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Implications of a resource-poor future for the development of armour materials

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ABSTRACT

We are using too much resources with too many people much too fast on a global scale. For a number of essential resources, amongst others regular oil and a number of metals, the maximum possible rate of production has been reached or will be reached soon, causing a growing gap between restricted supply and growing world demand. The problem of mineral resources is not so much the dwindling of supplies but the increasing amount of energy required to extract the same amount of minerals from lower ore grades while at the same time energy is steadily becoming less affordable. By getting by on less energy and resources and by using careful substitution, by recycling and by reusing we can anticipate the future restrictions in materials selection. Not coincidentally, important material technology breakthroughs from a less energy-intensive past may point towards armour material developments for future mass production which are suitable for a less energy-intensive future. Examples are armour steels using minor amounts of alloying elements (development started a century ago) and aluminium-magnesium alloys (developed half a century ago).

INTRODUCTION

Resource constraints are nothing new if you look into the history of humankind. A relatively recent example is shown by World War II (WWII) where the parties in the conflict ran short on items ranging from fuel to rubber and various types of metals. Substitution as a (temporary) solution is also nothing new. An example is the shortage of tungsten by the Unites States during WWII which they than substituted by molybdenum in tool steels and construction steels.

The major issue however is not so much the impending shortage of essentials minerals, but the looming energy crisis. Our present level of energy consumption, almost entirely based on fossil fuels, essentially dictates and enables our present way of living in a complex society with accompanying material wealth. Like any system with exponential growth, we will eventually approach the limits defined by nature. The signs of us reaching the limits are becoming recognisable for the informed mind at an increasing rate. We may be sleepwalking into a problem which is actually going to be very serious.

Governments, commercial producers and academic organisations (etc.) who accept the reality of decline and who understand that we will have to get by on less energy and fewer resources – possibly much sooner than most of us think – will have an advantage over those who don't.

The last part of this paper specifically addresses the possible implications of energy and minerals scarcity on affordability and availability of armour materials for mass production and gives recommendations for suitable future directions. The scope of this paper does not address specific applications (other than mass armour production) where special conditions may benefit special solutions. An example is the selective application of titanium armour in flying platforms where the cost of fuel consumption during the platform's life is a very strong incentive for weight saving.

ENERGY SCARCITY

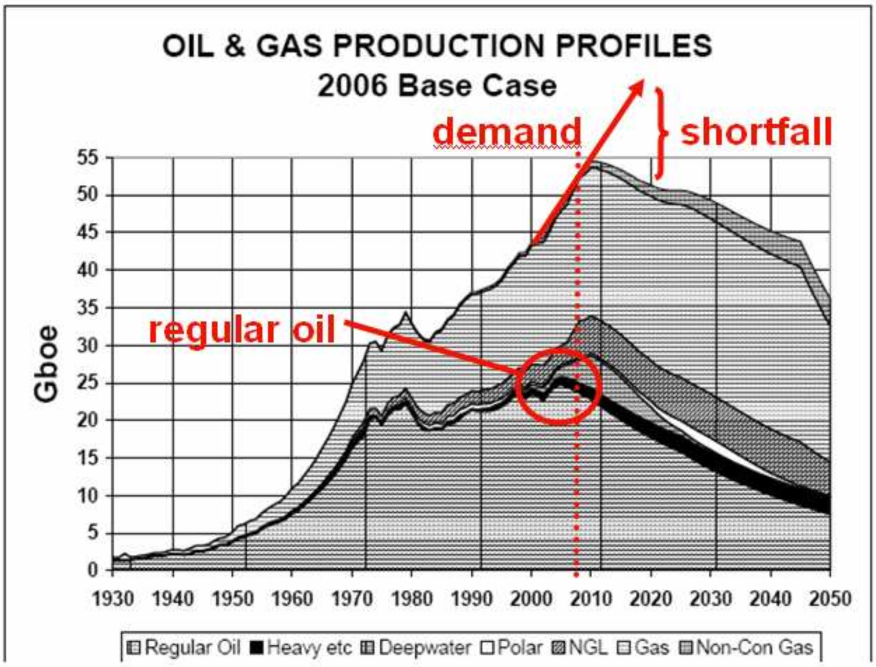

Figure 1: Past, present and future oil and gas supply (billion barrels of oil equivalent), including yet to be discovered supplies and including unconventional resources (tar sands and oil shale) [1]

The international Association for the Study of Peak Oil and gas (ASPO), originating from a lecture on oil depletion by Dr. Colin Campbell on December 7th 2000 at the university of Clausthal in Germany, has made a comprehensive and independent analysis of our worldwide oil and gas situation (see figure 1 [1]). The also independent Energy Watch Group (EWG), an international association of scientists and experts and initiated by the German member of parliament Hans-Josef Fell, supports the general "picture" of figure 1 and confirms the analysis that we are close at peak production of oil and gas [2]. The term “peak” means that the maximum possible rate of production is reached, so that supply can no longer grow and can no longer satisfy growing demand.

The picture given by figure 1 would be alarming enough at constant world demand. However, as world demand for oil and gas is increasing steadily year by year (currently driven by China, India and some major oil exporting nations like Saudi-Arabia), the ominous implication of this picture is a fast growing gap between demand and supply. Figure 1 also shows that the peak in regular (“easy”) oil production may already be behind us, and the accompanying shortfall has been made up until now by heavy oil, deepwater oil, gas condensates and stock withdrawals.

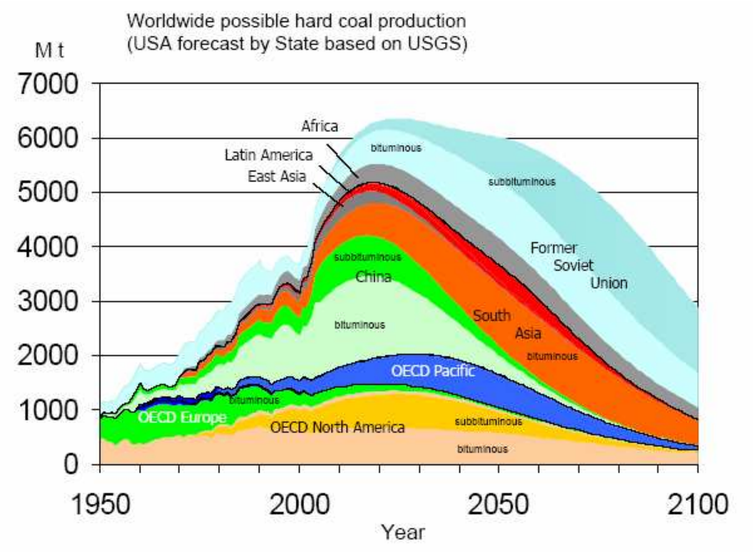

Figure 2: Past, present and future coal supply, including yet to be discovered supplies [3]

The overall energy picture becomes even more grim as we look into the alternatives of coal (figure 2) and nuclear fission (figure 3). “Peak coal” may be reached within a generation (around 2025) and there is insufficient rich enough uranium ore left to let nuclear energy bridge a significant part of the wide gap between energy demand and supply. It is being contested that the supply of uranium ores would be insufficient, however it takes about a decade (in today’s Western countries) to build and commission a nuclear power plant and it does not solve directly the growing supply gap of liquid fuels (mainly for transportation).

At the moment of writing this paper it is becoming clear that oil and gas use is partly being substituted by coal use, or rather that additional energy (electricity) is produced to a large part from coal instead of more oil or gas. This could help offset the downside slope of the curve of figure 1 to a plateau for the coming years, possibly changing a scary scenario (higher demand but lower supply) back into an alarming scenario (shortfall between growing demand and plateau supply) for the next years.

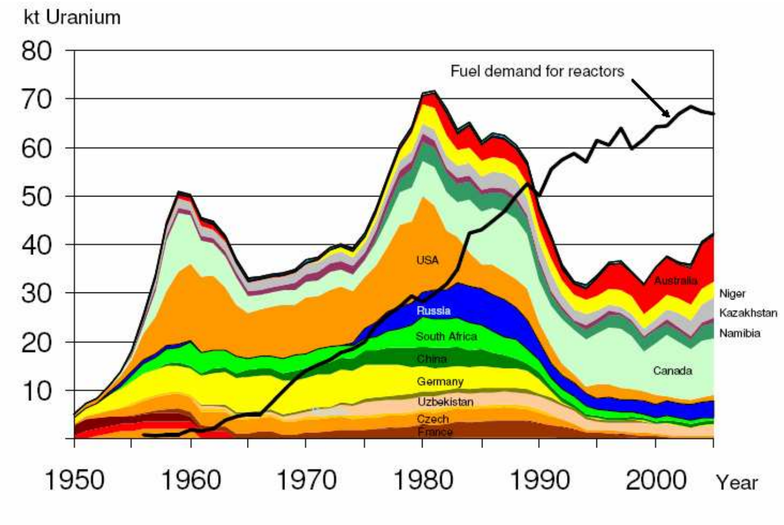

Figure 3: Past and present uranium supply [4]

Alternatives like solar and wind energy, essential as they are and will continue to be, offer only part of a solution for bridging the impending wide gap between energy demand and supply on a global scale. We have no economically scaleable alternatives to oil as the current global use is 30 billion barrels of oil per year. Discussion of this topic is outside the scope of this paper (further reading: start at [5]). A general remark is that viable solutions should be analysed in terms of energy output versus energy input during the lifetime of the solution. Example: a windmill should generate more energy during its life than needed for the construction of a new windmill to replace the old one. Nuclear fusion instead of fission would be an “ideal” solution, but we need a solution right now. The best solution now is probably to use less energy.

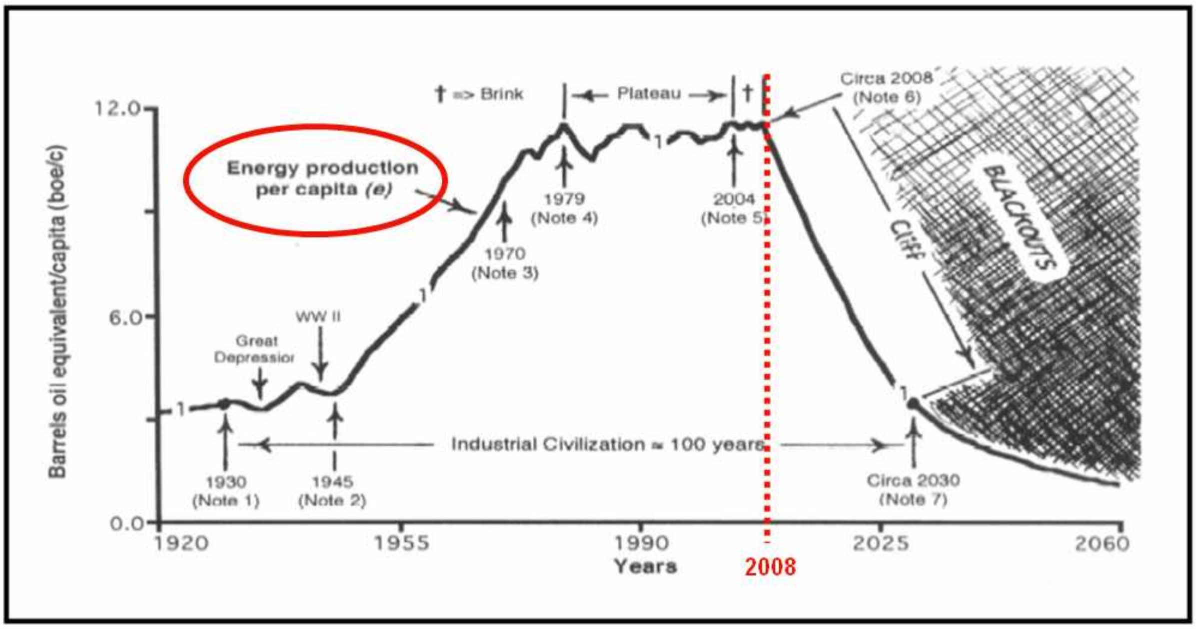

Figure 4: Past, present and future energy production per capita as function of time [6]

The bottom-line is that we are facing an energy crisis which cannot be solved by continuing doing "business as usual". An interesting graph (see figure 4) is made by R.C. Duncan [6] who has correlated population growth with energy consumption by using the energy production per capita. The peak in this graph was reached in 1979 after which followed a long plateau because the increase in world energy production was matched by world population growth. As world population continues to grow for the foreseeable future whilst global energy production will peak and decline, we will soon reach the down slope of the curve (predicted by Duncan to start in the 2008 – 2012 period). The graph of figure 4 applies to the world as a whole. Before we suffer global consequences, there will be regional and local shortages of energy. This is already happening in less wealthy countries today.

Further reading on energy scarcity: the comprehensible presentations by Matthew R. Simmons (www.simmonsco-intl.com) and the well-considered contributions and discussions on "The Oil Drum" (www.theoildrum.com).

MINERALS SCARCITY

An often encountered misconception is that the earth's crust holds virtually inexhaustible deposits of nearly all minerals, the general idea being that you could essentially find most elements in an arbitrary piece of granite rock. However, below a certain threshold of ore grade it is not possible anymore to meaningfully extract the desired elements (see figure 5 [7]). Below this so-called mineralogical barrier, you should essentially pull the rock apart chemically to extract all individual elements. This is of course extremely energy intensive. A clear example of the misconception of the supposedly inexhaustible resources available in the earth's crust is pure, crystalline silicon: for the production of efficient solar panels pure silicon is needed. Despite the fact that more than 25% of the earth's crust consists of silicon, there is already a worldwide shortage on pure silicon.

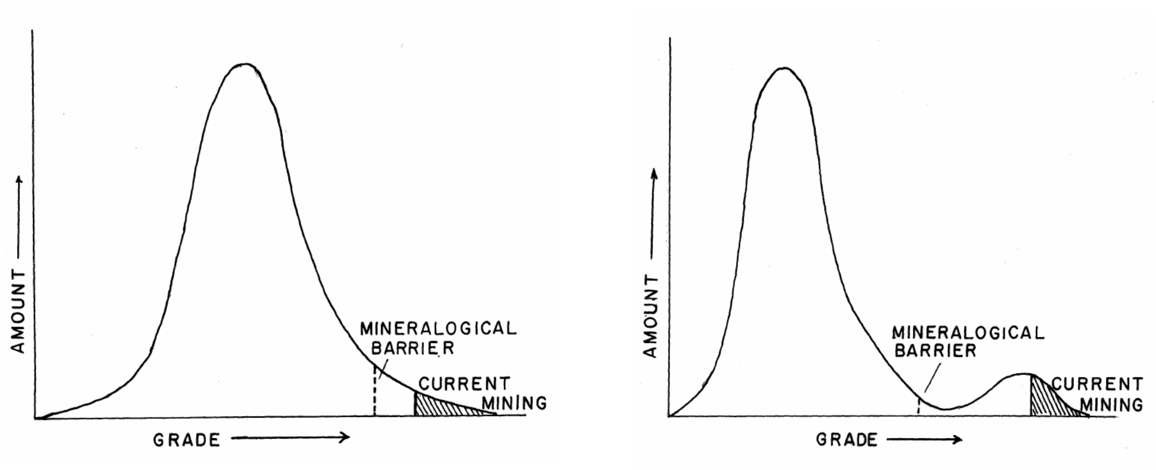

Figure 5: Mineralogical barrier for the most common elements
(left: elements ≥0.1% of the earth's crust, amongst others Al, Fe, Mg, Ti) and the other elements (right: elements < 0.1% of the earth's crust) [7]

Current mining operations use the richest ore grades available today. The ore grades already have been downgraded because of prior depletion of richer deposits. Example: in 1925 ore with a mean content of 25% copper was considered a mineral worth mining. In 1985, this “limit” was already eroded downwards to 0.7% copper [8]. For lower ore grades, the energy required to extract the same amount of the desired compound increases exponentially, as depicted in figure 6 for iron and aluminium [9]:

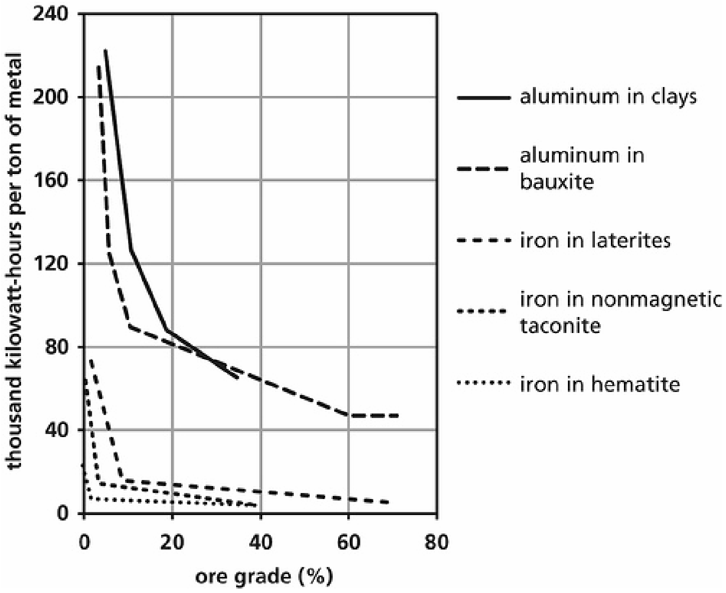

Figure 6: Relation between required energy for extraction and ore grade [9]

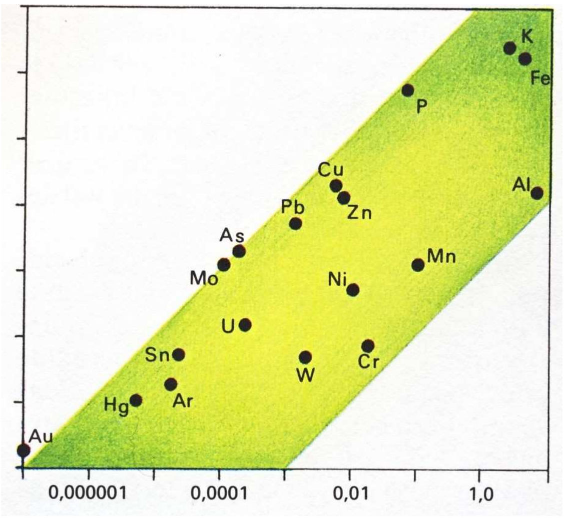

Figure 7: A number of important minerals in the earth’s crust (horizontal axis: presence in weight-%, vertical axis: US supplies around 1980) [8]

Figure 7 [8] shows on the horizontal (logarithmic) axis the abundance of a number of important minerals in the earth’s crust. The vertical axis shows US supplies around 1980 for these minerals. Although figure 7 shows that a metal mineral like manganese (Mn) is fairly common in the earth’s crust, the situation today is that the United States has to import essentially 100% of its needed supply of manganese since US deposits have been exhausted in the 1960s. A metal mineral like chromium (Cr) is also relatively abundant; however the main deposits are located in just a few countries (mainly South Africa and Kazakhstan). Bardi and Pagani [10] examined the world production of 57 minerals reported in the United States Geological Survey. They found 11 minerals where world production has clearly peaked and is now declining, amongst others mercury, lead and zirconium mineral concentrates. Several more may be peaking or be close to peak. According to Bardi and Pagani, the peaking of most mineral commodities appears to be clustered in a period that goes from the last decades of the 20th century to the first decades of the 21st century.

There are parallels between the issues involved in energy scarcity and minerals scarcity. Mineral deposits become harder to find. Discoveries are smaller and in less-accessible regions or geologic formations and in politically riskier countries. Besides the energy cost increase related to the lower ore grade, extra energy cost and effort is devoted in conducting the mining operation in more unfavourable conditions (larger distances, extra infrastructure, unfavourable climate conditions, deeper mining, ocean floor mining). Apart from the exponential increase in energy input to extract the same amount of material, the mining of lower ore grades is accompanied by an exponential increase of water usage and environmental issues. Furthermore, mining companies are very conservative about adding new production. The last big technology shift in the metals sector - from deep, underground shaft mining to vast, open-air pit mining – is decades old [11]. Together wit the present unfolding financial (liquidity) crisis which manifested itself since August 2007 (making money more expensive) and the steady cost increase of virtually all commodities, this forms a significant obstacle in funding new mining operations.

CONNECTING THE DOTS: MINERALS BECOME MUCH MORE EXPENSIVE

The problem of availability of mineral deposits and sufficiently high ore grades is not the main issue, since the earth's crust still holds enough deposits above the mineralogical barriers for primary production. The largest problem with minerals scarcity is the steady increase in energy cost because more and more energy is required to sustain the current levels of primary production of essential materials while at the same time energy becomes much more expensive. To make things worse, as with energy the global demand for all kinds of minerals and metal products is steadily increasing.

	GJ / ton
construction steel	58
stainless steel	115
aluminium	290
magnesium	415
titanium	560
polyethylene	80
nylon	180
natural rubber	6
synthetic rubber	140
bricks, pantiles	6
glass	24
carbon fiber reinforced plastic	4000

Table 1: Total energy required for primary production [12]

Table 1 shows the estimated (but founded) total amount of energy required for primary production for a number of materials, based upon the situation (e.g. ore grades) of around 2 decades ago [12].

This table gives an impression of the enormous amounts of energy required to produce important and essential materials.

Both energy scarcity and minerals scarcity are aggravated by substitution problems, just-in-time practice, uneven geological distribution and “peak psychology” of exporting nations:

Substitution problems

As minerals become scarcer, even as unconventional sources of minerals and substitutions come to market, the cost will increase because these new sources and substitutes are more expensive to produce than the substituted mineral used to be. The rise of a mineral price creates a price floor for the substitutes; as the floor moves up, new sources and substitutes become profitable. That might slow the price rise but it does not reverse it [11]. The problem in the global economy of today is that demand for a mineral which has become a substitute for another scarce mineral will outstrip supply very quickly. A recent example is the ongoing substitution of copper-nickel tubing in power plants by titanium and low nickel stainless steel driven partly by the high nickel cost [13]. As titanium cost also rose, most substitutions shifted towards low nickel stainless steel with molybdenum (3.7%). Now in turn the cost of molybdenum has risen significantly. If you consider the huge amount of money involved in the energy sector today, than it is not hard to imagine that there goes enough money around to outbid other users of the same scarce minerals if necessary. A trader’s rule of thumb says “in a blow-up all correlations go to unity”, meaning that once availability of essential resources has reached its maximum, there can be no safe haven [14].

Just-in-time practice

Based on the commonly accepted economic theory that tomorrow will be better than today (valid during exponential growth) and enabled by the free market economy, the Western world has essentially abandoned strategic supplies (like the US National Defense Stockpiles) with the exception of crude oil, because “stocks cost money”. For nearly all commodities we lack the necessary buffers to mitigate or soften the shock waves caused by sudden changes in the gap between demand and supply. In contrast, the Chinese government has organised strategic supplies of various commodities.

Uneven geological distribution

The remaining reserves of both fossil fuels and mineable mineral deposits are increasingly concentrated outside the Western world, sometimes in just a few countries. Most of the remaining oil and natural gas reserves are found in the Middle East and in Russia. A number of essential minerals are found mainly in one or a few countries, e.g. around 90% of the primary production of tungsten originates from China at the moment.

“Peak psychology” of export nations

We will probably suffer from various export crises of both energy and minerals before actual physical shortages occur. The reasons vary from increasing consumption of the commodities in question in the exporting countries, the lack of need to increase or even maintain export on current levels as the revenues per unit of commodity will steadily rise, profiteering (“tomorrow I will get more money”) and geopolitical factors.

So the aggravating problem is that free markets do not work when demand outstrips supply. And when resources run short, conflict is often not far behind, possibly aggravating the overall situation. It is not unthinkable that specific materials will become (temporarily) unavailable, regardless how much you are prepared to pay.

Figure 8 shows the results from the prepublication version of a recent study by the US National Materials Advisory Board on the supply risk and the impact of supply restrictions on the economy of the United States [15] for a selection of 13 minerals (some are grouped). The study confirms the risks involved with minerals scarcity and also confirms the issues and problems involved with substitution. For example, there are no satisfactory substitutes for manganese for the major applications (90% goes into steel and cast iron, 5% in other alloys), however US mineable ores were exhausted in the 1960s. Consequently, figure 8 shows manganese to be one of the minerals to be concerned about (at least for the US).

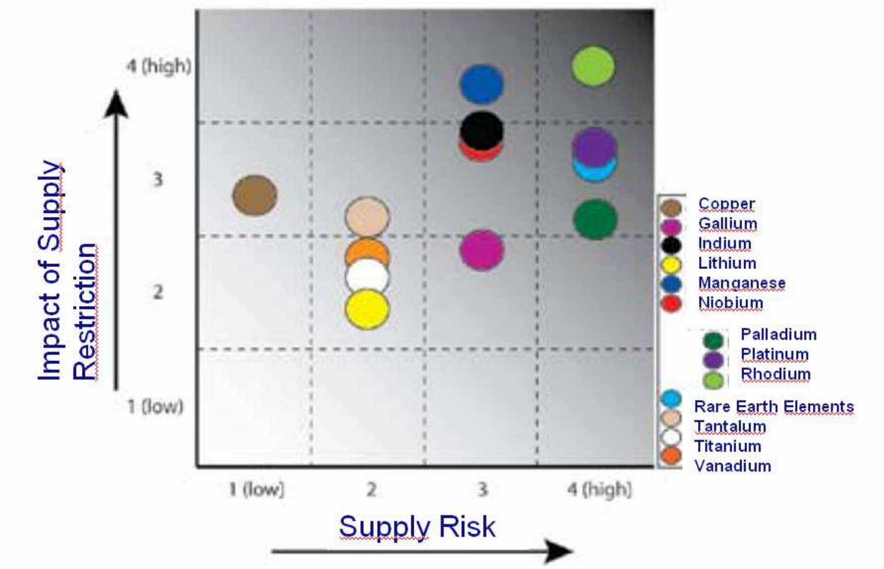

Figure 8: Risk analysis of minerals scarcity for the United States [15]

In summary, materials will get more expensive by two connected main causes, namely minerals scarcity requiring more energy and the steady cost increase of energy because of energy scarcity. Likewise, the cost increase of all kinds of materials will also aggravate the cost increase of energy production. As a consequence, minerals become exponentially more expensive, starting with the rare and with the difficult to substitute ones.

The growing scarcity (gap between demand and supply) of materials can be slowed down by the following mitigation strategies (partly from [16]):

Substitution

History shows that elements once regarded as irreplaceable can be substituted. An example is mercury, the only good conducting metal which is liquid at room temperature, which has been replaced by semi-conductors. However, alternatives usually cost more energy and the hard to imagine scale of materials consumption leads to a cascade of substitutions (see substitution problems described above).

Recycling

Currently recycling is overall of the order of 30% or more. It should be noted that there are always losses (100% recycling is not possible) because of dispersion, chemical degradation etc. Extreme recycling is unlikely until serious shortages occur. It should also be noted that recycling costs energy, although much less than primary production.

Reuse

Reuse is unlikely until serious shortages occur.

Doing with less

This is the largest future “source”. It is the easiest and also the most unlikely mitigation until a crisis really hits.

Metals

For the first 40 years of their development the armour of tanks consisted solely of high strength steels with 0.25-0.4% carbon, 0.5-3.75% nickel, 0.5-1.8% chromium and some other minor components (amongst others molybdenum) [17]. These armour steels had an ultimate tensile strength (UTS) between 850 and 1700 MPa. During WWI the applied relatively thin (8 to 14 mm) plates had a Brinell hardness of 420 to 650 BHN. At the end of WWII, the Germans managed to produce and apply a front armour plate with a thickness of 250 mm (Jagdtiger) and a useful toughness at the expense of hardness (estimated at around 220 BHN). The 1960s brought us the 4340 ESR (electro slag remelted) armour steel with a UTS of 2190 MPa, a hardness of 550 BHN and yet a considerable ductility and toughness. Again, this was achieved by using only minor amounts of alloying elements: 0.4% carbon, 1.7% nickel and 0.8% chromium.

Today, some of the most promising steel developments relevant for potential armour application try to combine a high UTS (up to 1050 MPa) with a very high toughness (up to 50% or more failure strain). All these developments (amongst others TRIP-, TWIP- and TRIPLEX-steels [18]) are based on large percentages of manganese (typically 14% to 28%) in their composition, making them much more susceptible to steady cost increase than the steels originating from the WWI-WWII period and the 1960s which are based mostly on iron (94% and more). At this moment, only thin plates of these materials are being produced. Further developments in this field comprise so-called super-TRIPLEX-steels with a UTS higher than 1400 MPa and a failure strain over 50% using no more than 5% additional alloying elements (chromium, vanadium and/or molybdenum) in addition to manganese (14-18%) and aluminium (2-12%) [18].

The first lighter vehicle with a hull welded out of aluminium armour alloy was the U.S. M113 armoured personnel carrier, whose design started in 1956 and production in 1960 [19]. Its hull is welded out of Kaiser aluminium alloy 5083, an aluminium-magnesium alloy (around 4.5% magnesium) with a UTS of 300 to 350 MN/m² and a hardness of 75 BHN. All in all the areal density is about the same as that of ballistically equivalent steel armour, although more aluminium is required against high velocity bullets and less aluminium is required against shell fragments. The primary reason for application of aluminium armour in lighter vehicles is the weight saving on purely structural components (e.g. structural stiffeners) from the increased rigidity of the thicker hull walls. During the 1960s the stronger heat treatable (precipitation hardened) 7039-alloy (around 4% zinc and around 3% magnesium) was introduced in aluminium-armoured vehicles, later followed by other types of the aluminium 7000-series. However, no new alloy has yet improved upon the *overall* ballistic performance (including resilience against heavier fragments) and overall properties of the 5083-alloy.

Other nonferrous metals have been investigated and have been applied to some extent as armour material. Titanium alloys are of special interest as these have ultimate tensile strengths and ductility comparable with steel alloys and yet have a density of only 4.4 to 4.5 kg/dm^3 [19]. Unfortunately, titanium alloys are much more difficult to process and have remained much more expensive than aluminium alloys and steel armour. Magnesium alloys are interesting by nature of their low density (around 1.8 kg/dm^3), but until today no magnesium alloy has been developed which can match the ballistic performance of aluminium armour unless significant amounts of relatively rare or even exotic (and thus much less affordable) elements are used.

Ceramics

The development of aluminium oxide (Al_2O_3) ceramic armour in combination with layers of steel or aluminium during the 1960s was aimed at a mass efficient means of protection against shaped charge attacks and resulted during the 1970s in the application of the so-called Chobham armour and similar types of armour in Western tanks. From the 1960s onwards, ceramic tiles were developed as strike face for protection against high velocity bullets. Today, a whole range of ceramic armour materials is available for various applications. The basic principle of ceramics production is densification by heating (sintering). All non-oxide ceramics require an inert gas atmosphere or vacuum, giving Al_2O_3 an inherent advantage over the other armour ceramics. The most energy-intensive process is pressureless sintering or liquid phase sintering which requires a temperature around $2/3^{rd}$ of the melting temperature Tm [20]. Pressureless sintering can produce the ceramics Al_2O_3, SiC, TiB_2, Si_3N_4, AlN and WC. Less energy-intensive (but requiring expensive equipment) is hot-pressing, i.e. simultaneous application of heat and pressure, requiring a temperature around half of Tm. Hot-pressed ceramics are SiC, TiB_2, B_4C, Si_3N_4, AlN and WC. The least energy-intensive can be reaction bonding (applied since the 1950s), i.e. densification via a chemical reaction, which can produce SiC, B_4C and Si_3N_4, albeit at the expense of possible residual porosity and by-products.

Of all mentioned ceramics, only tungsten carbide (WC) could pose serious problems in terms of future availability and cost because of tungsten minerals scarcity and because most remaining tungsten deposits are located in China which has a steady domestic demand growth for tungsten (tools, alloys and alloyed steels, chemical applications). Ceramics are suitable for recycling but suffer more “losses” (in terms of material grade and energy) than metals because of the efforts that are required to reprocess used ceramics into the required particle size distribution and purity of the components for the production of new armour-grade ceramics. This will be especially true for future improved ceramics which will use nano-/micron-sized reinforcing elements for improved microstructure (increased dynamic resistance to fracture).

Polymers

The most widely used polymers for armour applications comprise the broad family of urethanes (from rubbers to adhesives and foams) and the broad family of fiber reinforced plastics (amongst others with aramid and polyethylene fibers) for ceramic armour backings, spall-liners and some structural components. Aramid fibers were developed during the 1960s-1970s by DuPont and AKZO and polyethylene fibers were invented in the late 1970s by DSM. These fibers and their applications, ranging from fragment resisting vests to moulded shapes (helmets) and plates, are unmatched up until today. Other fibers, like the WWII-vintage ballistic nylon fibers, later aramid-/nylon-like fibers like the 1980s-developed “Zylon” and the relatively new mechanically stretched polypropylene fibers, lack the performance and properties of aramid and polyethylene fibers.

Polymers will suffer “double” from the scarcity of fossil fuels, since besides an energy source these fossil fuels are also a raw material for polymers and are difficult to substitute as such. Compared to metals and ceramics, recycling of polymers gives large constraints because of the degradation of these materials during their useful life (physical and chemical ageing) and the difficulties of extracting and reprocessing the original compounds from the used materials to recycle these back into the feedstock required for manufacturing the same product again. This will be especially true for future improved high strength fibers which may be treated with nano-sized particles for improved ballistic performance or other purposes (e.g. processing properties).

Hybrid materials

Ceramic tiles are generally too brittle to be used by themselves and have to be combined with steel or aluminium alloys to form layered or laminated armour. In order to optimise this type of armour it could be tried to combine ceramics and metals in one layer for certain applications. Such a hybrid ceramic-metal armour offers increased toughness and multihit capacity relative to a ceramic layer and offers the possibility to enhance the ballistic performance against high velocity threats relative to a metal-only layer by incorporating the erosive action of embedded sharp and hard ceramic particles. Figure 9 [21] shows a high metal content hybrid material with ceramic particles and/or fibers made from SiC, Al_2O_3 or possibly other ceramic materials.

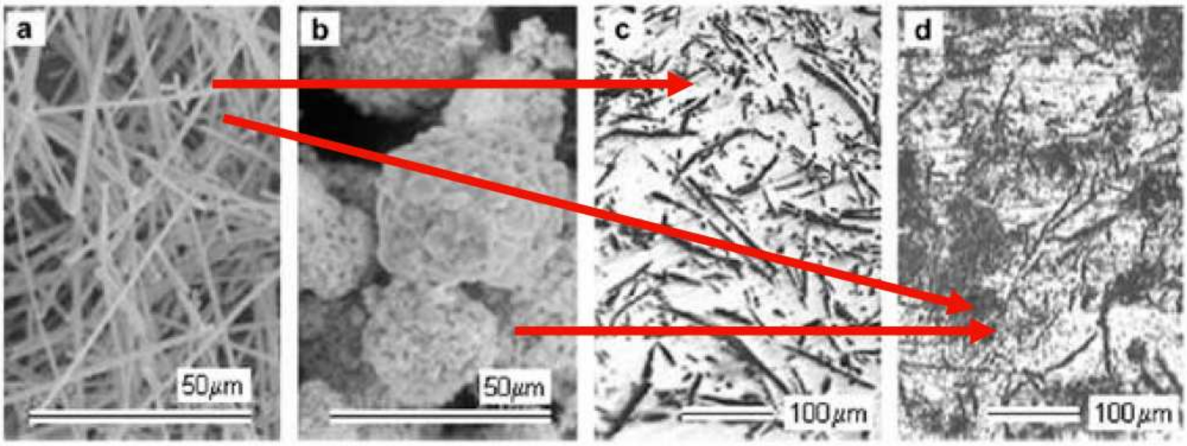

Figure 9: Metal reinforced by ceramic particles and/or fibers [21]

Hybrid materials could also offer a favourable solution for reprocessing recycled metals and ceramics into new (but potentially lower-grade) armour products which are less sensitive to the specifications of the composing (reprocessed) ingredients.

CONCLUSIONS

The bottom-line cause of the unfolding energy crisis and the related steady cost increase of essential materials is the fact that we are using too much resources with too many people much too fast on a global scale. By getting by on less energy and resources and by using careful substitution, by recycling and by reusing we can anticipate the future restrictions in materials selection. Not coincidentally, important material technology breakthroughs from a less energy-intensive past may point towards material developments which are suitable for a less energy-intensive future.

The resource-poor future pictured in this paper strongly appeals to the ingenuity and creativity of engineers and scientists (and others) to cope with a limited choice and availability of resources. Fortunately, unlike fossil fuels and mineral resources, ingenuity and creativity are unlimited.

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