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MACHINING OF A DROP FORGED BRAKE DISC IN Al BASED COMPOSITE - THE FEASIBILITY OF MASS PRODUCTION

EKONOMIČNOST KOVANJA I MAŠINSKE OBRADE ROTORA AUTOMOBILSKE KOČNICE IZRADJENOG IZ Al KOMPOZITA

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ABSTRACT

Drop forging and machining of brake discs made from commercial Al-matrix ceramic composite was performed. An economic analysis of the feasibility of current customer design and future mass production of a drop forged Al MMC brake disc, fully machined using PC under wet and CVD diamond inserts under dry cutting conditions, demonstrated that the major cost barriers in producing Al MMC brake discs are the cost of the composite material and the cost of forging. The investigation also confirmed that the current cost of PCD and CVDD inserts consumed per machined disc does not exceed 10% of the cost of the composite material. Experiments showed that the stage of machining consuming most inserts (about 80%) is rough cutting.

The relatively low cost of tooling inserts (less than 3 USD/disc in this preliminary study and less than 1.50 USD/disc estimated for future mass production) indicates that machining with PCD and CVDD in both cases represents a cost-effective operation.

Key words: brake disc, hot forging, machining with PCD and CVDD inserts, economic feasibility

IZVOD

U radu je opisana izrada i mašinska obrada rotora automobilske kočnice. Rotor je izradjen pomoću klasičnog toplog kalupnog kovanja dok su za mašinsku obradu upotrebljeni posebni alati iz polikristalnog dijamanta (PC) –za mokru ili dijamantnog filma nanešenog hemijskom depozicijom (CVD)-za mašinsku obradu na suvo. Ekonomska analiza pojedinačnih faza proizvodnje je pokazala da bi najskuplji elementi buduće masovne proizvodnje bili kompozitni materijal i kovanje. Bez obzira na upotrebu posebnih dijamantskh alata, ocenjeni troškovi mašinske obrade ne premašuju 10% cene kompozitnog materijala. Eksperimenti ukazuju da je trošenje dijamanskih alata najizraženije (do 80%) u fazi grube mašinske obrade otkivaka, što bi se moglo izvesti jeftinijim karbidnim alatima.

Relativno malo trošenje dijamantskih noževa (manje od 3 USD/rotor u ovoj preliminarnoj studiji i manje od 1,5 USD/rotor kako je ocenjeno za buduću masovnu proizvodnju) ukazuje, da bi mašinska obrada rotora automobilske kočnice iz Al kompozita mogla da bude cenovno ugodna za obe vrste upotrebljenih dijamantskih alata.

Ključne reči: rotor automobilske kočnice, toplo kovanje u kalupu, mašinska obrada sa PCD i CVDD alatima, ekonomska analiza

1 INTRODUCTION

Driven by the desire to reduce vehicle weight and improve fuel efficiency, the car industry has dramatically increased the use of aluminum in passenger vehicles in recent years [1].

One area that is being examined for potential weight reduction is the brake system. The brake systems currently in use are fairly heavy and are typically made of cast iron and cast gray iron.

In recent years, producers have started to develop lighter and more advanced discs and drums for passenger cars. Cast aluminum and aluminum-based metal-matrix composite (MMC) discs and drums, as well as aluminum-alloy discs with aluminum-composite cladding have been reported [2]. The weight reduction can be as much as 45-60 % [2]. However, the high cost of Al MMCs relative to conventional aluminum alloys [3] has prevented widespread industrial applications.

In contrast with the general opinion that to be cost-competitive with cast iron, Al MMC brake discs must be manufactured using a cost-effective casting approach [4], a recent forging trial performed at semi-industrial level demonstrated that commercial Al MMC brake discs could be drop forged as practiced for non-reinforced aluminum alloys, introducing some necessary adaptations only in the cutting and trimming operation [5]. Because drop forged MMCs do not lend themselves to near-net-shape fabrication, the materials require extensive machining [4] of the trimmed components to obtain the final functional shape of the brake disc. This in addition generates significant quantities (20-25%) of fabricator scrap, which has to be recycled in order to keep the overall production cost competitive.

On the other hand, although conventional casting techniques are able to produce composite castings with an acceptable quality level and are the most practiced fabrication route for the current production of Al MMC brake discs, several changes need to be made to metal melting and handling systems, as well as to gating system design and mold yield. Conventional filling and gating systems have to be adapted when going from the usual foundry alloys to Al MMCs. In addition to this, the filling system has to be adjusted to avoid any macroscopic turbulence in the molten composite flow. If such precautions are not taken, most of the air bubbles trapped in the liquid composite entering the part will remain captured by the ceramic particulates and will result in large porosity [6]. Another serious problem is segregation or inhomogeneous distribution of ceramic particulate reinforcement occurring during solidification, which is caused by the density difference between the aluminum and ceramic phases [2].

A forged Al MMC disc has superior mechanical properties, a homogeneous microstructure and surface, and can be finished by low cost finishing operations such as grinding, pickling or sand blasting and is also well suited to the usual coating processes. Drop forging also offers cost advantages for tools. Whereas castings in general depend on relatively complex and costly tools, the cavities of forge dies can be made comparatively quickly and cost-effectively, particularly for small series in which the costly casting moulds cannot be amortized by virtue of the batch size.

Machining MMC brake discs with diamond tooling has shown considerable promise [7], though more work is needed to optimize the procedure and disseminate the data to various machining plants and end-users. Polycrystalline diamond (PCD) coatings for inserts became standard for machining Al MMCs [8]. However, one of the issues with PCDs is the cost. One edge of PCD is at or above the one hundred dollar range in the current market. Even if the cost of PCD inserts would be reduced to half the current price to reflect the volume purchasing discounts of an automotive segment, the machining of an Al MMC brake disc remains more expensive than the machining of its gray cast iron counterpart. As an example, some previous studies indicated that the total cost of PCD inserts per brake disc in mass production would be about 1.3 USD [7].

One class of tool material that has shown promise in machining of Al MMCs is CVDD (Chemical Vapor Deposition Diamond) [8]. Past studies generally indicated PCD as the better choice because CVDD inserts often failed catastrophically due to the failure of braze holding the CVDD to the tungsten carbide substrate [8].

Recently, novel techniques have been developed to create a CVDD insert that gives a number of significant advantages [8]. No longer does the CVDD crystal need to be brazed on the tip of the carbide substrate. Rather, techniques have been developed where a thicker crystal is directly deposited on the insert to cover the entire substrate, thereby giving a much stronger overall tool with multiple edges. This alone will lower the cost of tooling by a multiple of the number of edges. In addition, the initial purchase price of these tools is almost half of what a typical PCD tool costs [8].

Hence, the purpose of the current study was to investigate the economics of machining of drop forged Al MMC brake discs by using commercially available PCD and CVDD inserts and to determine under what conditions machining of Al MMC brake discs becomes cost-effective.

2 EXPERIMENTAL PROCEDURES

A cast billet, 200 mm in diameter (Al composite F3S.20S; producer DURALCAN) was cut with a 375 mm diameter saw blade, tipped with 54 polycrystalline diamond teeth (supplier: KINK Company, Taipei, Taiwan). The PCD saw blade, requiring no lubricant, cut through the billet in one pass. At a cutting speed of 1-3 rev/s, the cut was completed in 25 s. The width of cut was 4 mm.

The cut bars were heated at 500±10°C for 2 h prior to forging. The temperature of the forging die was maintained at an average of 325±20°C. The process of forging was performed on a 1000 t screw press with three consecutive hits at a deformation rate of $3s^{-1}$. Non-trimmed forgings typically had a flash consisting of 3% of the forged bar material.

Forgings were hot trimmed using a 60 t mechanical press and blades made from high-alloy steel hardened to 58 to 60 HRC. Hot trimming was accomplished in conjunction with the hot-forging process at a flash temperature of around 350-400°C.

Forgings were machined on a vertical CNC lathe (Mori SEIKI VL-25) using SPG-422T square CVDD coated insert for rough cuts and TPG-322T CVDD coated inserts for the finish cut. Both types of insert (supplier: sp^3, Inc., Mountain View, CA, USA) were with complete CVDD coverage on one side providing four cutting edges. All machining was made dry. Typical machining parameters for rough cutting were as follows: cutting speed 7.7 m/s, feed rate 0.5 mm/rev and depth of cut (DOC) 2.5mm. The cutting parameters for finish cutting were: cutting speed 7.7 m/s, feed rate 0.125 mm/rev and depth of cut 1.3 mm. The run size of 24 ventilated brake discs were fully machined with CVDD inserts.

In a separate set of machining tests, PCD inserts (CPG-422; supplier: Gilmore Diamond Tools, Inc., E. Providence, RI, USA) were used in order to compare the cost of both machining routes. For rough cutting, the machining parameters were: cutting speed 4.5 m/s, feed rate 0.3 mm/rev and depth of cut 2.5 mm. The finish cut was performed at a cutting speed of 6.7 m/s, a feed rate of 0.15 mm/rev and a depth of cut of 1.3 mm. All machining with PCD inserts was done under a flood of 8% water-soluble oil. The total number of fully machined ventilated brake discs using PCD inserts was 12.

In order to estimate the insert cost per brake disc machined, it was assumed that the PCD insert should be changed at a maximum of 0.35 mm flank wear while CVDD inserts should be replaced when flank wear exceeds 0.20 mm. The flank wear of the inserts was determined by optical microscopy after each cutting trial. The volume of the material removed was calculated from the mass of chips collected during the machining trials.

Machined brake discs were finally solution annealed (2±0.5 h at 535±5°C) and subsequently artificially aged (8±0.5 h at 175±5°C).

3 RESULTS AND DISCUSSION

In the forging trial performed, Al MMC brake discs were prepared by drop forging, Fig. 1.

The measured loss of material during cutting of the extruded rods was about 2%.

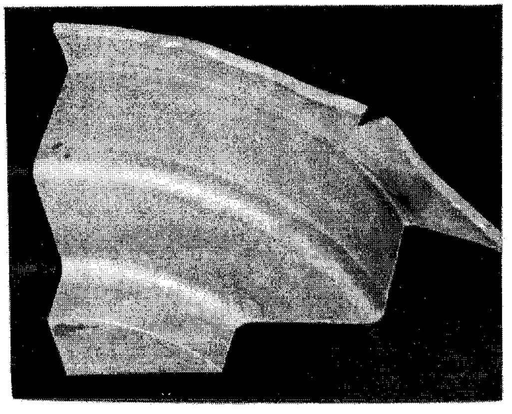

Figure 1 - Hot forged Al MMC brake disc
Slika 1 Toplo kalupno otkovan rotor automobilske kočnice iz Al kompozita.

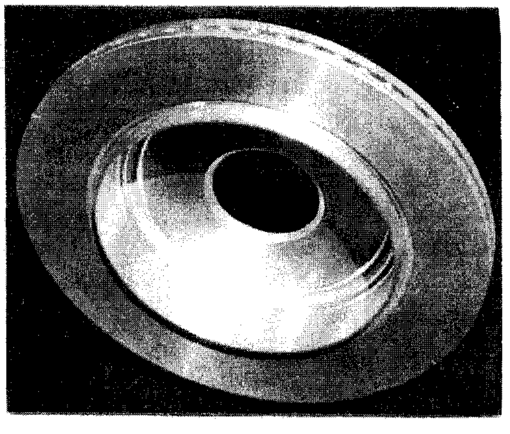

Figure 3 - Fully machined Al MMC brake disc
Slika 3 - Mašinsko obradjen rotor

Non-trimmed forgings typically had a flash consisting of a maximum of 20% of the forged Al MMC bar.

All forged brake discs were dimensionally inspected; the findings confirmed that the tolerances specified in DIN 1749 were achieved. No problems arose which could prevent the transformation of Al MMC bars by means of the forging process itself.

No failures in the microstructure of the forged Al MMC bars were observed, Fig. 2.

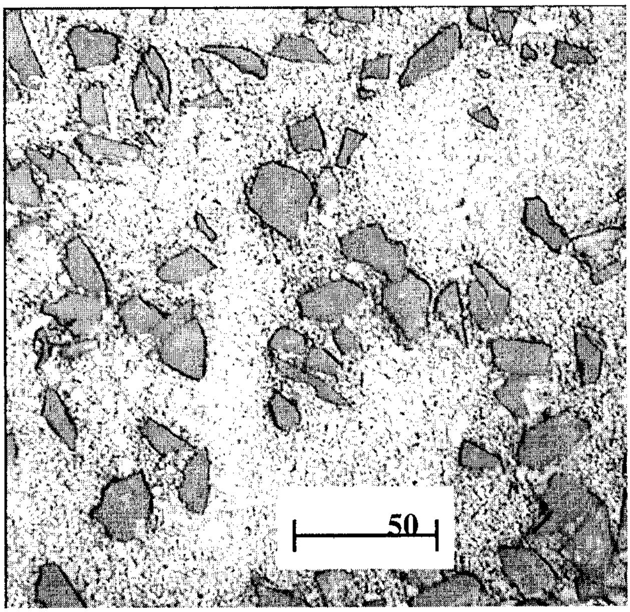

Figure 2 - Microstructure of hot forged Al MMC
Slika 2 - Mikrostruktura otkovanog rotora

Forging and trimming die-life could not be verified due to the limited number of forged and trimmed pieces. However, since the forging behavior of the Al MMC material was very similar to that of non-reinforced aluminum alloys, one can also propose a similar productivity.

The only necessary difference was introduced in cutting and trimming procedures. In cutting, saws using blades with PCD-tipped teeth were necessary. In trimming, instead of cold trimming, hot trimming with additionally hardened and hardfaced trimming blades had to be applied.

On that account, the cost of producing an AlMMC brake disc (involving the cost of cutting, hot forging, trimming and heat treatment) was calculated to be only 25% higher in comparison with the typical cost of producing a non-reinforced aluminum forging.

However, the cost of the material is significantly higher. Currently, the cost of Duralcan's F3S.20S MMC product is approximately 5.50 USD to 6.50 USD per kg, depending on the quantity of material purchased. In any case, this is more than three times higher than the cost of the non-reinforced matrix. Because in cost-sensitive industries such as the automotive industry such an expensive material cannot be used, a significantly lower cost (2.4 USD/kg) of Al MMC was proposed in our study. This estimate is based on the recently reported economy of a new rapid mixing process and a lower-cost of the ceramic reinforcement [9].

The machining trials performed demonstrated that Al MMC brake discs could be successfully machined using conventional machining shops and both PCD and CVDD cutting tools, Fig. 3.

Because of the limited number of forged brake discs available for the machining trials, only the CVDD insert applied in dry roughing cut trial was run until completely worn out.

The results for tool wear obtained after fully machining of Al MMC brake discs with CVDD and PCD inserts are summarized in Table 1.

Table 1 - Results for tool wear after fully machining of Al MMC brake discs with CVDD and PCD inserts.

Tabela 1 - Trošenje CVDD I PCD dijamantskih alata nakon kompletne mašinske obrade rotora automobilske kočnice.

Insert	Discs machined	Insert wear (mm)	Material removed (cm^3)	Wear rate ($\mu m/cm^3$)
CVDD SPG-422T	10	0.20	1483	0.13
CVDDTPG-322T	24	0.08	3776	0.02
PCD CPG-422	12	0.11	5520	0.02

In Fig. 4, the increase of insert wear, measured by optical microscopy, as a function of the number of brake discs machined is plotted. As evident, the increase is almost linear. Based on this and taking into account the previous assumption that the PCD insert is changed at a maximum of 0.35 mm flank wear while the CVDD insert is replaced at 0.15 mm flank wear, one can extrapolate the consumption of inserts and also calculate the total cost of PCD and CVDD inserts per fully machined brake disc. Considering roughing cuts, approximately 10 Al MMC brake discs can be machined by one cutting edge of the CVDD insert. Because the CVDD inserts used in this study had four cutting edges, one insert would be sufficient for rough cutting of 40 brake discs.

More promising results were extrapolated for finish cutting of Al MMC brake discs with CVDD inserts. It was found that approximately 45 brake discs can be machined with one cutting edge, means that 180 brake discs can be finish cut with just one CVDD insert.

The data for PCD inserts are in line with findings of other researchers [7]. Based on the extrapolated data, approximately 38 Al MMC brake discs can be fully machined by applying one PCD insert with a single cutting edge.

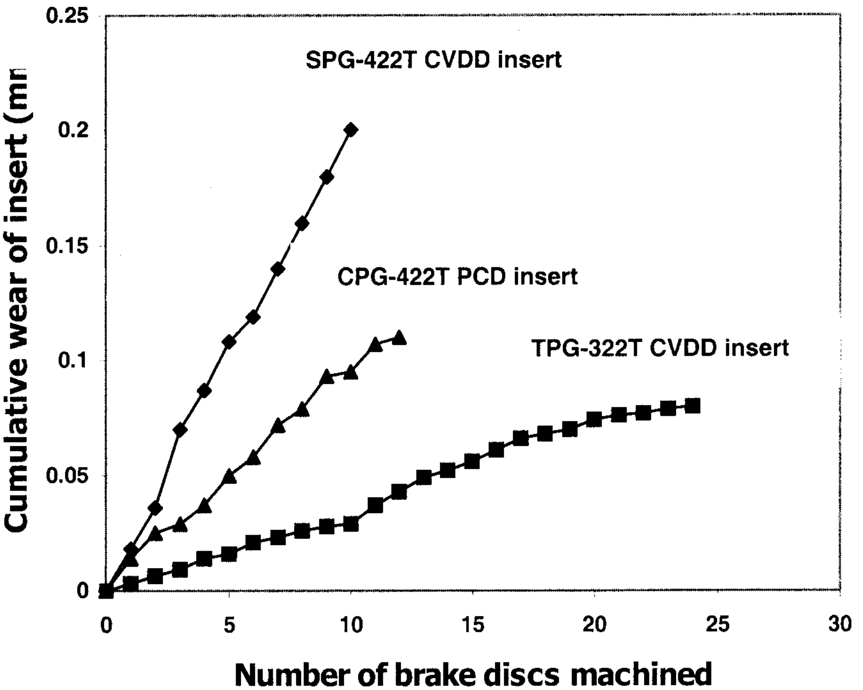

Figure 4 - Cumulative wear of PCD and CVDD inserts used for machining as a function of the number of brake discs machined. Accuracy of measurement: ± 0.005 mm

Slika 4 - Kumulativno trošenje PCD I CVDD alata za mašinsku obradu kao funkcija broja obradjenih rotora. Tačnost merenja je ± 0.005 mm

Further assuming that for mass production the cost of the four cutting edge CVDD inserts used in this study would be in the range of about 35 USD, while the cost of a PCD insert with a single cutting edge would be about 50 USD, the total cost of CVDD inserts per disc would be about 1.1 USD. In the case of a PCD insert, the total cost per disc would be 1.3 USD. Although calculated costs are similar for both kind of inserts, it is important to note that CVDD inserts enable cutting without flood coolant in dry conditions.

As evident from the accumulated data, in order to improve the economy of dry machining with CVDD inserts, it is important to reduce the extent of rough cutting. Rough cutting is usually applied for removing casting scales and the in-gate of the casting.

This could be another important reason for producing Al MMC brake discs by forging. On the surface of a forged brake disc there are no casting defects and hence significantly less rough cutting is necessary for obtaining the final part.

The machining cost data reported here is an estimate. It does not represent a statistically valid sample size, and it does not include any estimate of capital, overheads, labor, or other associated costs that vary significantly from facility to facility.

The reported data indicate that the cost of consumables for complete machining of Al MMC brake discs with CVDD inserts is just slightly more cost-effective than with conventional single edge PCD inserts. This is because the cost of CVDD inserts consumed in rough cutting of material represents the most significant contribution (about 80%) to the total cost of consumables.

Due to the lower surface roughness of forged parts in comparison with some castings, forgings usually require less intensive rough cutting. This additionally decreases the cost of machining when forging is selected as the forming method.

Any consideration of the large-scale production and usage of Al MMC brake discs demands that the issues of recycling of the fabricating scrap (and old scrap) be also addressed [10] Due to the fact that during trimming and machining scrap generation reaches 50-60% of the weight of the forged component, recycling significantly influences the cost of the product. In the current study, it was assumed that Al MMC scrap could be resold to the supplier of Al MMC billets at 80% of the price of new material.

For the complete machined Al MMC brake disc fabricated in this study (weight 3.5 kg), the total scrap generation (including scrap generated by cutting of bars, trimming of forgings and machining) was weighed to be about 2.0 kg. The structure of the generated scrap is presented in Table 2.

On this basis, the reduced cost of raw material per brake disc can be calculated.

The data are summarized in Table 3 together with the cost of PCD and CVDD inserts necessary for the complete machining.

Table 2 - Structure of the scrap generated during cutting of forging bars, trimming and machining of the Al MMC brake disc fabricated in this work. The fully machined brake disc weighted 3.5 kg

Tabela 2 - Strukturi udeo otpadnog materijala koji nastaje tokom kovanja, odrezivanja kovačke brade i mašinske obrade rotora automobilske kočnice, otkovanog iz Al kompozite. Masa mašinsko obradjenog rotora iznosi 3,5 kg

Operation	Weight of scrap generated per brake disc	
	(kg)	(%)
Cutting	0.11	1.8
Trimming	1.10	18.5
Machining	1.24	20.8
Total	2.45	

Table 3 - Cost breakdown for a hot forged and machined Al MMC brake disc with an annual production volume of three million parts

Tabela 3 - Struktura cene otkovanog i mašinsko obradjenog rotora automobilske kočnice iz Al kompozite. Podatci se odnose na planirani obim proizvodnje: 3 miliona rotora godišnje.

Cost element	Current contribution to the total cost		Contribution to the total cost estimated for the future+	
	(USD)	(%)	(USD)	(%)
Material*	25.9	~53	9.6	~33
Forging	20.2	~42	18.5	~63
PCD insert	2.6	~ 5	1.3	~ 4
CVDD insert	2.2	~ 5	1.1	~ 4

+For an annual production volume of 3 million parts

*Cost of material is reduced by the value of scrap accumulated

As evident from the data in Table 3, the current cost of PCD and CVDD inserts represents less then 10% of the current cost of the Al MMC material. Comparing the cost of the raw material and PCD and CVDD inserts estimated for the future, (when the rapid mixing process [9] or similar cost-effective producing routes will be associated with the complete recycling of internal, fabricator and old Al MMC scrap), almost the same cost ratio is obtained.

However, the contribution of the cost of forging will increase in future due to the predicted lowering of the cost of Al MMC composite. Because of that, one can expect that further development of forging and other forming technologies will be directed mainly toward the reduction its fabrication costs.

Summarising, the major cost barrier in the current production of Al MMC brake discs is the cost of the Al MMC composite material. In future, that will mostly represent the cost of the forming procedure. The relatively low cost of tooling inserts (less than 3 USD/disc in this preliminary study and less than 1.50 USD/disc estimated for future mass production) indicates that machining with CVDD as well as PCD inserts in both cases represents a cost-effective operation. However, additional work is required to validate the consistency of the data presented in this work, particularly because the brake disc population size used in this study was far too small to yield statistically significant results.

CONCLUSION

Al MMC brake discs were successfully drop forged as practiced for aluminum alloys, introducing some necessary adaptations only in the cutting and trimming operation. No significant failures in the microstructure of the forged Al MMC parts were observed.

The fabrication cost of an Al MMC brake disc (involving the cost of cutting, hot forging, trimming and heat treatment) was calculated to be only 25% higher in comparison with the typical cost of producing a non-reinforced aluminum forging.

Machining of forged parts with polycrystalline diamond (PCD) and chemically vapor deposited diamond (CVDD) inserts was performed routinely, using a conventional machining shop. The cost of PCD and CVDD inserts consumed for machining was found to be in the range of 1.1-1.2 USD/disc, which is about ten times lower than the cost of the raw material. On that account, this economic feasibility study of the mass production of a fully machined hot forged Al MMC brake disc demonstrated that the major cost barrier to its production is the cost of the raw material. Moreover, the relatively low cost of tooling inserts (less than 3USD/disc in this preliminary study and less then 1.5 USD/disc calculated for future mass production) indicates that machining in both cases represents a cost-effective operation. Although the Al

MMC brake disc cannot be drop forged to a near-net-shape, its lower surface roughness in comparison with castings significantly reduces the necessity for rough cutting, the stage of machining consuming most inserts. Because of that and also the cost advantages of the required tools, forging could be currently used as a cost-effective way of producing of both ventilated and non-ventilated Al MMC brake discs in a medium batch size. To remain cost competitive in the future, when the cost of Al MMC composite material is expected to decrease to 2.4 USD/kg and the batch size will exceed 3 million parts per year, further cost reduction of forging is necessary.

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