, two test series with milling times of 15 and 30 minutes were carried out.

As expected, the residual iron content in the product increases with increasing solids content per litre at a lower activation time (<15 minutes). That means the ilmenite dissolves at a lower rate. For the technical process, this result is disadvantageous.

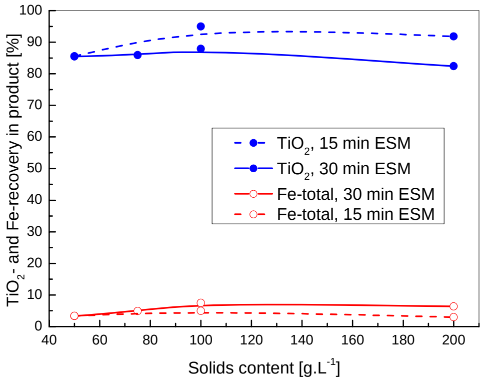

Fig. 8. Influence of the solids content on the precipitation of anatase; leaching temperature 150°C, 15/30 min eccentric vibratory milling, 30% H_2SO_4, 6% Fe-powder

Products

Table 1 shows the composition of the products produced using this anatase process: synthetic anatase and copperas.

Table 1: Composition of the products produced using the anatase process: synthetic anatase and copperas

Specimen	Al_2O_3 [%]	CaO [%]	Fe_2O_3 [%]	P_2O_5 [%]	SiO_2 [%]	TiO_2 [%]	ZrO_2 [%]
Anatase	0.34	1.20	3.32	0.007	1.70	95.23	0.004
Copperas	0.88	0.32	52.48	n.d	0.76	0.45	0.015

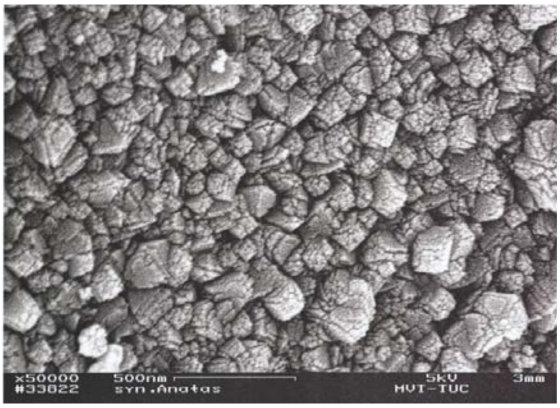

Fig. 9. Scanning electron microscope image of the produced synthetic anatase

A scanning electron microscope image of the synthetic anatase shows a narrow particle size distribution with an x_{50} value of 0.99 µm, (see figure 9). The X-ray analysis of the anatase product (JCPDS 021-1272) (see figure 10) shows traces of rutile. The crystallised copperas, shown in the X-ray diffraction pattern in figure 11, is characterised by high purity. It is the compound $FeSO_4.4H_2O$ (JCPDS 016-0699).

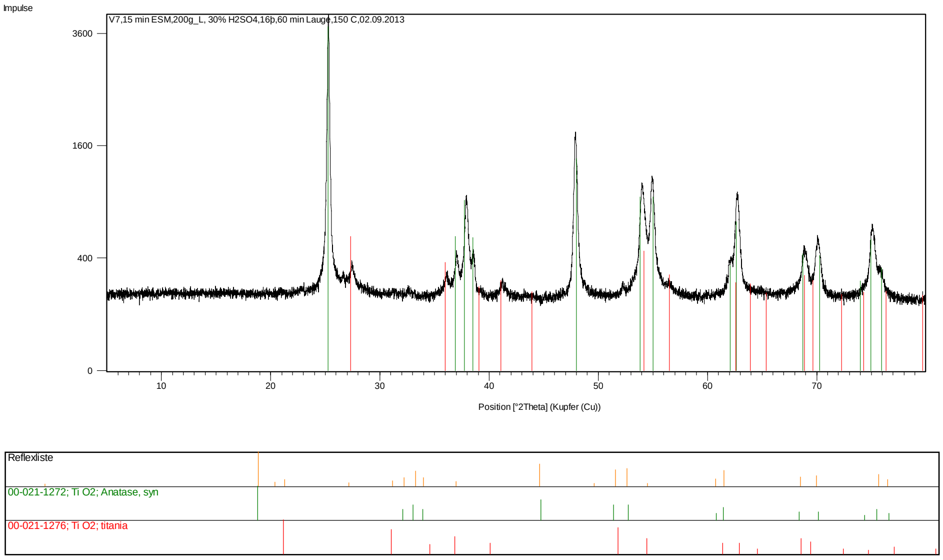

Fig. 10. X-ray diffraction pattern of the produced synthetic anatase

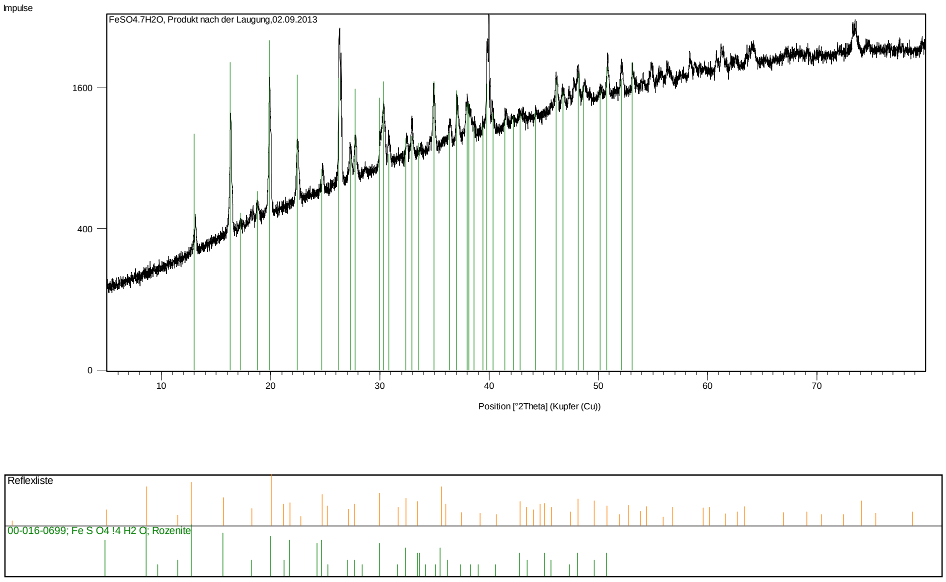

Fig. 11. X-ray diffraction pattern of the produced copperas

Process evaluation

As already mentioned in the introduction, none of the investigations that are known from the literature on the leaching of ilmenites upon mechanical activation have led to any kind of technical applicability [30-38]. In different mills, milling times of up to 200 hours were required and, with one exception, the solids content for the leaching process was only 10 g/l [35]. The operating parameters are summarised in table 2. Hydrolysis products were gained in only two cases [32, 36].

The operating conditions determined in this investigation fulfil the requirements for a technical implementation of the process for the production of a synthetic TiO_2 product, which is suitable for use in aluminothermic alloy production. **Figure 12** shows the process flow chart on the coupling of hydrometallurgical processing of ilmenites into synthetic TiO_2 concentrate (anatase) with the aluminothermic production of TiAl alloys.

Table 2: Operating parameters from the literature on the mechanical activation of ilmenite for direct leaching with H_2SO_4.

Bibliography	**Mill**	**t [h]**	**H_2SO_4 [%]**	**c [g/l]**	**T [°C]**	**T_L [h]**	**m [%]**	**Product**
Welham, N., Llewellyn, N.J., (1998), [30]	Vertical ball mill	0.25 - 100	50	10	up to 120	0.5 - 8	Ti: 90	solution
Chen, Y. et al. (1999), [31]	Vertical ball mill, in air and vacuum	10 - 200	50	10	100	2	Ti: 100 (vacuum) Ti: 70 (air)	solution
Li, Ch. et al. (2008), [32]	Vertical ball mill	4	5, 10, 15	10	100	0.25 - 4	Ti: 85 Fe: 100 (0.25 h)	TiO_2 (95%) rutile Fe_2O_3 (0.5%) SO_3 (4.1%)
Li, Ch. et al. (2006), [33]	Planetary ball mill	0.5 - 10	50	10	up to 100	0.25 - 2	Ti: 82	solution
Sasikumar, C. et al. (2004), [34]	Planetary ball mill	0.5; 1.5;4	50	10	up to 120	0.5 - 4	Ti: 65 Fe: 90	solution
Sasikumar, C. et al. (2007), [35]	Planetary ball mill	0.5; 1.5; 4	16-75	111-167	up to 120	0.5 - 4	Ti: 40 Fe: 78	solution
Li, Ch. et al. (2007), [36]	Ball mill in air and vacuum	2, 4, 6, 10	5, 10, 20	10	up to 100	0.25 - 4	Ti: 90 Fe: 90 (0.5 h)	TiO_2 rutile $Fe_2(TiO_3)_3$ pseudorutile
Li, Ch. et al. (2006), [38]	Vertical ball mill simultaneous milling and leaching (attritor)	0.5 - 4	50	26	up to 120	0.5 - 4	Ti: 77	solution

t – milling time; c – solids content; T_L – leaching time; m - recovery

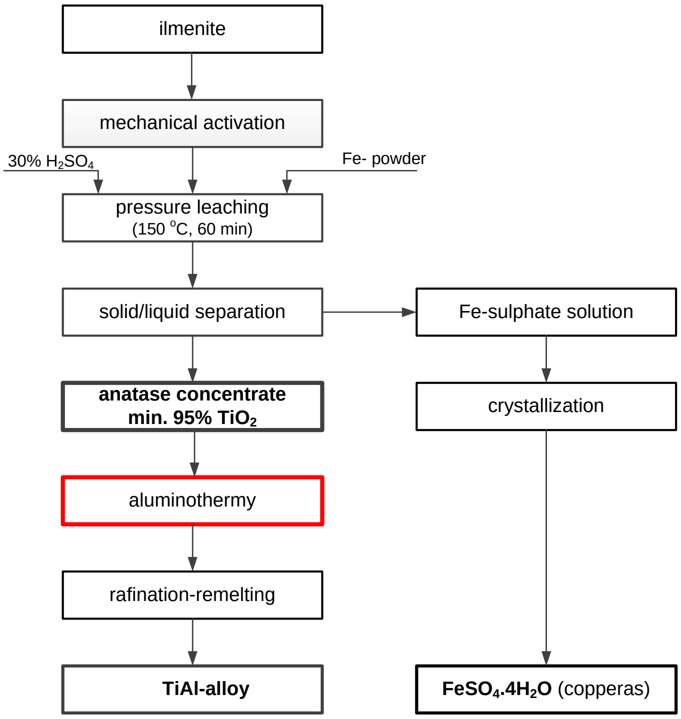

Fig. 12. Process flow chart on the coupling of hydrometallurgical processing of ilmenites with the aluminothermic production of TiAl alloys.

The energy required per tonne of synthetic anatase is expected to be 506 kWh. Based on current costs for energy, this corresponds to approx. 212 euro per tonne of synthetic anatase. The use of untreated ilmenite in aluminothermic processes would result in the production of ferrotitanium. The reduction of by-components in ilmenite is more favourable than the reduction of titanium dioxide because of their lower oxygen affinity. This investigated pretreatment of ilmenite with mechanical activation and leaching enables new cost-effective production methods for titanium based alloys. Due to the increase of TiO_2 content up to 95% the usage of synthetic anatase in aluminothermic reaction is feasible and attractive [47]. So far, only high purity rutile pigments have been used for the aluminothermic production of TiAl alloys [48-50]. The potential reduction reactions of by-components have specific enthalpies that must be taken into account for the thermochemical calculations of the aluminothermic reaction mixture. The effect of grain size and morphology on the aluminothermic process is not predicable and has to be investigated in-depth. At 95% TiO_2, the synthetic TiO_2 concentrate (anatase) that we produced meets the requirements for aluminothermy in order to produce Titanium based alloys instead of Ferro-based alloys from ilmenite.

Summary

The reaction kinetic conditions for the processing of mechanically activated ilmenite by means of direct hydrometallurgical conversion in autoclave to synthetic anatase at 150°C with 30% H_2SO_4 were investigated and the parameters for technical implementation determined. Based on the found operating data, a process flow chart on the coupling of the hydrometallurgical processing of mechanically activated ilmenite into synthetic anatase with the aluminothermic production of TiAl alloy products was established.

For the first time ever, this concept supplies a suitable TiO_2 raw material for aluminothermic processes in order to produce Titanium alloys from ore concentrates by means of direct hydrometallurgical processing of ilmenites after mechanical activation.

Acknowledgements

The authors would like to express their gratitude to the Deutsche Forschungsgemeinschaft for the financial support provided as a part of the Forschergruppe 1372/Titan.

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