Ecological impact of a sapphire cover on a typical mechanical Swiss watch

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Abstract

Sustainability is an increasingly important concern for both consumers and manufacturers alike. Sapphire is an essential component in modern watches due to its outstanding transparency and hardness. However, its exceptional characteristics also make its processing highly energy-consuming, and only a fraction of the material produced is turned into final parts.

The current body of work presents a partial audit of the environmental footprint left during production of a mechanical watch equipped with sapphire glass. It is inspired by and based on D. Weber's report *"Case Study of the Ecological Impact of a Typical Mechanical Swiss Watch.*[1]*"* The current article reviews the energy and CO_2 impact of manufacturing a watch's sapphire more profoundly, complementing theoretical estimates with factual data from the industry.

Excluding the embodied material energy, D. Weber's analysis showed that 61% of the energy used for manufacturing a watch — and, therefore the main CO_2 emission — is attributed to the manufacturing of the sapphire cover. We explain why real values are even higher: the sapphire cover represents up to 88% of the total watch manufacturing energy and CO_2. This article reveals and discusses potential solutions for the watch industry to reduce its environmental footprint.

Résumé

La durabilité a une importance croissante pour les consommateurs et fabricants alors qu'agir pour un futur viable devient urgent pour tout un chacun. Le saphir est un composant essentiel dans les montres modernes, utilisé pour sa transparence et sa dureté exceptionnelle. Ces caractéristiques rendent sa transformation en produit fini gourmande en énergie, et seule une fraction du matériel produit peut être transformé en pièce finie.

Dans cette étude, nous présentons un audit partiel de l'impact environnemental de la production d'une montre mécanique équipée d'une glace en saphir. Cette étude est inspirée par et basée sur une publication de D. Weber intitulée *"Case Study of the Ecological Impact of a Typical Mechanical Swiss Watch.* [1]*"* Dans la présente étude, les aspects concernant le saphir sont étudiés plus en profondeur, en se basant sur des données industrielles.

L'analyse menée par D. Weber a montré que 61% de l'énergie consommée — et donc de CO_2 émise — dans la fabrication d'une montre est consacrée au verre saphir. Nous expliquons pourquoi les valeurs réelles associées à la fabrication du saphir sont considérablement plus élevées et sont responsables de jusqu'à 88% de l'énergie et des émissions de CO_2 de la production totale de la montre. Cet article révèle les raisons qui se cachent derrière et discute des solutions potentielles permettant à l'industrie horlogère de réduire son empreinte écologique.

1. Why does it matter?

The world is striving to reduce CO_2 emissions and energy consumption. Watches should not be exempted from this endeavour. Understanding how and where the watch industry uses energy is essential to identify areas that contribute the most to the emission and find innovative solutions to reduce their footprints. Such concerns are particularly relevant to Switzerland: a country renowned for its large watch manufacturing industry as well as its commitment to reduce its environmental footprint.

Energy consumption also has direct financial consequences for manufacturers. Growing demand for energy could lead to higher prices, as well as higher taxes, as States apply pressure to increase energy efficiency.

Environmental organisations often criticise watch manufacturers. According to an environmental rating and industry report from the Swiss WWF in 2018,[2] *"[...] Most of the surveyed companies have taken no or very limited steps to actively counter climate change. The problem of climate change itself and the global challenges associated with it have not been appropriately addressed, no ambitious targets have been set and no notable measures have been taken by the industry."*

Moreover, it revealed: *"There is a lack or even non-existence of reporting and transparency among the evaluated brands, and an apparent absence of commitment to determined action, [...]. This is highly undesirable for the environment, but also for consumers, investors, communities, political bodies and other stakeholders. Furthermore, it is a major economic and reputational risk for the industry itself."*

On consumer sentiment, the Swiss WWF reported: *"Sustainability has become a key factor for consumers. There is an evident trend for a transition towards more sustainable patterns of production and consumption. [...] Customers are now demanding leadership from brands to succeed in dealing with planetary challenges: they expect more responsible stewardship of natural resources and the environment and more transparency."*

2. How is energy used in the making of a typical mechanical Swiss watch

2.1 The watch under study

The study was conducted by a class of engineering students led by Prof. D. Weber,[1] who designed a 'typical' watch. It features a circular dial, a domed sapphire watch cover, and a seconds dial that is offset (Fig. 1). The movement is mechanical with manual rewinding and oscillates at 3 Hz. The watch consists of 147 components and features a metal case of diameter 40 mm and a thickness of 15 mm.

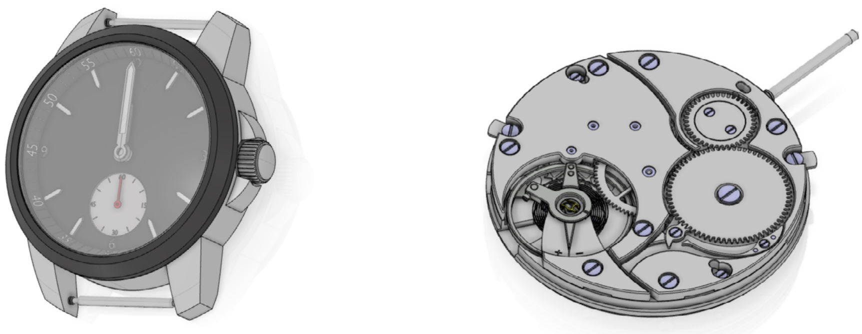

Figure 1. The watch under study: habillage (left) and movement (right).

2.2 Methodology

The partial[1] eco-audit focuses on embodied and manufacturing energies.

- The *embodied energy* is the energy required to create a rough part (ingot, chunk, etc.) which eventually leads up to fine processing.

- The *manufacturing energy* is the one required for processing the rough part into a final ready-to-use item.

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[1] *A complete eco-audit of a watch would also include studying raw material mining, transport, maintenance and recycling.*

While working with a dedicated database, D. Weber selected the materials that represent watch production as close as possible. Certain special alloys that did not exist in the database were replaced by their most resembling equivalents in terms of composition and physical properties.

The processes were also chosen to be as close as possible to reality within the limits of the database, which encompasses: casting/injecting, roll forming, forging, extrusion, machining, grinding, and non-conventional machining. For surface treatments he considered electroplating and, for the dials, painting.

All values are based on best estimates and represent high-volume production.

The amount of CO_2 emission is usually proportional to the consumed energy, but the source of energy itself significantly impacts the CO_2 emission per kWh. For example, while a typical coal-fired power plant would emit 0.8-1.2 kg of CO_2 per kWh,[3] a hydropower reservoir such as a dam would only emit equivalently 23 grams of CO_2 per kWh.[4] Therefore, the results for the CO_2 emission would vary substantially depending on the country where the watch is manufactured. In Switzerland, the CO_2 equivalent is around 89 grams of CO_2 per kWh[5], while the worldwide average is around 475 grams.

Taking the above into account, we ask the reader to focus on the proportion between the footprints of the watch parts rather than on absolute values.

2.3 Results of D.Weber's study

D.Weber's article shows that, in the analysed case, embodied energy accounts for 86% of the total energy of the watch production, and manufacturing energy accounts for the remaining 14% [1]. The biggest amount of embodied energy stems from transforming Al_2O_3 into raw sapphire. The exact value depends on the growth method to produce the crystal.

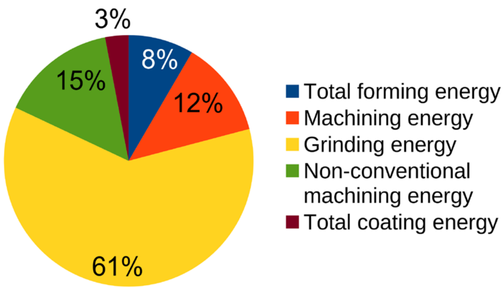

Figure 2. Processing energy proportions of the entire watch, as presented in [1].

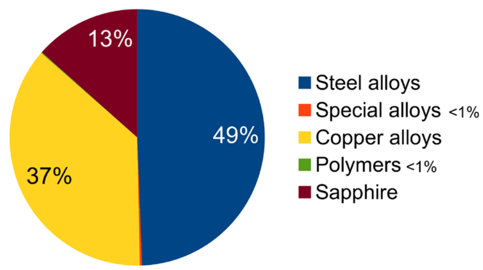

Figure 3. Repartition of the energy consumption per material group, as presented in [1].

In Figure 2, we see which processes require the most energy for the watch. Grinding stands out as the biggest consumer.

A typical mechanical watch will generally use several steel parts, some copper alloys, ruby, special alloys for springs, polymers for the hermetic seal, and sapphire for the cover.

Figure 3 presents the importance of these materials in the total energy requirements. We see that steel, in particular stainless steel, requires the biggest energy portion. It isn't a surprise, as steel constitutes roughly 38% of the weight of the final watch. Copper alloys are also well represented, as they are used for the gears and a lot of material gets removed during processing. The third is sapphire, with 13% of the energy cost, while it represents only 7% of the total weight. Figure 4 shows the total energy requirements (embodied + processing) of each material per unit weight.

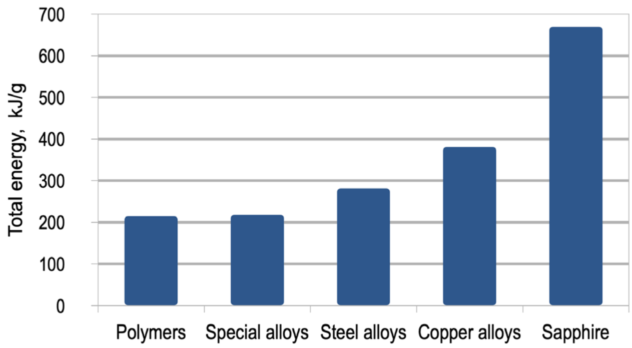

Figure 4. Total energy per gram of watch materials, as presented in [1].

2.4 Grounds for re-evaluation

Considering information obtained from crystal manufacturers and an evaluation of the efficiency of sapphire production, our study reveals that the actual energy values of sapphire are several times higher than those in D. Weber's publication[2].

The main reason is the relatively low extraction efficiency in sapphire production. While Weber's study uses a database value of the energy cost of sapphire, it does not take into account the amount of sapphire lost at different processing stages in order to produce one gram of quality crystal.

Figure 5 shows the proportions of energy required for the sapphire cover versus the rest of the watch parts.

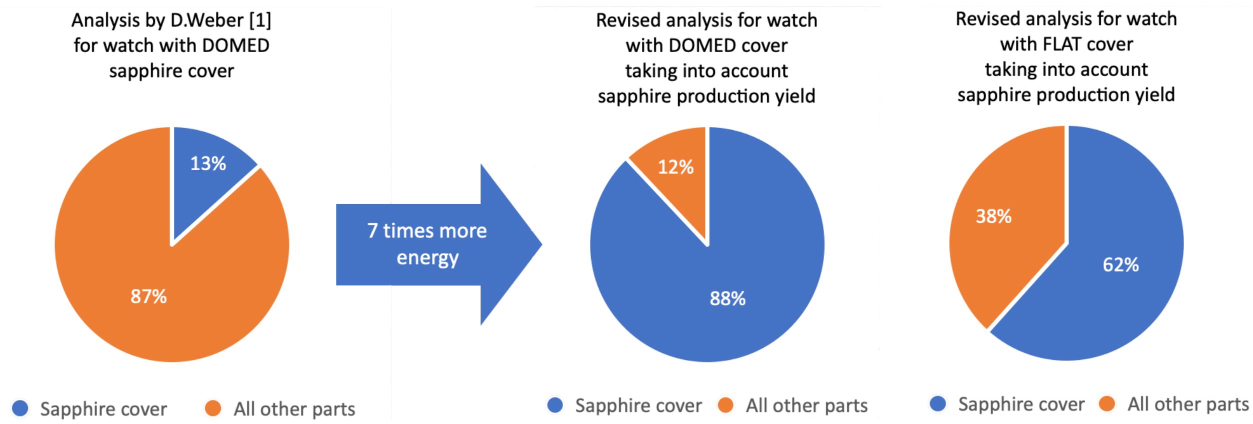

Figure 5. Pie charts of the total energy partition per parts. Left: as in D. Weber article for dome cover [1], middle: re-evaluated with sapphire production yield for dome cover, right: re-evaluated with sapphire production yield for flat cover.

[2] *The values for the rest of the watch are assumed to be correct, although the evaluation of micro-machining and special processes as used in the watchmaking industry may differ from the mean database values for standard mechanical machining, as mentioned in D. Weber's study.*

According to D. Weber's study, while the embodied energy of the sapphire is about 6% of the embodied energy of all other components, the manufacture of the sapphire cover is of staggering importance, accounting for 61% of the total manufacturing energy consumption. Normalized for the amount of sapphire material present in the watch, the sapphire cover accounts for about 13% of the total energy requirements (Fig. 5, left).

Our revised analysis, which takes into account the practical efficiency of sapphire extraction, provides values about 7 times higher. The total energy of sapphire amounts to 88% of the whole watch with a domed sapphire cover (considered in the study by D. Weber) and 62% of the whole watch in case of a flat dial cover (Fig. 5 middle and right, respectively).

Let us look at the detailed justifications.

3. What makes sapphire manufacturing so energy-intensive?

There is often a wrong perception of the embodied energy associated with a final watch cover.

A manufacturer of raw watch covers delivers to its customer only the sapphire that meets the quality requirements. However, before that stage, a significant part of the initially grown sapphire had already got rejected for various reasons. They include the irregular shape of a raw crystal, a highly defective seeding area and the proximity of the surface, which is usually defective. A manual quality controller usually exacerbates these factors by taking a large safety margin to avoid delivering a defective piece.

3.1 Re-evaluation of sapphire's embodied energy

Although there are several methods for producing sapphire crystals, all of them are based on melting Al_2O_3 powder (High Purity Alumina, HPA) and then cooling the melt in a controlled way to allow crystallisation. The current study does not include the most upstream stages, such as ore extraction. It starts with sapphire crystallisation and covers all downstream stages (Fig. 6).

The common crystallisation methods to supply sapphire to watch industry are *Verneuil, Kyropoulos* (KY) and *Edge-defined Film-fed Growth* (EFG, also known as Stepanov). The *Heat Exchange Method* (HEM), although not yet commonly used in the watch industry, represents a competitive alternative.

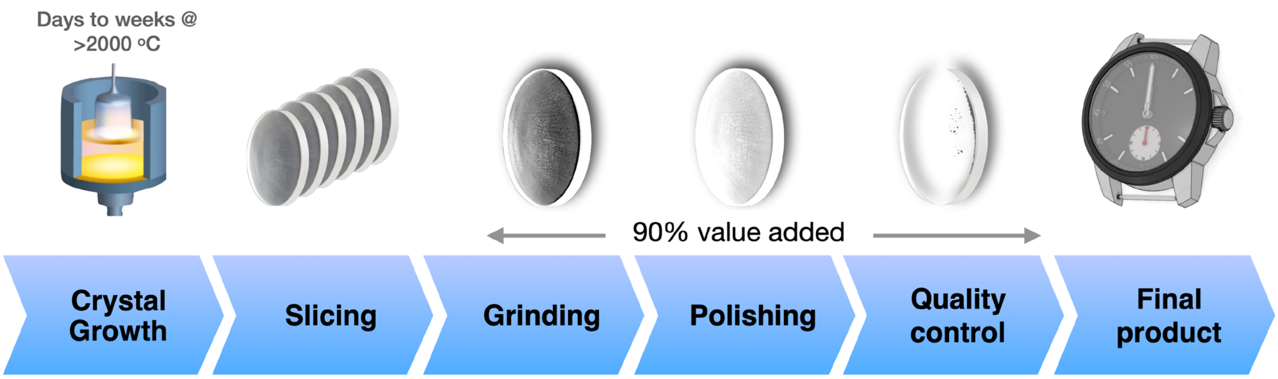

Figure 6. Typical processing steps of a sapphire cover in the watchmaking industry.

a) *Verneuil method* consists of dropping HPA powder on a crystal seed. The alumina powder is falling through hydrogen-rich flame and getting in contact with a molten layer of early-grown sapphire, where it melts, then cools down and crystallises. Due to the stress induced by high temperature gradients, the resulting carrots have to be annealed for several hours in an oven to reduce the tension. The annealed carrots are then machined to a cylindrical shape. The carrots typically reach Ø20-45 mm and 80-180 mm in length. Extracting a cylinder from a raw Verneuil carrot creates >70% volume loss due to the cutting of the head and bottom and the grinding of the carrot's irregular shape to its smallest diameter (see Fig. 7 as example).

Verneuil method requires 1'800 kJ to produce a gram of sapphire in an annealed carrot. It assumes that the hydrogen has been produced by electrolysis.

b) *Kyropoulos method* allows getting bigger crystals, ranging from 10 to over 400 kg. The technique consists of melting HPA and sapphire crackles in a crucible, inserting a seed at the top, and pulling it upwards while slowly rotating and closely monitoring all the temperatures. The process may take several weeks, depending on the crystal size.

Kyropoulos method consumes around 920 kJ per gram of raw sapphire produced. The figure can increase up to 50% depending on the manufacturer and the sizes of the boules. The extraction yield for a large Kyropoulos sapphire is around 27% if one extracts cores for watch covers.

The 73% remaining volume is the spaces left between the extracted cores.

c) *The HEM method* seems the most efficient as it requires ~350 kJ per gram of raw sapphire, and its form factor allows an extraction yield of 35% to 40%.

The energy consumption of the *EFG method* is comparable to Verneuil, but the sapphire volume produced by this method is much lower. Therefore, we will not examine it separately.

The wasted sapphire blocks can be re-used for growing new crystals with KY, HEM, or EFG methods. It requires milling them to grains of a few mm size.

Once the cores have been extracted from either Verneuil, KY, or HEM crystal, they must be sliced, ground, and polished to create the final watch cover. It induces a minimum ~15% of additional loss of the material. The loss is higher in the case of curved shapes.

The watch industry has been progressively changing the mix of growth methods for the last couple of years, and this trend is accelerating with the 2022 geo-political tensions. We will therefore base our calculation for the whole watch industry on a hypothetical equal production split between Verneuil, KY, and HEM sapphire.

Considering all the above factors, the embodied energy of a final sapphire watch cover is equal to 3'676 kJ/g (line 4 in Table 1).

		Energy for raw material [a] kJ/g	Scrapping factor [b] %	Form factor yield [c] %	Yield of cores [d] %	Slicing Yield [e] %	Combined yield [f] %	Energy for final product [g] kJ/g
Current growth methods with manual quality control								
1	Verneuil	1’800	10	42	87	85.1	28	6’431
2	Kyropoulos (KY)	923	4	34	95	85.1	26	3’498
3	Heat Exchange Method (HEM)	360	5	45	90	85.1	33	1’099
4	**Averages [h]**	**1’028**	**6**	**40**	**91**	**85.1**	**29**	**3’676**

Impact of digital quality control (DQC)							
5	Potential improvements with DQC, in ppt [i]	1 ppt	5 ppt	2 ppt	3 ppt		
6	**Average after introduction of DQC, %**	**5**	**45**	**93**	**88**	**35**	**2’933**

Impact of digital quality control at the scale of the Swiss watch industry (21 millions watch covers /year)		
7	Reduction in embodied energy, assuming an average cover weight is 5 grams	7.8 E+10 kJ per year
8	Reduction in CO_2, assuming a worldwide average conversion factor of 475g CO_2 per kWh [j]	10’295 tons CO_2 per year

Table 1. Ecological impact of sapphire watch covers.

(a) Energy to produce 1 gram of raw sapphire. For the Verneuil method, we counted electrolysis-generated hydrogen.

(b) Amount of raw crystals entirely scrapped after crystallisation due to significant volume defects.

(c) Volume of cylindric cores that are extractable from raw sapphire crystal. This factor can vary by +/- 10 ppt depending on the boule size and the extracted core diameter. The factor includes the top and bottom parts of the crystal, which are usually quite defective.

(d) Yield of the extracted cores. Please note that the most defective volumes have already been removed in (c) above. The values represent a typical quality grade observed for each growth method. This factor can vary by +/-5 ppt and also depends on manual quality control performed today in the industry.

(e) Slicing yield to cut 2 mm watch cover, assuming a 0.35 mm loss during slicing, grinding, and polishing

(f) Combined yield taking into account (b) to (e)

(g) The energy required to obtain 1 gram of final sapphire watch cover that qualifies the industry quality requirements.

(h) Average energy required to obtain 1 gram of final sapphire watch cover that qualifies the industry quality requirements. The values assume an equal production split between Verneuil, Kyropoulos, and HEM growth methods.

(i) Takes into account improvements in the growth yield, processing yield, as well as reduction in the machining of initially defective pieces due to digital quality control.

(j) As the raw sapphire is produced globally, we used emission coefficient of 475 g CO_2 per kWh, which is the worldwide average https://www.iea.org/reports/global-energy-co2-status-report-2019/emissions

3.2 Sapphire manufacturing

The steps to produce a circular watch cover generally include (Fig. 6):

- coring (for KY method) or rounding (for Verneuil) — see section 3.1
- slicing into raw discs, commonly named *préparages*
- grinding
- multiple stages of chemical-mechanical polishing, from rough to final.

Coating and metallisation may be applied optionally.

Slicing is an operation done with diamond wires and a cooling liquid. The total energy required for slicing a 36 mm blank is approximately 55 kJ, although this energy only accounts for powering the machine, and it is based on an estimate of power and time.

Next, a crystal is ground to correct exterior dimensions. At this stage the required energy highly depends on the final shape of the cover. A domed sapphire cover will typically lose 80% of its weight during the process, while a flat one would only lose between 5 and 15%. A complicated geometry will also often require a multi-axis machine, which further augments the energy expenditure.

Sapphire watch cover	Raw weight, *g*	Final weight, *g*	Embodied Energy, *kJ*		Cutting and grinding energy, *kJ* (a)	Total Energy, *kJ*		CO2 emission, *g*	
			KY	*Verneuil*		*KY*	*Verneuil*	*KY*	*Verneuil*
Flat	16.47	4.61	16’124	29’648	1’255	17’379	30’903	430	764
Dome	73.14	4.57	67’508	131’651	9’055	76’563	140’706	1’893	3’479

Table 2. Weight and energy consumption for producing a flat or a domed sapphire cover. It assumes 89 g of CO_2 per kWh (Swiss emission energy mix) [5].

Table 2 reports the weight and energy consumption values necessary for the manufacturing of two typical watch covers.

During the grinding process, a flat and domed sapphire of 36 mm in diameter is estimated to consume 1.2 MJ and 9 MJ energy, respectively.

Assuming that the sapphire is grown and processed in Switzerland the total energy to produce a dome sapphire cover from a Verneuil carrot is equal to driving 34 km in a modern car emitting 100 g of CO_2 per km. This may appear little, but significant portion of the 21+ millions sapphire watch covers is processed in different regions where the electricity production emits 4 to 8 times more CO_2 per kWh.

The next chapter considers what can be done to reduce the embodied energy.

(a) Does not count the energy required to extract cylindric cores from raw crystal.

4. What can be done to reduce the environmental impact of watch sapphire?

On a superficial level the solution could be to abolish sapphire altogether and use a less energy-intensive crystal, such as spinel, to protect the dial. The problem is that sapphire is used in watchmaking because of its hardness (9 of 10 on the Mohs scale), allowing scratch- and abrasion-resistant dial covers.

Figure 7. Verneuil-grown sapphire crystal (left) and its digital twin with defect pattern and wafering plan (right). The extraction yield (green: defect-freepréparages) is 33.6%.

Any ersatz would be softer and hence less durable, making it unlikely for Swiss watch brands to accept such a decrease in aesthetic and lifetime. While a sapphire substitute may be discovered in the future, today it remains rather a hypothetical option.

Decreasing energy consumption during crystal growth is also not very likely. The crystallisation energy of sapphire is determined by the nature of its atomic lattice. As a reminder, to grow a sapphire (regardless of the method), one must first melt Al_2O_3 powder at ~2050°C, which is one-third of Sun's surface temperature, and then maintain this temperature for several hours to several days. Thermal insulation technology for furnaces and crystallisation techniques are constantly improving, but it is hard to expect a significant breakthrough in this area anytime soon. Instead, we are convinced that the fundamental solution lies in smarter growing and smarter processing of sapphire.

All calculations in this article are given per a single watch disk. However, to produce one watch disk of a complex shape weighing 4.5 g, one must grow and use up to 107 g of sapphire.

Let's understand why.

The first losses occur when a freshly-grown crystal is cored into cylinders. It happens because of raw crystal geometry: when you cut small cylinders out of a carrot or a bell-shaped piece, it leaves a substantial volume unused. Typical extraction yield for a Verneuil-grown sapphire carrots is below 35%. Figure 7 shows an example of such 118 mm long carrot, containing one volume defect, sliced to 1.8 mm thick préparages. For KY-grown crystals, which are becoming increasingly popular with watchmakers, the yield is still in the same order (Fig. 8)

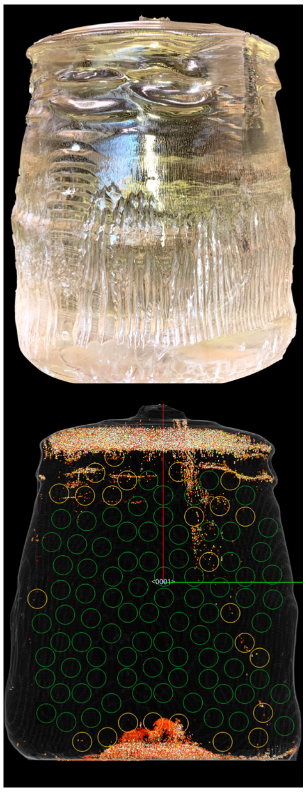

Figure 8. 260 kg KY sapphire (top) and its digital twin with defect pattern and coring plan. Green – defect-free cores; yellow – partly defective ones. The extraction yield is 31%.

But, even worse, some of the cored cylinders will also be discarded. It is due to crystal defects — tiny bubbles, micro-cracks, grain boundaries, etc. — which only become visible after cutting, sawing and polishing the blanks. The raw crystal surface makes it impossible for the human eye to see the vast majority of defects directly inside the raw crystal. And even when the most significant flaws are visible, it is impossible to tell precisely where they are. Sapphire has one of the highest refractive indices, therefore, the apparent position of a defect is substantially different from its actual one.

With other growth methods — Verneuil and EFG — the situation is similar. Despite some attempts to rationalize the process, the grown crystals are still inspected manually to mark only the largest defects. Then an ample space around such a mark is abandoned to avoid the risk of including a defect.

A large proportion of the raw material containing micro-defects still enters energy-intensive processing. In the authors' experience, in Switzerland 7 to 15% of fully finished sapphire glass is rejected because of internal defects. This is added to the losses at upstream stages as described above, where 24 to 107 gram of raw sapphire is currently used to produce just 4.5-gram flat or dome shape watch cover.

Such situation is calling for a principally new approach.

Switching to large-size sapphire crystals is nothing but a part of the solution. The use of large volumes essentially decreases the consumption of both energy and materials, so the ecological footprint per watch cover diminishes. The growth of one 200 kg crystal is less energy expensive than that of the corresponding quantity in smaller crystals.

However, the key solution lies in the smarter, more optimal use of sapphire.

The industry can enjoy both economic and ecological benefits by abandoning archaic human-eye controls and gut-feeling decisions, and switching to automated quality inspection and data-based process optimisation as, for example, the automotive industry, did dozens of years ago. Modern technologies enable the detection of defects directly in raw crystals, as well as an intelligent downstream processing that takes them into account.

Today crystal scanners can locate up to 96% of microscopic defects directly in raw crystals, whatever the crystal size is. Figure 8 shows a digital twin of a 260 kg KY crystal cored for the watch industry.

Such digital twins allow to:

1. Calculate optimal positions of future cores to keep crystal defects out of them, thereby minimising material wastage.

2. Obtain the maximum length of the cores, taking into account specific shape of each raw crystal.

3. Cut defective cores into préparages, considering location of their defects. Displacing the core to the wire grid by a little pre-calculated offset makes it possible to bring more defects in between discs, thus yielding up to 7% quality discs as compared to conventional cutting, see Figure 9.

4. Remove defective préparages before they enter energy-consuming grinding and polishing processes. With modern scanning technology, defective préparages can be identified based on the defectiveness of the crystal and its cutting plan. Or, alternatively, they can be sorted out by automated quality control straight after slicing.

These improvements are expressed in point of percentages (ppt) in line 5 of Table 1. A corrected average yield is calculated in line 6 of Table 1.

The combined improvements resulting from automated quality control scanners are calculated in lines 7-8 of Table 1. Only for the watch industry, it will bring a yearly saving of 16'661 tons CO_2. This is equivalent of ~20'800 modern cars emitting 100g CO_2/km driving each 8'000 km per year.

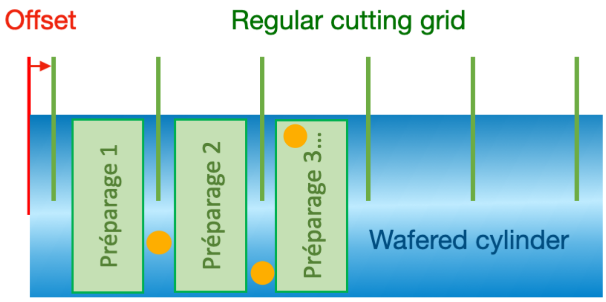

Figure 9. Principle of Smart Wafering: pre-computed offset of cutting grid increases the number of good wafers (patent pending). Yellow dots schematically represent defects.

Generally speaking, all the points above are about bringing Industry 4.0 digitalisation approach to sapphire makers. Unlike the human eye control used today, digital inspection is objective and allows gathering digital fingerprints of individual crystals as well as entire factory for fact-based production optimisation.

Scientific Visual is proud to be at the forefront of this development, and to offer smart processing technologies to its customers.

Conclusions

We examined in detail the energy consumption and CO_2 emission resulting from production of a sapphire cover of a mechanical watch. The study took into account footprints of the materials and manufacturing processes, as well as different watch cover shapes and crystallisation methods.

The study revealed that:

1. Both the manufacturing and embodied energy of sapphire are major contributors to the total energy required for the watch, reaching up to 88% of its total consumption and corresponding CO_2 footprint. The embodied energy of the materials is more important than the manufacturing energy, but it heavily depends on the process used.

2. Differences in growth methods and part geometry have a major influence on the energy expenditure.

3. The key solution to reducing environmental footprint lies in integrating Industry 4.0 approach for smarter and more eco-friendly use of the energy-expensive sapphire crystals.

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