ECONOMICAL AND TECHNICAL ASPECTS OF PRODUCING OF DIAMOND IMPREGNATED TOOLS

Joanna BOROWIECKA-JAMROZEK[A], Jan LACHOWSKI[B]

[A]*Department of Applied Computer Science and Armament Engineering, Faculty of Mechatronics and Machine Design, Kielce University of Technology, Al. Tysiąclecia PP 7, 25-314 Kielce, Poland, e-mail: jamrozek@tu.kielce.pl*
[B]*Chair of Applied Computer Science, Faculty of Management and Computer Modelling, Kielce University of Technology, POLAND; Kielce 25-314, Al. Tysiąclecia PP 7, e-mail: jlach@tu.kielce.pl*

Abstract

In the paper the analysis of dynamics of mining, production and prices of industrial diamonds and cobalt was performed during 1900-2011 years. Cobalt is using as a based material used for matrix of diamond impregnated tools for cutting of natural stones.

Until the early 1950s the developments in diamond tools were relatively slow. In that period only mined diamond crystals were available. Much faster developments in the tool manufacturing technology was caused by development the production of synthetic diamonds. Only the possibility of producing synthetic diamond allowed for controlled modification of the shape and properties of particles, from very fine-grained, used for grinding and polishing, to large, strong crystals of the regular, multifaceted shape. In the new millennium the market for diamond tools continues to grow rapidly.

The effective use of diamond impregnated tools is strongly depended on the retentive properties of the metal matrix, which must hold diamond grits firmly. The diamond retentive capability in a matrix is a complex property, affected mainly by chemical or mechanical interactions during hot pressing and then cooled to room temperature. Due to mismatch between thermal expansion coefficients of the matrix and diamond, the stress/strain field is generated in the matrix at diamond surroundings, which plays a major role when retentive properties are considered. The potential retentive capability of a matrix can be associated with the amount of elastic and plastic deformation energy and the size of a deformated zone which occurs in the matrix around diamond particles.

The costs of producing diamond impregnated tools are influenced by the costs of cobalt metallic matrix. After World War II the price of cobalt further fluctuated on a balanced level, until the mid 1970s when the price increased rapidly The possibility of substitution of cobalt with the other cheaper alloys was considered which as a matrix material gives similar utilizing properties.

Key words: *cobalt, industrial diamonds, sinters, metallic matrix, diamond impregnated tools*

1. INTRODUCTION

In the industry of diamond impregnated tools for cutting natural stones and building materials circular saws with a working layer in the form of segments soldered to a steel disk between special cuts are used (Fig. 1). The segments constitute the working elements of a saw are produced by means of the technology of powder metallurgy.

The process of producing diamond impregnated sinters consists in mixing the powder constituting the metallic matrix (Fig. 2a) with the diamond particles, natural or synthetic (Fig. 2b), pressing fittings, and then sintering or hot pressing them. As a result of those operations one receives sinters commonly known as diamond impregnated segments. The segments are soldered to steel disks (Fig. 1) and they constitute cutting elements of circular saws used for cutting materials [1].

Technological progress in the production of modern diamond impregnated tools is expressed in the producers' striving for producing tools of better and better functional properties with the use of lower production costs. Good quality of a tool is influenced mainly by:

- suitable structure of a tool,
- proper choice of the matrix material,
- proper choice and location of diamond particles in the matrix material.

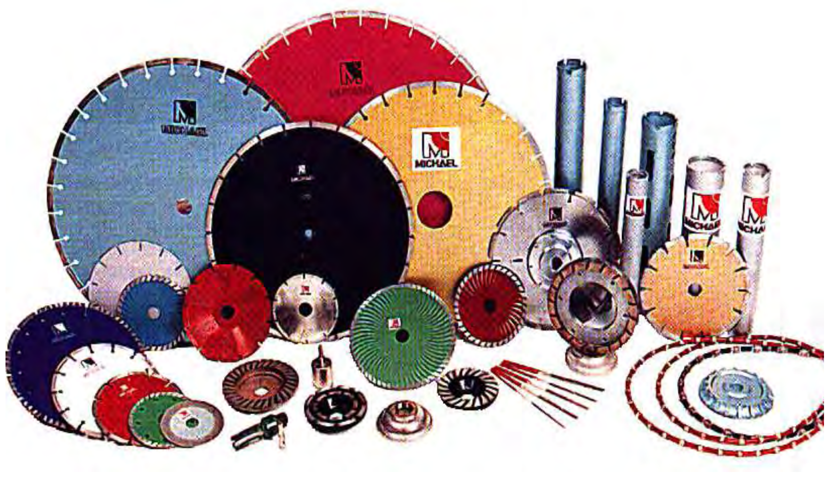

Fig. 1: *Modern diamond impregnated tools*

Cobalt is the material that is most often used for the matrix of diamond impregnated sinters [2]. However the price of that material is high and at the same time unstable. The economic situation forces producers to seek possibilities to replace cobalt with other, cheaper material, which as a matrix material would ensure similar functional properties of tools with lower costs of their production [3].

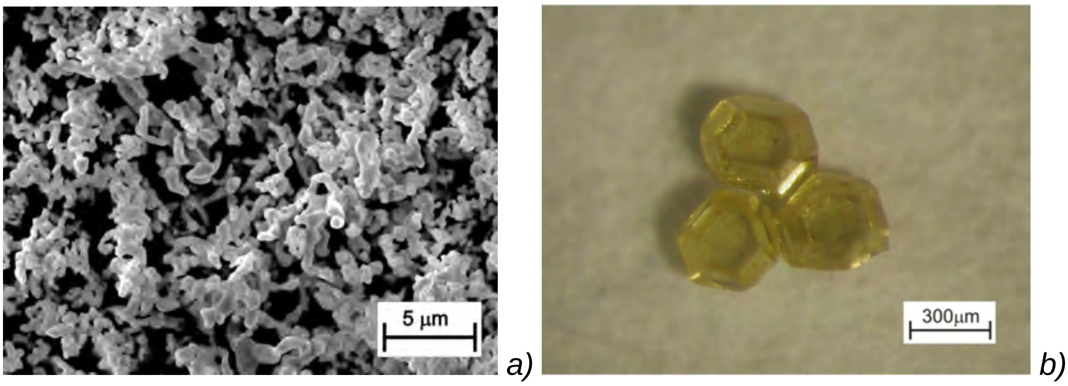

Fig. 2: *Powder of SMS cobalt a), Synthetic diamonds b)*

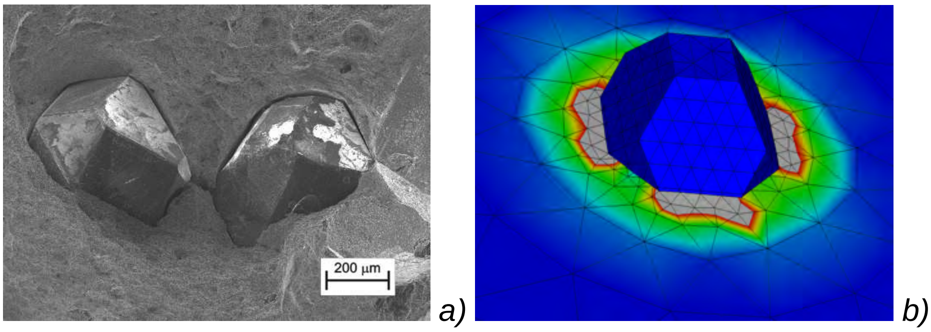

Fig. 3: *Fractured surface of a segment with diamond particles a), numerical model of a diamond particle with the surrounding plastic zone at a surface of segment b)* [2]

2. USING OF DIAMONDS IN METALLIC MATRIX OF TOOLS

In the past the use of diamond as a tool material was limited to its natural variant. As a result of crushing and sorting of diamond bort, diamond powders of different particle sizes were obtained.

Only the possibility of producing synthetic diamond allowed for controlled modification of the shape and properties of particles, from very fine-grained, used for grinding and polishing, to large, strong crystals of the regular, multifaceted shape (Fig. 2b). Diamonds particles are used for cutting stones and ceramic materials that are most difficult for processing.

A significant property of the matrix material is retention – i.e. maintaining (Fig. 3) particles of a diamond during the work of a diamond impregnated tool. Diamond particles are maintained in a matrix thanks to mechanical or chemical connections, or by both of those connections simultaneously [1]. Mechanical connection is obtained during the cooling after the process of hot pressing. Because diamonds have a very small coefficient of thermal expansion in relation to metals [4,5,6], diamond particles are pressed by the shrinking matrix (Fig. 4a). Maintaining appropriate mechanical connection depends on elastic and plastic properties of the matrix material. The analysis of the retention of diamond particle in relation to mechanical properties of the matrix was conducted in papers [7,8]. The most significant parameters of the assessment of retention are elastic strain energy and plastic energy of the deformed matrix around a diamond particle (Fig. 4b) [8,9].

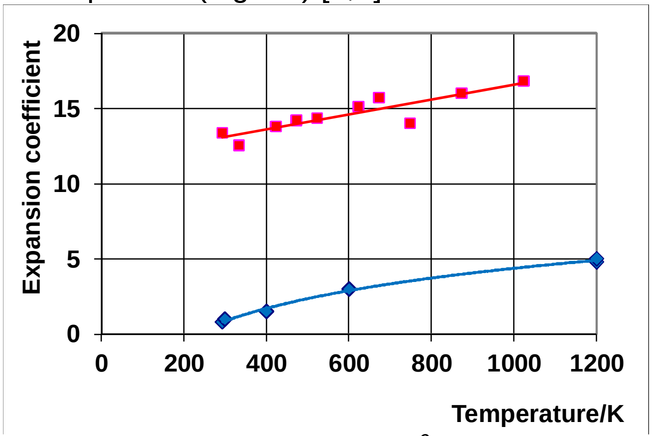

Fig. 4: *Expansion coefficient multiplyed by 10^6 for cobalt (red squares) and for diamond (blue squares)*

3. PRODUCTION AND PRICES OF INDUSTRIAL DIAMONDS

Industrial diamond was produced in 30 countries in 2010. Total industrial diamond (synthetic and natural) production was estimated to be more than 880 Mg (4400 million carats). Natural industrial diamond world production was estimated to be more than 110 Mg (55 million carats) which decreases from year to year. The production of industrial diamonds increases rapidly from 2,5 Mg in 1950 year to 876 Mg in 2010 year [10].

Efforts to manufacture synthetic diamond crystals date back at least several hundred years. They had remained fruitless until 1953, when positive and fully reproducible results were obtained by a team of researchers at ASEA in Sweden. Quite independently, and entirely without knowledge of what ASEA had been doing, General Electric announced its capability to manufacture synthetic diamonds on an industrial scale in 1955. While ASEA kept the diamond experiments secretive, General Electric was first to describe the process in the scientific literature and patented it.

The rapid increase in the plot (Fig. 5) was at 1988 year when the production of synthetic diamonds were included in the statistics. Firstly China published data of its production of synthetic diamonds in 2004 year that can be seen in the Figure 6.

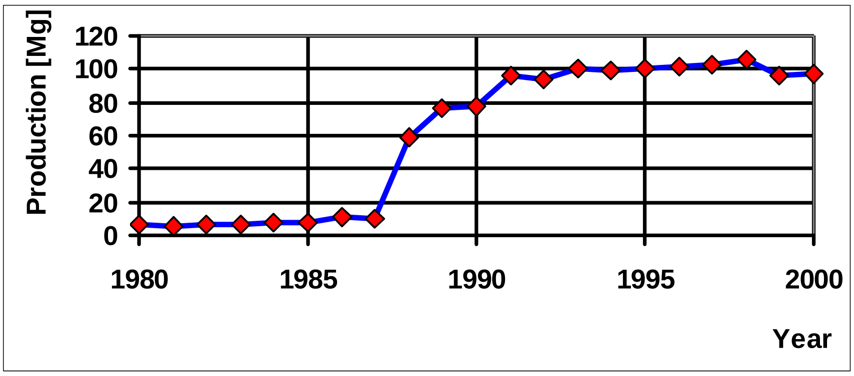

Fig. 5: *Production of industrial diamonds during 1980-2000 years*

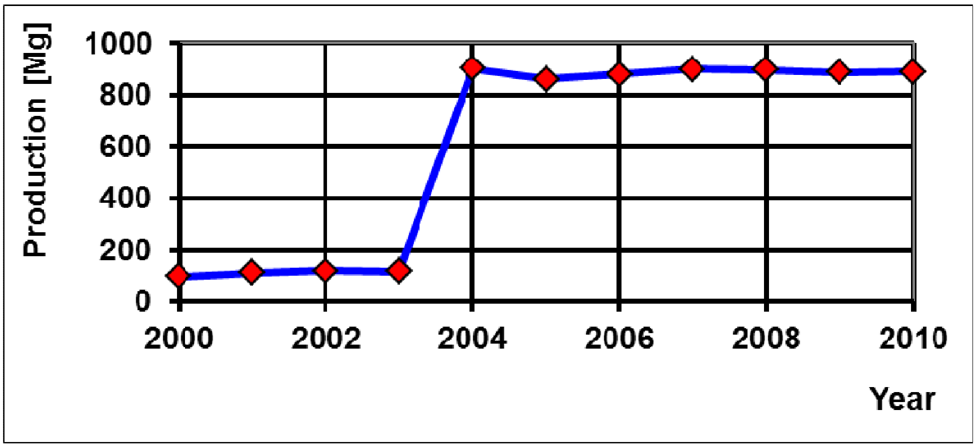

Fig. 6: *Production of industrial diamonds during 2000-2010 years*

Russia was the leading producing country of natural industrial diamonds, followed by Congo and Australia. These three countries produced more than 73% of the world's natural industrial diamond. The technology of the production of synthetic diamonds was mastered in at least 15 countries [10]. The United States has been a major producer of synthetic diamond for decades. Now China is the leading producing country of synthetic diamonds, followed by the United States (Fig. 7). The distinct increase of the consumption of industrial diamonds in USA is presented in the Figure 8.

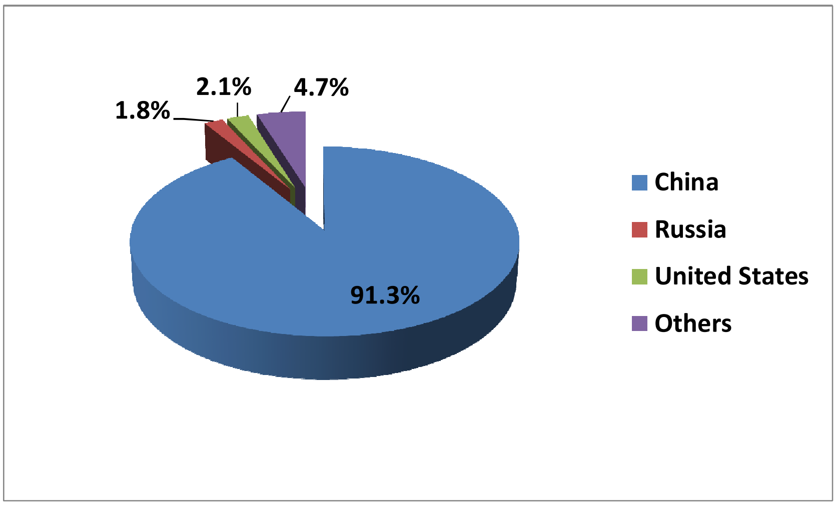

Fig. 7: *World production of synthetic diamonds in 2010 year*

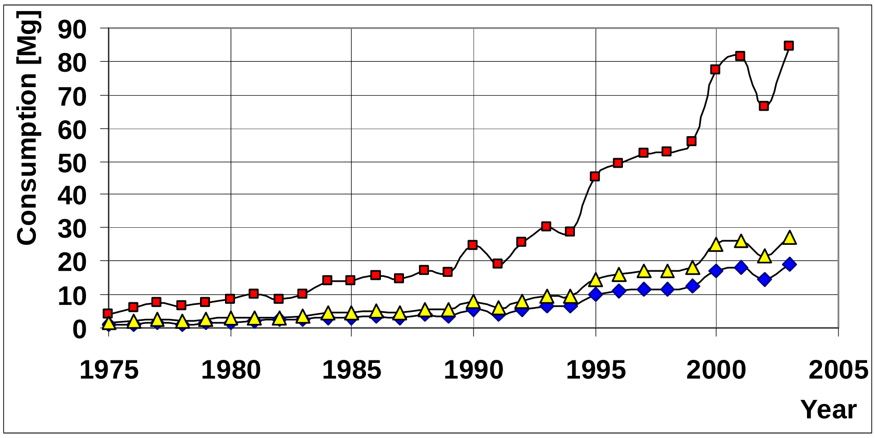

Fig. 8: *Consumption of industrial diamonds in USA, the red color – total consumption, the blue color– consumption in stone and ceramic production, the yellow color – consumption in machinery manufacturing*

Natural and synthetic industrial diamonds differ in price. The price of natural diamonds varies from an average of $1 per carat (0.2 g) for bort size material to about $2.50 to $10 per carat for stone. The prices for synthetic diamond dust, grit, and powder used in grinding and polishing range from as low as $0.26 to $1.70 per carat. Strong material for sawing and drilling sells for $1.00 to $3.50 per carat.

Due to the price, synthetic diamonds constitute more than 90% of all industrial diamonds, despite they posses worse functional properties. The annual average prices of industrial diamonds is presented in the Figure 9 and the Figure 10.

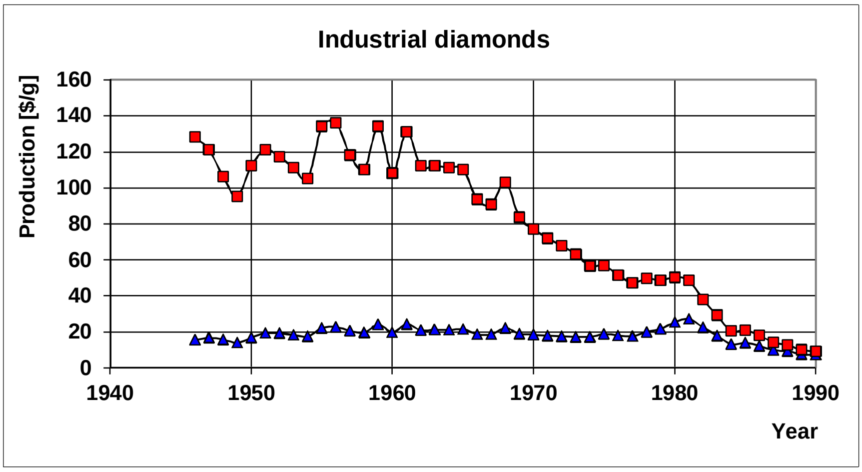

Fig. 9: *The annual average prices of industrial diamonds from the Second World War to 1990 year, blue plot – nominal average price, red plot – average price with US dollar reduced to 1998 year*

***Fig. 10:**. The annual average prices of industrial diamonds from 1990 year to 2010 year*

4. THE LEVEL OF MINING, PRODUCTION AND PRICES OF COBALT IN 1900-2010

Statistical data concerning the production and the prices of cobalt have been collected since 1900 [11,12]. Analysing the production and the consumption of cobalt one can observe two periods (Fig. 10). In the period from 1900 to 1938 the consumption of cobalt was not high. Then since 1939 (the outbreak of World War II) there has appeared a quick increase of the consumption of cobalt.

From the moment when the technology of obtaining synthetic diamonds on an industrial scale was developed, the use of diamond impregnated tools increased significantly [1] as the price of synthetic diamonds is definitely lower from the price of natural diamonds. That caused a further increase in the demand for cobalt; the production and the consumption of cobalt increased rapidly. If in the period to 1938 the average consumption in the USA amounted to about 200 tonnes per year, then in the years 1950-2010 the average value amounted to about 8000 tonnes per year.

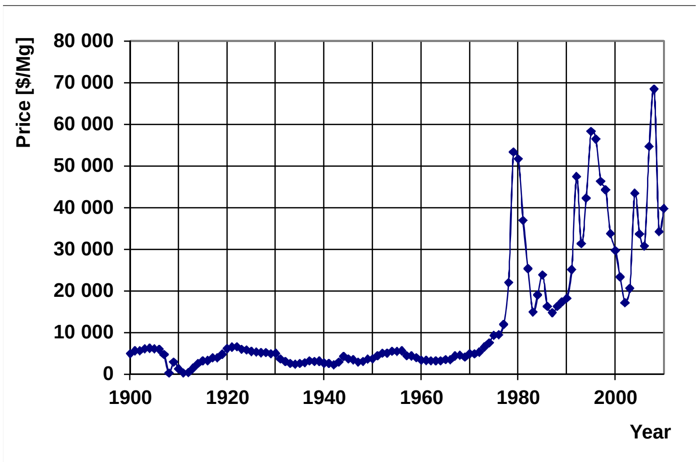

***Fig. 11:** The amount of the consumption of cobalt in the USA (in tonnes) starting in 1900*

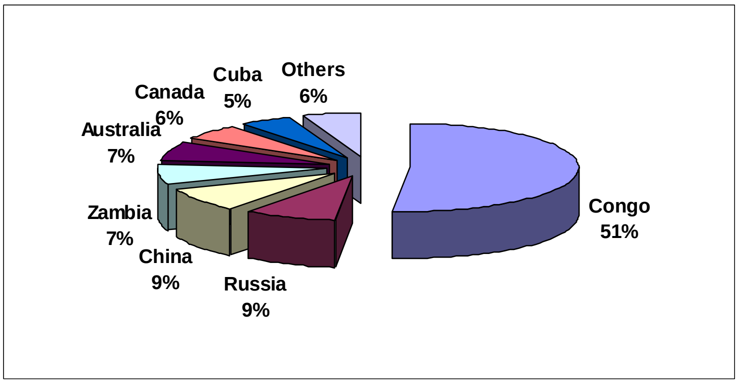

Fig. 12: *The percentage share of individual countries in the mining of cobalt*

The mining of cobalt in 2009 in total amounted to 72.3 thousands of tonnes and it was focused on a small group of countries, mainly in: Congo, Russia, China, Zambia, Australia, Canada and Cuba. The participation of individual countries in the mining is shown in Figure 12. In 2010 there appeared a further strong increase in the mining which is estimated at 88 thousands of tonnes.

The fastest increase in the mining of cobalt in the last decade was noted in Congo (Fig. 13). From approximate 10 thousands of tonnes in the years 2002-2003, to the estimated 45 thousands of tonnes in 2010. In 1994-1995 the mining in that region amounted to approximate only 3.4 thousands of tonnes.

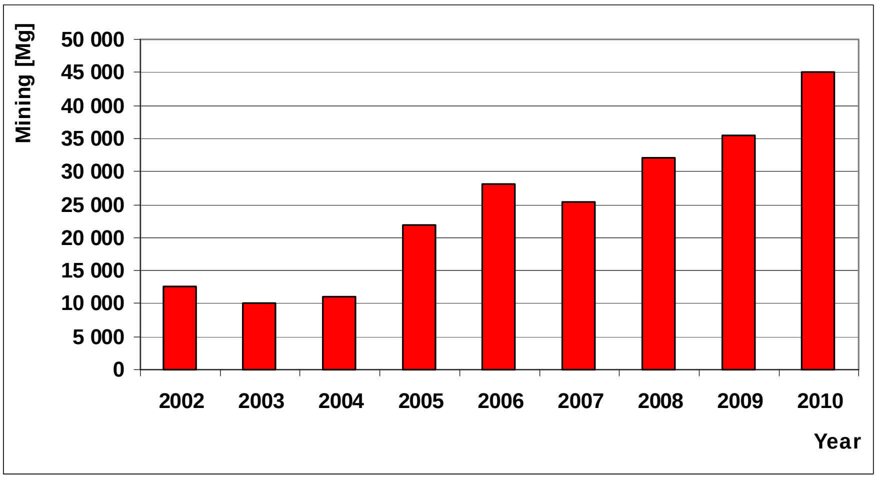

Fig. 13: *The dynamics of the mining of cobalt in Congo in the last decade*

Apart from large players in the mining of cobalt, also the producers of metallic cobalt are significant. Approximately 31% of the production of metallic cobalt takes place in the countries in which there is no mining. Those countries include: China, Finland, Canada and Australia (Fig. 14).

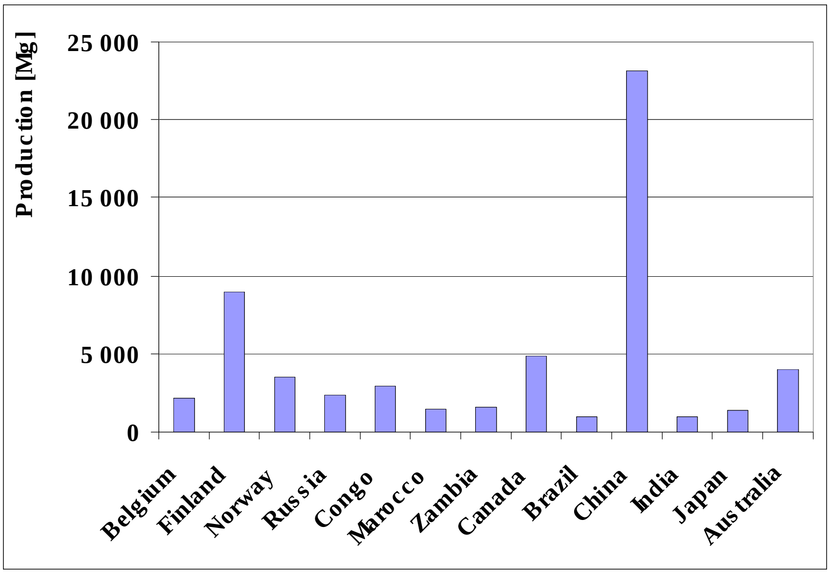

Fig.14: *Production of rafinated cobalt in 2009 year*

In the first considered period (to 1938) the price of cobalt showed greater stability and fluctuated around an average value amounting to 4045 $/tonne. The range of the price change was between 230 $/tonne (1908) to 6590 $/tonne (1922). After World War II the price of cobalt further fluctuated on a balanced level, until the mid 1970s when the price increased rapidly (Fig. 15).

The price of cobalt has shown strong fluctuations since 1977 till the present moment (Fig. 15). Political events occurring in the regions connected with the mining of cobalt had a significant impact on its price. In the years 1977-1978 there was a rebellion in the Katanga province in Congo (Zair). The rebels based in Angola carried out a series of attacks on Katanga. The rebellion was brought under control with the help of French and Belgian troops.

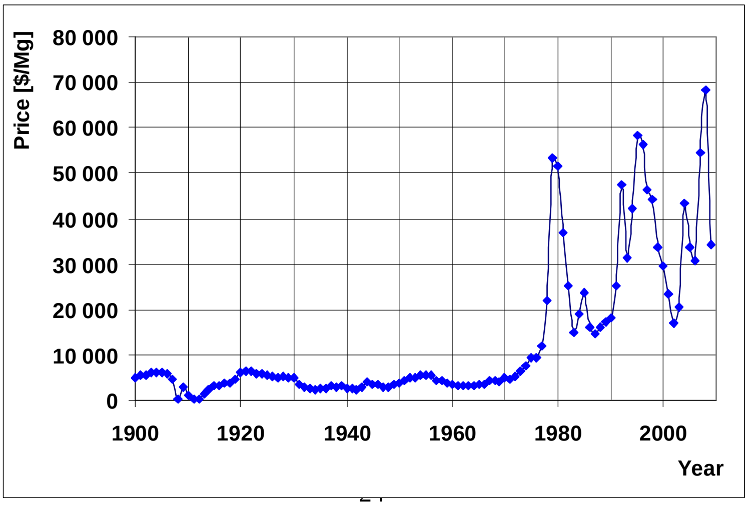

Fig. 15: *Dynamics of the price of cobalt in the years 1900-2009*

In 1996 ethnic conflict between the Hutu and Tutsi tribes in the neighbouring Rwanda spread onto the area of Zair. The military activities called the First Congo War led to overthrowing the president Mobutu and the return to the previous name of Congo (*Democratic Republic of Congo*). These events led to a strong increase in the prices of cobalt in the mid 1990s.

In the years 2007-2008 there was again a strong increase in the prices of cobalt (Fig. 15). The price tripled, and then decreased to the previous level [12]. In the years 2009-2010 the price was more stable, yet it still showed fluctuations.

6. SUMMARY

Since 1977 both the increase as well as strong fluctuations of the price of cobalt have been observed. However, in contrast with the price of cobalt, there has been observed a constant decrease in the price of synthetic diamonds.

Indeed, the costs of producing diamond impregnated tools are influenced by the costs of metallic matrix. That is why new materials are being sought for the matrix of the diamond impregnated segments in order to decrease the cost of producing a diamond impregnated tool. Works are conducted in that direction to replace cobalt with other cheaper alloys of metals, among others, sinters of cobalt with copper are used as matrices [3]. Copper enables to decrease the temperature of sintering or hot pressing, and hence the reduction of costs of the production of tool segments.

The global use of cobalt in 2009 was as follows [12]: lithium batteries – 25%, superalloys – 20%, hard materials – 18%, catalysts – 10%, other applications – 27%. The demand for cobalt will remain high, especially for applications in electric batteries. Lithium batteries, used in hybrid electric vehicles, contain large amounts of cobalt. Signalled by large automotive companies (Hitachi, General Motors, Honda) [12], the increase of production of hybrid vehicles will be an additional factor forcing the price of cobalt in the future.

Considering the above, it should be stated that it is appropriate to seek new materials for the matrix of diamond impregnated tools to free the production of those tools from cobalt.

4. REFERENCES

[1] Konstanty J., Powder Metallurgy Diamond Tools, Elsevier, Oxford, 2005.

[2] Lachowski J., The operational and economic aspects of using cobalt in metallic-diamond tools, in Selected problems of mechanical engineering and maintence, ed., Radek N., Kielce University of Technology, Kielce 2012, 36-41.

[3] Borowiecka-Jamrozek J., 'Engineering Structure and Properties of Materials Used as a Matrix in Diamond Impregnated Tools, Archive of Metallurgy and Materials', Vol. 58, No 1/2013, 5-8.

[4] Rare Metals Handbook, ed., Hampel C.A., Reinhold Publishing Company, London 1961.

[5] Springer Handbook of Condensed Matter and Materials Data, eds., W. Martienssen and H. Warlimont, Springer, Berlin Heidelberg 2005.

[6] Properties of diamond, De Beers Industrial Diamond Division, Special publication K4000/5/89, 1989.

[7] Romański A., Lachowski J., Konstanty J., Diamond retention capacity – evaluation of stress field generated in a matrix by a diamond crystal, Industrial Diamond Review, Vol. 66, No. 3, 2006, 43-45.
[8] Romański A., Lachowski J., Frydrych H., Energy of plastic deformation as an estimator of the retentive properties of the metal matrix in diamond impregnated tools, Diamond Tooling Journal, vol. 1, 2009, 28-36.
[9] Romanski A., Lachowski J., Effect of friction coefficient and mechanical properties of the matrix on its diamond retention capabilities, 5th International Powder Metallurgy Conference, October 8-12, 2008, Ankara, Turkey, 298-307.
[10] U.S. Geological Survey, Minerals Information, [online, cited september 2012], Available from: http://minerals.usgs.gov/minerals/pubs/commodity/diamond.
[11] U.S. Department of Interior, US Geological Survey; [online, cited september 2012],
Available from: http://minerals.usgs.gov/minerals/pubs/commodity/cobalt.
[12] British Geological Survey,World Mineral Production 2005-09, Keyworth, Nottingham; [online; cited February 2011]. Available from: http://www.bgs.ac.uk/mineralsuk