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Steam engines - The autoclave in the investment casting process

In most of the investment foundries worldwide so-called steam autoclaves are used to remove the wax quickly and gently out of the ceramic shell. In the following report we would like to have a closer look at this technique and its history, and reveal the latest trends and further development.

Investment casting, lost wax technology or dewaxing procedures, all these are different words describing the same technique, i.e. the probably oldest prototype technique in human history.

1. Historical review

More than 5,000 years ago, Egyptians and Mesopotamians already poured bronze into a lost clay mould. Beeswax was used as a basic material for the master mould and with the aid of a charcoal fire the following three things were achieved:

1. The beeswax liquefied and leaked out
2. the clay was fired
3. The bronze pellets melted and flowed into the clay cavity.

Not only in the Middle East, but also in the Chinese HAN-dynasty, among the Aztecs in Mexico and in Benin, which is now Nigeria, the procedure was well-known. It was improved and used to manufacture artefacts, tools and weapons.

At the end of the 19th century the investment casting process experienced the first technological leap, because in America it was used for the first time to produce crowns and inlays in the dental field. And another 40 years later there was a new development boost, because the Army’s demands on precision and material quality increased during the 2nd World War in a way that they could no longer be fulfilled conventionally. The development of technical waxes and alcohol-based binder systems was certainly conductive for this trend.

After 1945 the investment casting process was consistently refined and trimmed to series production. And it is used whenever high-precision and complex workpieces with a minimum of rework are needed. Many highly liquefying alloys, such as titan and alloyed steel can be cast precisely into mould shells only. So most of the golf clubs today, as well as medical implants of chrome-cobalt and many components of the automotive industry, the racing and the aerospace sector are manufactured by investment casting.

And if you have a look at the booming investment casting industry, you will get the impression that we are only at the beginning of an even bigger development: The latest magic word among the investment casters today is “directional solidifiation” and “single crystal technology”. A special bunch structure and mould shell materials in connection with a special casting and solidification technique create components which consist of only a few megacrysts arranged in parallel. Carried to extremes, we will get a cast part of one single crystal only, which has no grain boundaries and is therefore much more loadable from the mechanical and thermical point of view. Many turbine blades of aircraft engines and gas turbines for electric power generation are manufactured exactly the same way and boost their effectiveness to a an unimaginable height. While the first single crystal components were only as big as a thumb, they are continuously growing with their demands. The biggest SX components measure meanwhile about half a meter, and an end of this suspenseful development is not foreseeable yet.

2. The different dewaxing techniques

But no matter if we talk about the 5,000 year old fertility goddess made of bronze or a compressor stage for a Jet made out of a superalloy, on principle it is always the same process: You make a mould out of wax, you jacket the wax with ceramics and finally you try as gently as possible to remove the wax again by melting it.

2.1 Flash-fire

As we all know, many roads lead to Rome, so there were a lot of ideas around the subject of dewaxing. The oldest, easiest and most effective possibility was the burnout, which at the same time solidified the shell and melted the metal. Nowadays things are certainly not that simple any more, but the “flash-fire” which is still applied, is a late descendent of the archaic process. The shell is put into an oven which was preheated to at least 850°, the wax inflames immediately, melts, leaks out and burns.

At the same time, the ceramic shell is bisqued to a fireproof casting mould. This way you kill two birds with one stone. Disadvantage: It generates very much smoke and soot so that this procedure is hardly permissible in Europe with regard to the current maximum allowable emission values. Furthermore the scrap rate is quite high, because the wax expands before melting and burning, and damages the shell.

It is still often used in the USA, which has the most investment foundries, also for historical reasons. In Europe, the dewaxing with “flash-fire” is quite unusual; also in Asia and India, it is barely used.

2.2 Wax dip

On the Indian subcontinent another simple but effective method is applied, the dipping into boiling oil or even wax. Depending on the specific boiling point the temperature is between 130 and 180°C. Provided that it is correctly dipped in, the wax liquefies in the shell and leaks out. The equipment is quite simple: An oil barrel which has been halved lengthwise and a gas burner, and that’s it. Under most bizarre conditions the shells, which are hanging on wires, are dipped manually into the boiling oil or wax. Numerous and severe accidents are willingly tolerated, as well as a re-soaked and therefore weakened shell.

2.3 Microwave

Recently some investment foundries are tentatively using microwaves for dewaxing. The waves penetrate the mould shell and bring the water, which is bound in the wax to the boil, which makes the wax liquefy and leak out. On principle this technique works quite reliably, but it has two serious disadvantages:

1. It only works in the non-metallic field, i.e. all wax bunches with steel cores, nuts or screw threads, and these are definitely more than half of the bunches, are not suitable for this process.

2. The heart of a microwave, the so-called magnetron, is extremely expensive for industrial equipment and must be exchanged at least once per year in everyday use.

This might be an explanation for the fact that microwaves are still used quite rarely.

2.4 Convection oven

This procedure works as follows: A sometimes deep-frozen bunch is put into the oven, which was preheated at 165°C. The hot air melts the wax from the inside. The deep-frozen shell is supposed to ensure a higher stability. The emphasis is on “supposed to”, for in practice many shells split and burst, and therefore the procedure is mainly used in the field of Rapid Prototyping and individual production. The investment costs are extremely low, in the simplest case a household convection oven would be sufficient.

2.5 Steam autoclave

The worldwide most common method for dewaxing is still the steam autoclave. The principle of autoclaves has been known for a long time and traces back to the French Denis Papin in the year 1674, who is considered to be the inventor of the steam engine and the submarine. He puts the awareness into practice that the boiling point of water is directly related to the ambient pressure. At a low ambient pressure, which exists for example in the highlands, water starts boiling and passing into the gas phase already at 70°C. If the pressure is increased accordingly, the effect inverses and the boiling point increases as well. At a pressure of 10 bar, water begins to boil at 183°C and exactly this effect is used for the steam autoclave in order to get a higher energy density.

Also in our daily lives we are faced with this technique. The pressure cooker is nothing else but an autoclave, which enables you to cook quickly and therefore cost-efficiently. But Papin's invention does not only bring our potatoes to the boil more quickly, his pot is also used in the medical sector, for example for sterilization, in the food industry for the preservation of canned food and in the industrial sector for the production of laminated safety glass.

And one day an investment caster had the good idea to misuse such a vapour pressure boiler to dewax his mould shells. This technique works as simply as efficiently, such a "steam engine" consists of only a few components, and because of the high energy density of water vapour it is perfectly suited for quick melting.

3. The process

First of all there is the steam generator, a boiler, which is half filled with water that is brought to the boil by means of electric heating elements or a gas burner. As soon as the right pressure and temperature are reached, the so-called transition valve is opened and the saturated steam with a temperature of 183° passes into a second boiler, which contains the two shells, at just below sound velocity, namely with up to 260 m/sec. In order to increase the degree of efficiency and to preheat the inner boiler for free, the steam generator boiler is usually arranged around the inner boiler, i.e. the actual autoclave.

After the pressure compensation, the high-energy steam precipitates at the bunches, condensates and through the shell it immediately transfers its heat to the wax. The surface melts, the wax leaks out and partially penetrates into the mould shell. Since all this happens very quickly, the shell does not suffer any expansion and crack formation. If one parameter is not right, or if the pressure is generated too slowly (and achingly), the scrap rate also bounces up in the autoclave.

After 10 – 20 minutes the pressure in the boiler is reduced by opening another valve. And as soon as it matches the ambient pressure, the special door can be opened by a kind of bayonet lock, and the perfectly dewaxed bunches can be removed – in the ideal case.

Nevertheless, the following still applies: It is not the casting process, where liquid metal is filled into the shell, that means the highest stress for it. It is rather the very unspectacular (since almost invisible) process of dewaxing that means the worst torture for the green strength ceramic shell and decides on top or flop.

3.1 Working with excess pressure

A lot helps a lot. Transferring this simple perception to the autoclave process, it means that the steam generating boiler should be sufficiently large in order to be able to start the process with a convenient surplus of saturated steam. As a rule of thumb, the volumes of the two boilers, i.e. the pressure generator and the actual autoclave, which contain the shells, should be about 1.3 : 1. This is the only way to make sure that filling the empty boiler with steam, i.e. a steam inlet under optimal conditions, lasts about 4 seconds. With every shell that is brought into the autoclave for dewaxing this time is extended, because the cold surfaces of the shells makes the steam condensate and requires more energy.

Ideally, the pressure in the steam generator should therefore be higher than 10 bar and the temperature should be 183°C to make sure that even in the case of a complete filling of the autoclave the maximal pressure is reached in less than 10 seconds. Only at this temperature it is guaranteed that only saturated steam, that means an optimally balanced mixture of air and steam streams in. In the worst case, falling below these values leads to cracks in the shell and slows down the process, exceeding them wastes energy.

3.2 Symmetric steam inlet

Not only the filling speed has an enormous influence on the dewaxing result and the scrap rate. Also the way of steam inlet is of an often underestimated importance. Usually there is only one point where the vapour streams in and diffuses quite asymmetrically. As a consequence, there are shells which have a “box seat” and others, which have to wait for the steam to reach them. The ideal thing is therefore a steam inlet from both sides over the total depth of the autoclave in order to fill the interior quickly and steadily. This aerodynamic trick has proven itself in practice and helps to reduce the scrap rate considerably.

3.3 Optimal steam inflation

When working with steam autoclaves of the latest generation, another trick is applied in order to reach an optimal inflation. In the standard process applied so far, the door was locked at the beginning of the process, i.e. in the autoclave sector there was 1 bar filled with standard air and the pressure generator was charged with 8 bar water steam. By opening the transition valve, these 8 bar of vapour streamed into the autoclave boiler, blended with the air of one bar and the pressure decreased accordingly and reached an effective steam pressure of 7 bar.

Today we use a so-called “delayed shut-off valve” in order to avoid this reduction of efficiency. A special control unit allows the retarded closing of the outlet valve in the area of 0.1 -1 second. This way the inflating steam pushes the cold air forward to the outlet valve and pushes it out before it closes and the pressure can build up. The benefit of this switching trick is obvious: The saturated steam inside is no longer diluted, but the shell gets the energy from the “truthful” 8 bar, which corresponds to an efficiency increase of 12%.

3.4 Perfect pressure reduction

However, pressure intensity and filling speed are not the only guarantors for success of the dewaxing process, much damage can also be caused by a wrong depressurization. During this process step we are still dealing with an unburnt ceramic, which takes offence at any rude treatment. If the pressure decreases abruptly, the high flow velocities in connection with the residual wax adhesion and wax penetration can lead to spallings and micro cracks, with the appropriate fatal results for the subsequent cast. So we have to treat the shell like the proverbial “raw egg” and to initiate a harmonious, i.e. homogenous pressure reduction. The following figures clearly show what pressure reduction means: One litre of saturated steam under 10 bar corresponds to 1,000 litres normal steam when it is released into the atmosphere – it howls and hisses enormously and must be controlled accordingly.

A normal "dumb" valve cannot be used for this purpose, because as a digital system it only knows "open" or "closed", intermediate positions are not possible. In this case so-called "smart valves" are required, i.e. an intelligent valve which controls the pressure reduction autonomously. In accordance with a determined period of time in which the overpressure should be neutralized again, the valve opens, checks the pressure decrease within a time slot and extrapolates accordingly. If the pressure is decreasing too fast, it reduces the outlet and vice versa. This check-up and readjustment takes place within steps of milliseconds and therefore guarantees almost iteratively a perfect pressure reduction along an arbitrary line.

Those who still think it is too fast can select a ramping function. The valve closes according to freely selectable units of time in order to hold the pressure constant. The decompression does no longer occur along a line, but in "sloping" steps. At least for very sensitive shells, this is another way to an even more gentle process and helps to minimize the scrap rate.

3.5 Water processing

In terms of figures, an autoclave is designed for 200,000 load cycles. Under normal conditions this corresponds to about 25 years of continuous operation. In practice, however, the service life is determined by many factors, in the first place of the water quality. Water is continuously added to the process and under the influence of energy, i.e. heat, it turns into steam. Since this steam consists mainly of distilled water, all impurities of the feed water, such as lime and salt precipitate in the steam generator. So if you want to avoid that the expensive autoclave looks like a limestone cave with oxidations and calcifications after a short time, it is worthwhile to invest in a suitable water processing. The processing is structured in 4 single steps, 2 outside the autoclave and 2 within the autoclave.

The water inlet is equipped with a softening system, which bonds as many minerals as possible, such as calcium carbonate, and prevents them from entering into the storage basin. In a second control circuit the ion concentration is measured and adjusted by adding appropriate alkalizers. If the feed water has been processed properly, this is very helpful to reduce deposits in the boiler and at the heating elements. However, it is impossible to avoid them completely.

Therefore it is necessary to provide for a proper water processing also within the machine. For this purpose the calcium and salt content of the water is measured continuously. As soon as a critical value has been exceeded, a so-called draining valve at the boiler end opens, creates a swirl, disperses the lime scales and drains them off. In the upper section there is a conductivity probe, which skims and drains off the salty upper layer of the water by means of a control valve and replaces it by adding fresh water.

These 4 single steps ensure a perfect water processing and provide for a long-lasting and trouble-free operation. These measures are complemented by the installation of a so-called buffer. At the downstream side this decompression boiler and mixing cooler ensures that no boiling water and no pressurized steam directly reach the drain line and destroy it sooner or later.

3.6 Waste-wax collection

The disposal of all materials is as important as a clean processing itself – in our case, apart from the empty ceramic shell, this is wax. In most cases only little attention is attached to this chapter and a tub which is put underneath must suffice as a collection container.

Usually, the efficiency of steam-heated wax outlet tubes is also quite limited. If, for whatever reason, the steam generation fails, the wax “freezes” in the tube and it is very difficult to remove it. An electrically heated outlet tube, which always works, and which actively drains the wax from the boiler into a special big bag by using the residual pressure of about 0.8 bar, has therefore proven successful. It is a completely closed system and allows a nearly clean process. As soon as the big bag has been filled, the carriage is pulled out and the wax bag is exchanged against an empty one. The waste wax can be removed for recycling in the big bag.

Another “waste product” besides of the wax is the condensate, which precipitates at the inner surfaces, in the worst case interfuses with the wax, and causes enormous puddles of water when opening the autoclave. A simple and automatically working condensate valve, which is mounted in the autoclave boiler underneath the wax collection container, drains the water into the buffer and also provides for a clean working.

3.7 Clean and safe

However sophisticated all these components and auxiliary techniques may be, they help only indirectly in the case of trouble-free operation and perfect dewaxing results. At least as important as the automatic water processing is the daily cleaning of the system and a conscientious maintenance. For there is one thing that should not be underestimated: hot and pressurized saturated steam is one of the most aggressive media. Its hazardousness should not be underestimated, because in the long run it destroys seals, valves and tubes. There is good reason why a fourfold TÜV inspection is required to operate an autoclave. Apart from the welding and pressure inspection of the boiler there is a complete acceptance test of the system at the manufacturer’s facility. Finally the admission board wants to view the standardized and safe installation at the operator’s place – and then they get the formal blessing – but only for half a year. Then the first review is due. After 9 years there is a complete revision and the system, especially the boiler, must be opened and inspected thoroughly.

All this goes back to the beginnings of the Industrial Revolution, where exploding boilers in coal mines or factories killing worker were common occurrences. Therefore, our present very strict autoclave guidelines date back to this time, and it is due to them that today the autoclaves work reliably and safely over many years.

4. Prospects

The need of high-quality investment casts is permanently growing, and all over the world, especially in India and China new huge factories are built in the open countryside. As a rule, several lines are installed in parallel, but in most cases there is only one autoclave for the whole production. If everything works well, this is no problem, but if the "bottleneck" autoclave fails, the production stands still. The whole wax and shell construction is a continuous, i.e. fluent process. Only the autoclave works discontinuously and with batches, due to its pressure cycles. If it stands still, the production manager has a problem – a big one.

The simplest solution would be a redundant system, i.e. the investment in a second autoclave. But this is what many companies are afraid of, and they prefer the "ride on the razor blade". So what should be developed to make the process even more safe? Autoclaves in the future should definitely be extremely failsafe and all important components should be installed at least twice.

If possible, they should work more energy-efficiently, because with their power input of at least 100 kVA they are real power guzzlers. And maybe it is possible, at least on long term, to reach a continuous flow process. For as long as nobody invents a self-fusing or imploding wax, they will still be needed, these hissing and stinking and archaic monsters – but in fact very modern steam engines.

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