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ZAŠTO NEKA MOTORNA ULJA ZA OSOBNA VOZILA NISU VIŠE POGODNA ZA MOTORKOTAČE – PROBLEM POJAVE PITTINGA

Sažetak

Nove kategorije ulja za osobna vozila, koje propisuje American Petroleum Institute (API) usmjeravaju primjenska svojstva ulja na poboljšanje ekonomičnosti potrošnje goriva i smanjenje emisije. Taj trend je rezultirao povećanom ponudom motornih ulja, koja pogoduju uštedi goriva što se postiže smanjenjem viskoznosti i dodatkom modifikatora trenja. Smanjenje emisije je postignuto smanjenjem količine fosfora (% P) u motornim uljima, jer je nađeno da je fosfor otrov za katalizator u katalitičkim konverterima.

Kada su u formulacije ulja uvedeni modifikatori trenja, istraživači četiriju japanskih proizvođača motorkotača su objavili rezultate svojih studija (SAE 961217), koji pokazuju da ulja sa smanjenim trenjem mogu uzrokovati preveliko proklizavanje spojke startera, limited-slip spojke i višelamelne spojke. U spomenutom članku su autori izvijestili, da su konstruktori motora, koji kod razvojnih ispitivanja koriste motorno ulje gradacije SAE 10W-30, opazili pojavu pittinga, ako se koristi ulje niže viskoznosti od gradacije SAE 10W-30. Nakon te studije količina fosfora je smanjena u API specifikacijama od SG (bez ograničenja sadržaja fosfora) preko SH (0,12 % P) i SJ/SL (0,10 % P) do SM (0,08 % P). Poznato je, da fosfor iz Zn-ditiofosfata tvori zaštitni sloj između metalnih površina čime štiti zupčanike od trošenja i pittinga kada uljni film postane pretanak. Tijekom razvoja motornog ulja 10W-30 API SJ za motorkotače opažena je pojava pittniga kod testova na motoru CBR600. Kako je % P bio ograničen specifikacijom API SJ, a debljina uljnog filma određena viskoznošću SAE gradacije 10W-30, rješenje je nađeno u uporabi vrlo smično stabilnog poboljšivača indeksa viskoznosti, koji nije tipičan za motorna ulja osobnih vozila, te je zbog minimalnog pada viskoznosti ulja ostvarena potrebna debljina uljnog sloja u motoru motorkotača. Uporaba ekstremno smično stabilnog poboljšivača indeksa viskoznosti omogućit će, da se u uvjetima povećanog smicanja u motorima motorkotača koriste ulja s manje fosfora, što zahtijevaju specifikacije API SJ i više, te viskoznosti niže od SAE 10W-30.

UVOD

Nove API specifikacije motornih ulja za osobna vozila imaju naglasak na smanjenju emisije i ekonomičnosti potrošnje goriva. Smanjenje emisije je postignuto redukcijom količine fosfora u motornim uljima, jer je ustanovljeno, da je fosfor otrov za katalizatore u katalitičkim konverterima. Smanjenje potrošnje goriva je postignuto sniženjem viskoznosti i ugradnjom veće količine modifikatora trenja u ulja.

Kada su se pojavila motorna ulja s većom količinom modifikatora trenja, istraživači četiriju japanskih proizvođača motorkotača su objavili rezultate njihovih istraživanja (1), koji su pokazali da neka motorna ulja za osobna vozila nisu više pogodna za motorkotače. Dokazali su da ulja sa smanjenim trenjem mogu uzrokovati previše proklizavanja u spojkama startera, jednosmjernim limited-slip spojkama i u višelamelnim mokrim spojkama. U spomenutom članku su objavili, da svi za razvoj motora koriste ulje SAE gradacije viskoznosti 10W-30, jer je kod svih opažena pojava pittinga, ako se koristi ulje niže SAE gradacije viskoznosti.

Proizvođači motorkotača žele postići uštedu goriva i ostvariti povećanu snagu uporabom niskoviskoznih ulja s modifikatorima trenja, ali ne na račun proklizavanja spojki i pojave pittinga u mjenjačima. U tu svrhu je iniciran razvoj niskoviskoznog motornog ulja SAE 10W-30, koje pruža uštedu goriva, kvalitete API SJ, s mogućnošću pomaka u API SL kategoriju.

Količina fosfora se morala smanjiti na najviše 0,10 %. Nadalje, ulje je trebalo osigurati smanjeno trenje radi manje potrošnje goriva, ali bez uporabe modifikatora trenja na osnovi molibdena, jer ovi mogu uzrokovati proklizavanje spojki. Tijekom razvoja novog ulja provedena su ispitivanja u svrhu ocjene frikcijskog ponašanja, oksidacijske i termičke stabilnosti, zaštite od stvaranja taloga i sprječavanja trošenja i nastanka pittinga zupčanika. U ovom članku je posebna pažnja posvećena proučavanju pittinga zupčanika.

EKSPERIMENTALNI DIO

Ispitivana ulja

U razvoju ulja za motorkotače su za ispitivanje korištena tri motorna ulja, čije karakteristike su prikazane u tablici 1. Sva tri ulja su formulirana kao 10W-30 uz korištenje baznih ulja grupe II. Sva ulja sadrže paket aditiva kvalitete API SJ, što znači, da sva imaju manje od 0,10 % P. Ulje A sadrži samo bazno ulje SN 150, dok ulje B sadrži 75 % baznog ulja SN 150 i 25 % SN 500, dok je viskoznost na gornjoj granici SAE gradacije. Oba ulja sadrže poboljšivač indeksa viskoznosti tipičan kod ulja za osobna vozila. Ulje C sadrži bazna ulja SN 150 i SN 500 u omjeru 95 : 5, ali glavna razlika između ulja C i druga dva je u poboljšivaču indeksa viskoznosti (VII). Naime, ulje C sadrži ekstremno smično stabilan VII.

Tablica 1: Formulacije ulja

Ispitivano ulje	**A**	**B**	**C**
Gradacija viskoznosti	10W-30	10W-30	10W-30
Bazno ulje SN 150 grupe II	100 %	75 %	95 %
Bazno ulje SN 500 grupe II		25 %	5 %
Tipičan VII za osobna vozila	6 %	6 %	
Smično stabilni VII			6%
PPD	0,3 %	0,3 %	0,3 %
Paket aditiva za API SJ	>10 %	>10 %	>10 %
Kin. viskoznost kod 40ºC, mm^2/s	66,5	83,7	71,6
Kin. viskoznost kod 100ºC, mm^2/s	10,7	12,2	11,2
Indeks viskoznosti	150	141	148

Ocjenjivanje rezultata testova:

Za ocjenu utjecaja ulja na trajnost motora motorkotača s mokrom spojkom korišten je test, kojim je naprezanje motora znatno premašivalo uvjete u normalnoj vožnji. Ispitivanje je provedeno na dinamometru pod velikim opterećenjem motora kao kod vožnje vrlo velikom brzinom uz maksimalan otvor leptira rasplinjača.

Ispitivanje je provedeno na modernom četverocilindričnom motoru od 600 cm^3, s rasplinjačem i hlađenjem vodom, kakvi su česti u popularnim sportskim motorkotačima s 4 ventila po cilindru. Prijenos snage je ostvaren putem mokre višelamelne spojke i 6-stupanjskog mjenjača. Osnovne karakteristike su prikazane u tablici 2.

Tablica 2: Karakteristike motora

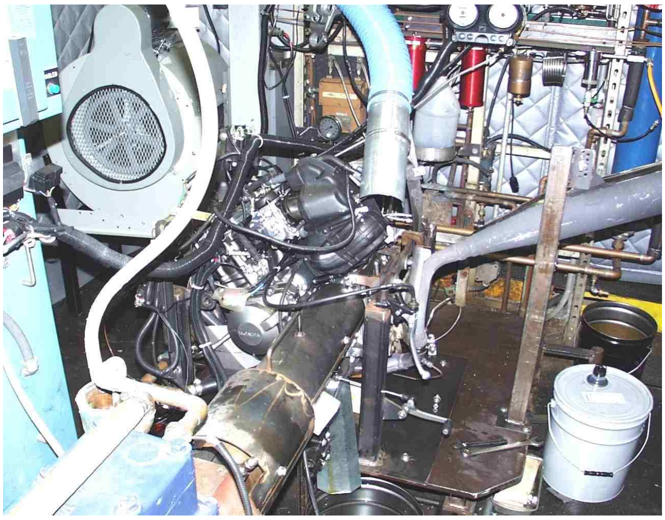
Tip motora	4-taktni, linijski, 4-cilindrični
Obujam motora	65 x 45,2 mm (600 cm^3)
Omjer kompresije	12 : 1
Razvod ventila	DOHC 16 ventila
Rashladni sustav	Hlađenje tekućinom
Podmazivanje	Pod pritiskom, mokri karter motora
Dobava goriva	Rasplinjač, stalni protok
Sustav paljenja	Tranzistorsko paljenje
Spojka	Višelamelna, mokra
Transmisija	6 stupnjeva
Primarna redukcija	1,863 : 1
Odnos zupčanika u 5. stupnju	1,2 : 1
Odnos zupčanika u 6. stupnju	1,086 : 1

Podmazivanje se postiže u uljnom krugu, kojim se ulje pod pritiskom dobavlja iz kartera motora u glavu cilindra, koljenasto vratilo i transmisiju.

Prije početka ispitivanja svi dijelovi, kod kojih može doći do trošenja, kao što su klipovi, cilindri, bregovi bregaste osovine i zupčanici su izmjereni, kako bi se mogle početne mjere usporediti s mjerama na kraju testa zbog ocjene istrošenja.

Nakon toga je motor sastavljen i instaliran na probni stol opremljen automatiziranim uređajima za praćenje i kontrolu otvora leptira rasplinjača, temperature ulja, temperature rashladne tekućine i broja okretaja motora. Motor instaliran na probnom stolu se može vidjeti na slici 1.

Slika 1: Motor na probnom stolu u Lubrizol R&D laboratoriju u SAD-u
Figure 1: Photo of test engine installed in a test cell at the Lubrizol R&D laboratory in the USA



Dodatno su bile mjerene vrijednosti potrošnje goriva, količina CO u ispušnim plinovima, temperature ispušnih plinova, vlažnost, temperatura svjećica i temperatura zraka.

U svrhu eliminacije utjecaja ulja, koje je korišteno kod pripreme motora, na ulje koje se ispituje, motor je ispran nekoliko puta svježim ispitnim uljem prije početka uraďivanja motora. Nakon 3-satnog uraďivanja izmjereno je propuštanje ventila u glavi motora, kompresija cilindara i blow-by. Tada je posljednji put zamijenjeno ulje i montiran je novi filtar ulja.

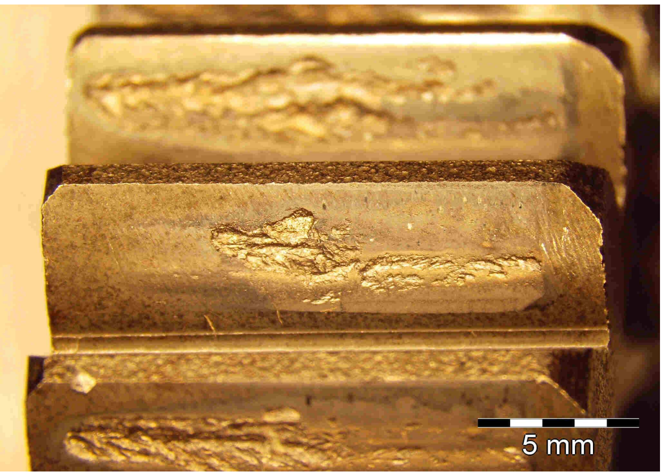
Ispitivanje izdržljivosti se sastojalo od 200 sati rada motora kod najvećeg otvora leptira rasplinjača i 9600 o/min. Temperatura ulja je bila 125 °C, a rashladne tekućine 100 °C. Treba naglasiti, da 200 sati rada motora kod punog otvora leptira rasplinjača odgovara 23000 prijeđenih milja (35000 km) bez zamjene ulja. Prvi dio testa je vožen u šestom stupnju prijenosa, dok je posljednjih 20 sati prijenos bio u petom stupnju. Tijekom ispitivanja je nekoliko puta provjeravana zračnost ventila i potrošnja ulja, što je zabilježeno u dnevnik testa. Ukoliko bi bio primijećen pojačan zvuk (cviljenje) zupčanika, postojala je mogućnost provjere njihovog stanja kroz poklopac na kućištu transmisije. U slučaju neprihvatljivog stanja, ispitivanje bi bilo prekinuto na osnovi ocjene stanja zupčanika.

Nakon testa motor je bio pažljivo rastavljen, a kritični dijelovi su pregledani, ocijenjeni i izmjereni. Istrošenje zupčanika je ocijenjeno na temelju izmjerene površine (u mm^2), na kojoj je zamijećen pitting. Površine s oštećenjima za svaki zupčanik su zbrojene i uspoređene. Ocijenjeni su pogonski i pogonjeni zupčanici petog i šestog stupnja mjenjača.

REZULTATI I DISKUSIJA

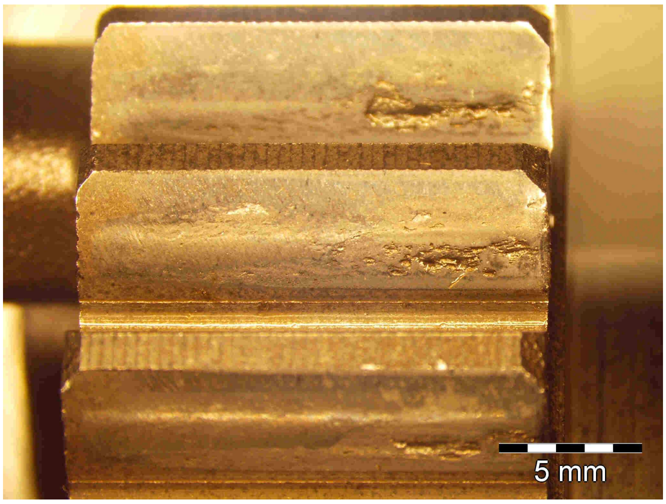
Prvi test na motoru uljem A iz tablice 1 je morao biti prekinut nakon 100 sati zbog jakog cviljenja zupčanika. Pregledom je ustanovljeno jako istrošenje zupčanika. Na slikama 2 i 3 je prikazano karakteristično istrošenje zupčanika uljem A.

Slika 2: Karakteristično istrošenje zupčanika pogonjene osovine uljem A nakon 100 sati ili 11500 milja
Figure 2: Average countershaft gear wear from the evaluation of test oil A after 100 hours or 11,500 miles

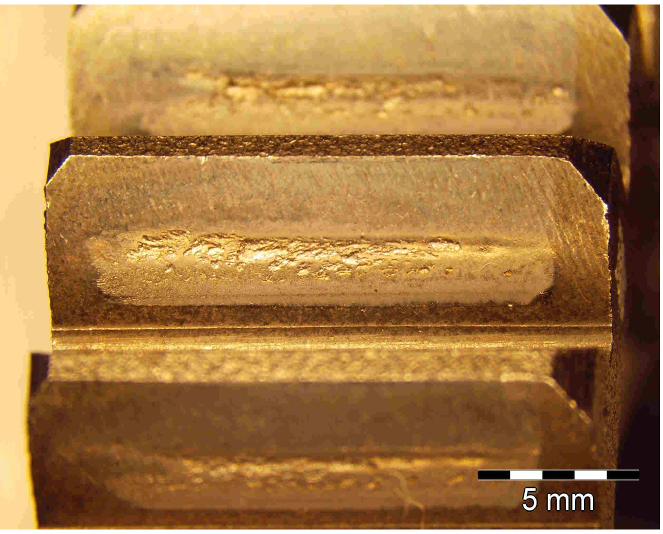


Ovo ispitivanje od 100 sati je bilo jednako vožnji od 11500 milja (18000 km) kod punog otvora leptira rasplinjača bez zamjene ulja. Test je zamišljen kao strogi test izdržljivosti i dobiveni rezultat je smatran neprihvatljivim. Trebalo je, dakle, promijeniti formulaciju ulja.

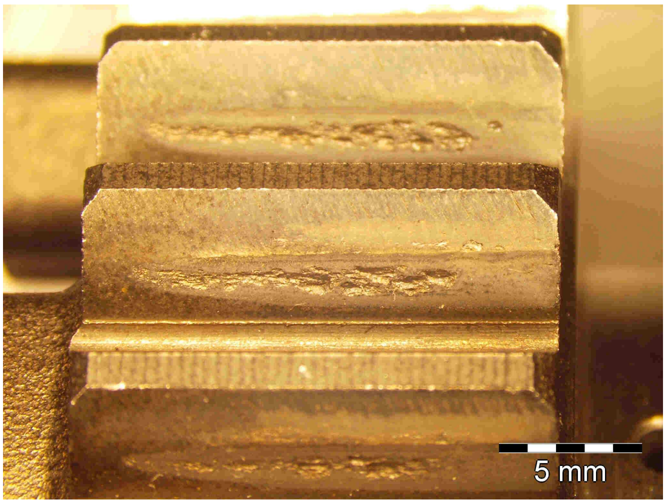
Slika 3: Karakteristično istrošenje zupčanika pogonske osovine uljem A nakon 100 sati ili 11500 milja
Figure 3: Average main shaft gear wear from the evaluation of test oil A after 100 hours or 11,500 miles



Slika 4: Karakteristično istrošenje zupčanika pogonjene osovine uljem B nakon 120 sati ili 13800 milja
Figure 4: Average countershaft gear wear from the evaluation of test Oil B after 120 hours or 13,800 miles



Slika 5: Karakteristično istrošenje zupčanika pogonske osovine uljem B nakon 120 sati ili 13800 milja
Figure 5: Average main shaft gear wear from the evaluation of test oil B after 120 hours or 13,800 miles



S gledišta kemijskog sastava moglo se postići bolju zaštitu zupčanika pomoću konvencionalnog aditiva Zn-ditiofosfata, ali ta opcija nije bila prihvatljiva zbog ograničenja količine fosfora propisanog specifikacijom API SJ. Drugi pristup je bio povećanje debljine uljnog sloja, tako da se poveća viskoznost do gornje granice SAE gradacije 10W-30.

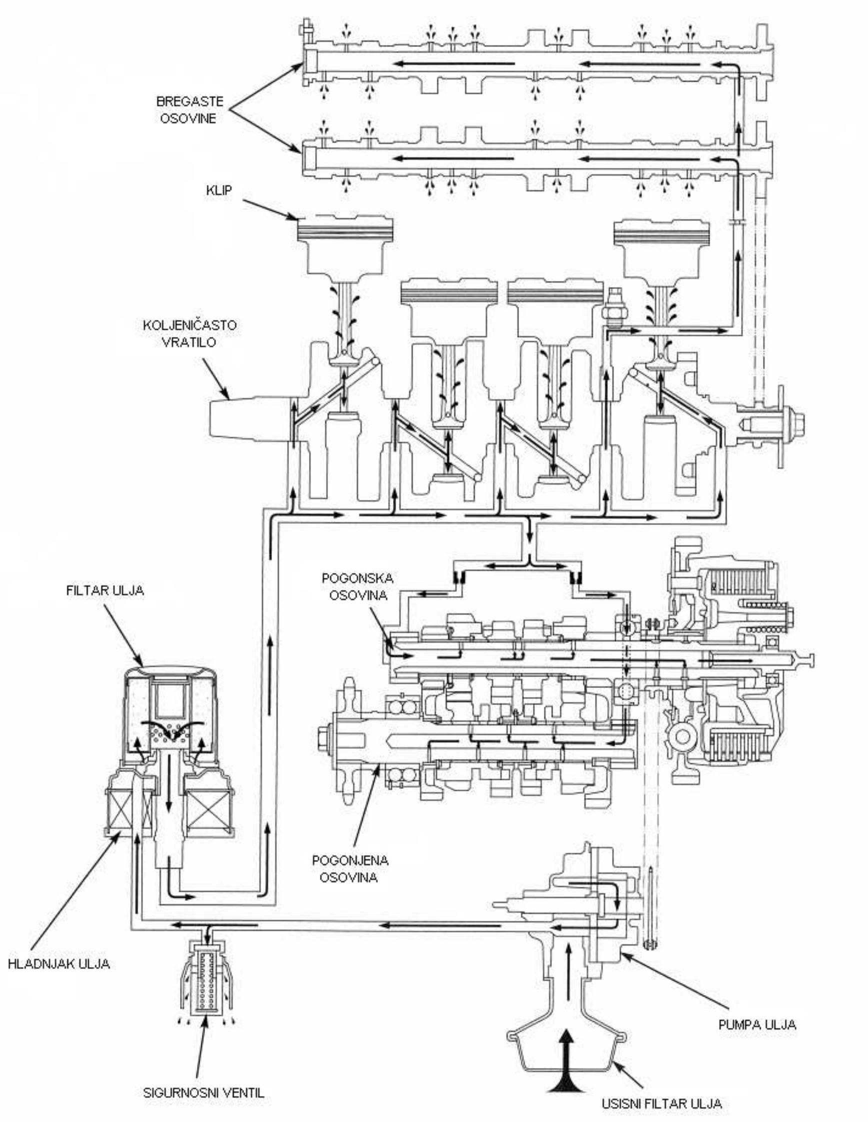
Drugi test, koji je proveden na istom motoru uljem B iz tablice 1 morao je biti prekinut nakon 120 sati, ponovno zbog jakog cviljenja zupčanika. Ponovno je pregled pokazao prekomjerno istrošenje zupčanika vidljivo na slikama 4 i 5.

Trajanje ovog testa je odgovarajuće vožnji od 13800 milja (20000 km) kod punog otvora leptira rasplinjača bez zamjene ulja. Iako je testiranje potrajalo duže od prethodnog, rezultat nije prihvatljiv, jer je istrošenje nastupilo prije predviđenog kraja.

Ovaj motor radi u uvjetima vrlo velikog opterećenja, kako bi oponašao vožnju kod maksimalnog otvora leptira rasplinjača i vrlo velike brzine. Ako pobliže proučimo sustav podmazivanja, koji je prikazan na slici 6, uočit ćemo, da u motoru ima pojedinih dijelova u kojima je ulje pod velikim smičnim naprezanjem.

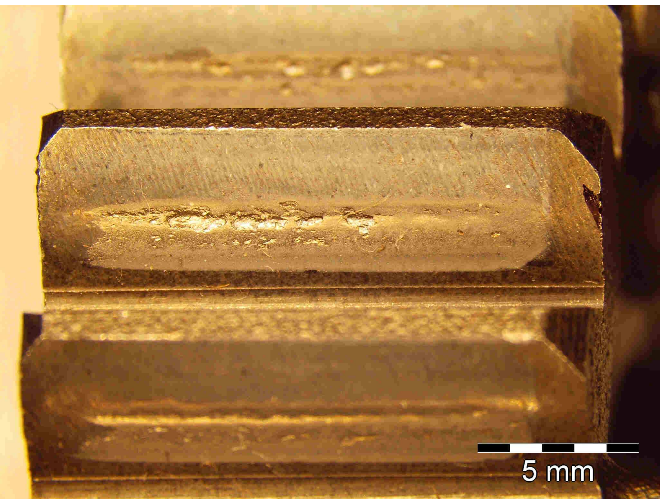
Kako motorno ulje prolazi kroz zone visokog smičnog naprezanja, moguće je, da dođe do stalnog pada viskoznosti, a time i smanjenja debljine uljnog sloja. U motoru, koji radi u uvjetima velikih opterećenja, pretanak uljni sloj može biti nedovoljan za zaštitu zupčanika prijenosa snage od trošenja. Da bismo potvrdili ovu teoriju, formulirali smo ulje C iz tablice 1 i ispitali ga u sljedećem testu.

Slika 6: Sustav podmazivanja

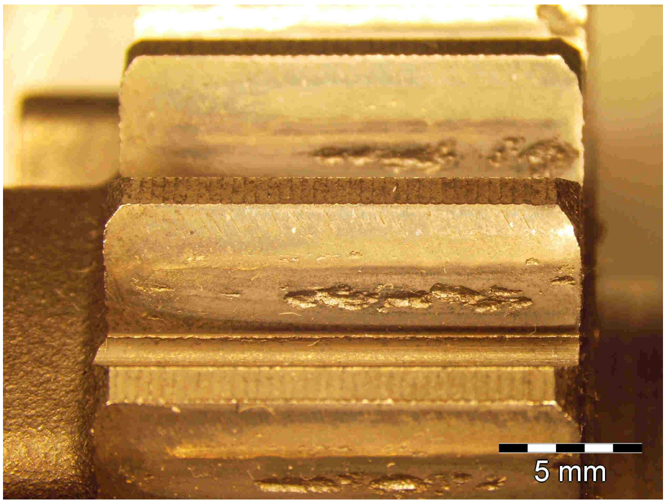


Ulje C je sadržavalo niskomolekularni smično vrlo stabilni poboljšivač indeksa viskoznosti, kakav nije uobičajen u motornim uljima. Ako poboljšivač indeksa viskoznosti izdrži smična naprezanja i uljni sloj zadrži svoju čvrstoću, zupčanici bi trebali biti zaštićeni, pa ne bi došlo do istrošenja i pittinga, a ulje bi trebalo izdržati do kraja ispitivanja.

Slika 7: Karakteristično istrošenje zupčanika pogonjene osovine uljem C nakon 200 sati ili 23000 milja
Figure 7: Average countershaft gear wear from the evaluation of test Oil C after 200 hours or 23,000 miles



Slika 8: Karakteristično istrošenje zupčanika pogonske osovine uljem C nakon 200 sati ili 23000 milja
Figure 8: Average main shaft gear wear from the evaluation of test Oil C after 200 hours or 23,000 miles



Kada smo testirali ovo ulje, test je završen uspješno do kraja, tj. punih 200 sati ili 23000 milja (30000 km) u vrlo oštrim uvjetima rada i bez izmjene ulja. Zupčanici i ostali dijelovi motora su ocijenjeni, a stanje je bilo zadovoljavajuće. Izgled zupčanika nakon testa prikazan je na slikama 7 i 8.

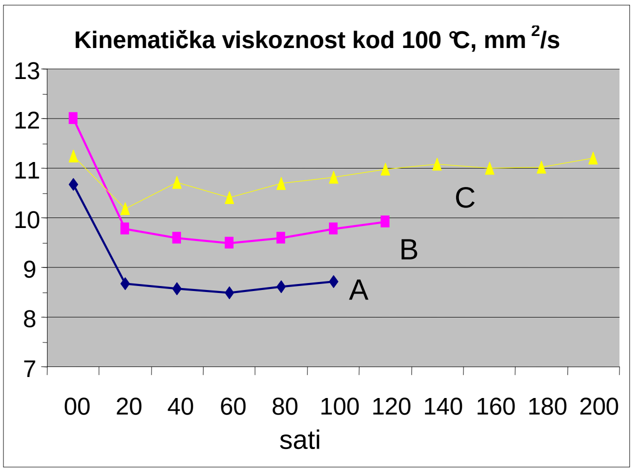
Rezultati svih triju testova su usporedno prikazani u tablici 3. U tablici su površine zupčanika zahvaćene pittingom sumarno prikazane za svako ispitivano ulje.

Tablica 3: Usporedba rezultata ispitivanja

	Ulje A	**Ulje B**	**Ulje C**
Trajanje testa, sati	100	120	200
Trajanje testa, milja	11 500	13 800	23 000
Pitting zupčanika pogonske osovine mm²)	103	172	129
Pitting zupčanika pogonjene osovine (mm²)	44	113	86
Ukupan pitting zupčanika (mm²)	147	285	215

Rabljena ulja nakon testova su analizirana s ciljem, da se ustanovi je li teorija o utjecaju smične stabilnosti bila ispravna. Analize ulja su grafički prikazane na slici 9.

Slika 9: Analiza rabljenih ulja iz motornih ispitivanja



Jasno je pokazano, da je ulje C najmanje podložno smicanju i da je zadržalo debljinu uljnog sloja, a time omogućilo da se test završi do kraja bez pojave pittinga na zupčanicima, što je bio slučaj s uljima A i B. Poslije početnog pada viskoznosti zbog utjecaja smicanja malo povećanje viskoznosti se može pripisati zgušnjavanju zbog oksidacije ulja. Ovi su rezultati bili objavljeni prije (3). Analiza površine zupčanika metodom fotoelektronske spektroskopije X-zrakama (XPS), koja je provedena na Case Western Reserve University na PHI 5600 spektrometru, potvrđuje našu pretpostavku.

Tablica 4: Debljina zaštitnog sloja - XPS

	Ulje A	**Ulje B**	**Ulje C**
	Debljina zaštitnog sloja (Å)		
Zn	800	900	200
S	800	800	400
P	1 200	1 200	500

Debljina tribokemijskog filma je iznosila 800 - 1200 Å za formulacije A i B. Formulacija C, koja je sadržavala smično stabilni poboljšivač indeksa viskoznosti, formirala je zaštitni sloj debljine 200 – 500 Å. Čini se, da je razlika debljine reakcijskog antitrošećeg sloja povezana s ponašanjem poboljšivača indeksa viskoznosti. Minimalna degradacija zbog smicanja ulja C rezultirala je održanjem tekućinskog (elasto-hidrodinamičkog) sloja.

Time je spriječen nastanak kontakta neravnina metalnih površina. U konačnici to znači, da je temperatura u zoni kontakata bila niža, a time je smanjena reakcija aditiva s površinom zupčanika. Nasuprot tome smanjenje viskoznosti ulja A i B rezultiralo je tanjim uljnim slojem, međusobnim dodirom metalnih površina, porastom temperature u kontaktnim zonama i konačno većom reaktivnošću aditiva na površini zupčanika. Rezultat je bio deblji tribokemijski zaštitni sloj.

ZAKLJUČAK

Zbog stalnog pritiska na formulatore motornih ulja, da razviju ulja za osobna vozila, koja će pogodovati smanjenju potrošnje goriva, ta nova generacija ulja manje je pogodna za motorkotače. Poznato je da ulja koja sadrže modifikatore trenja mogu uzrokovati proklizavanje spojki kod motorkotača. Također je poznato da ulja gradacije viskoznosti niže od SAE 10W-30 mogu uzrokovati pitting zupčanika u prijenosnicima motorkotača. Ovaj izvještaj pokazuje da čak i ulja SAE 10W-30 gradacije mogu uzrokovati pitting kada motorkotači voze pod velikim opterećenjem. Današnja motorna ulja za osobna vozila tipično sadrže smično manje stabilne poboljšivače indeksa viskoznosti. U motorima motorkotača, međutim, smična degradacija poboljšivača u kombinaciji s niskom viskoznošću i malom količinom fosfora tih ulja može rezultirati pojavom pittinga u ekstremnim uvjetima vožnje, kako je to pokazano provedenim ispitivanjima.

Zahvala:
Autori žele zahvaliti g. Masotoshi Akagi, Honda Motor Company, za vrijedne komentare u diskusiji dobivenih rezultata ispitivanja.

WHY SOME PASSENGER CAR MOTOR OILS ARE NO LONGER SUITABLE FOR MOTORCYCLES: GEAR PITTING ISSUES

Abstract

The new American Petroleum Institute (API) categories for passenger car motor oils have focused on improving fuel economy and reducing emissions. This has resulted in more fuel efficient oils being developed by lowering the viscometrics and by adding friction modifiers. The emissions reductions have resulted from lowering the percent phosphorus (% P) in the engine oils because phosphorus has been found to poison the catalyst in the catalytic converter.

When friction modifiers were introduced, researchers from four Japanese motorcycle manufacturers published the results of their studies (SAE 961217) which indicated that low friction oil cn cause too much slippage in starter motor clutches, one-way limited slip clutches, and wet multi-plate clutches. In that same study they reported that engine manufacturers use 10W-30 grade oil to develop new engine technology, and gear pitting was observed with oils of viscosity grades lower than 10W-30 in all four manufacturers' motorcycle engines.

Since that study, the % P has been lowered in engine oils as the API categories have evolved from SG (no % P limit) to SH (0.12% P) to SJ/SL (0.10% P) to SM (0.08% P). The phosphorus from zinc dithiophosphate is known to form a protective film between metal parts which provides protection against wear and gear pitting if the oil film becomes too thin. During the development of a 10W-30 API SJ motorcycle oil, gear pitting was observed when testing was conducted in a CBR600 engine. Since the % P was limited by the API SJ category and the oil film thickness was limited by the 10W-30 viscosity grade, the solution was to use an extremely shear stable viscosity modifier, not typically used in passenger car applications, to ensure minimum shearing, therefore maintaining the oil film thickness in this motorcycle engine. The use of this extremely shear stable viscosity modifier technology therefore will enable lower % P 10W-30 oils, formulated to meet API SJ or higher categories for passenger car applications, to be utilized in the higher shear environment of motorcycle engines.

BACKGROUND

The new API categories for passenger car motor oils have focused on reducing emissions and improving fuel economy. The emissions reductions have resulted from lowering the % P in the engine oils because phosphorus has been found to poison the catalyst in the catalytic converter. More fuel efficient oils have been developed by lowering the viscometrics of the oils and by adding high levels of friction modifiers.

When high levels of friction modifiers were introduced to passenger car oils, researchers from four Japanese motorcycle manufacturers published the results of their studies (1), which indicated that some passenger car oils are no longer suitable for motorcycles. They demonstrated that low friction oil can cause too much slippage in starter motor clutches, one-way limited slip clutches, and wet multi-plate clutches. In that same study they reported that engine manufacturers use 10W-30 grade oil to develop new engine technology, because gear pitting was observed with oils of viscosity grades lower than 10W-30 in all four manufacturers' motorcycle engines.

Motorcycle manufacturers would like the fuel efficiency and increased power delivered by highly friction modified, low viscosity oils, but not at the expense of clutch slippage and gear pitting. Therefore, in a recent motorcycle oil development, the targeted product was a fuel efficient 10W-30 oil meeting API SJ class with the possibility of being upgraded to an API SL class engine oil. Accordingly, the %P was limited to 0.10% maximum for this 10W-30 development. Furthermore, this oil was expected to have fuel efficiency, but without utilizing Mo-based friction modifiers which might cause clutch slippage. During the development of this oil, bench and engine testing was conducted to evaluate frictional performance, oxidative stability, thermal stability, deposit protection, wear protection, and gear pitting. It is the study of gear pitting that will be the focus of this paper.

EXPERIMENTAL

Oils Evaluated

Three of the oils evaluated during the course of this motorcycle oil development are shown in Table 1. These oils were formulated as 10W-30 fluids using Group II base stocks. Each contains an SJ class additive package. Therefore, by definition, each contains less than 0.1 % P. For the base oil mix, Oil A contains all 150N oil, whereas, Oil B contains 75 % 150N oil and 25 % 500N oil. Oil B was formulated at the high end of the specification on viscosity. Both Oil A and Oil B contain 6 % of a typical passenger car motor oil (PCMO) viscosity modifier. Oil C contains a 95:5 mix of 150N and 500N. However, the main difference between Oil C and the other two test oils is the viscosity modifier. Oil C contains an extremely shear stable viscosity modifier.

Table 1: Oil formulations

Oil Formulation	A	B	C
Viscosity Grade	10W-30	10W-30	10W-30
Group II 150N	100	75	95
Group II 500N		25	5
Typical PCMO Viscosity Modifier	6	6	
Shear Stable Viscosity Modifier			6
Pour Point Depressant	0.3	0.3	0.3
SJ Class Additive Package	>10%	>10%	>10%
Viscosity @ 40℃, cSt	66.5	83.7	71.6
Viscosity @ 100℃, cSt	10.7	12.2	11.2
Viscosity Index	150	141	148

Engine Test Evaluation

To evaluate the effects of engine oil on the durability of a wet-clutch type motorcycle engine, a test was designed to stress the oil and engine hardware to a degree far in excess of normal everyday driving. An engine dynamometer system was employed that simulates heavy load on the engine, similar to what would be experienced by full-throttle driving at very high speed.

The test engine chosen was a modern technology four cylinder, liquid cooled engine found in a popular sport bike type motorcycle. The engine is 600cc, has 4-valves per cylinder, and is carbureted. Engine power is transmitted through a multi-plate wet-clutch system to a 6-speed transmission. The main specifications are shown in Table 2.

Table 2: Engine specifications

Engine Type	4 Stroke Inline 4 Cylinder
Engine Displacement	65 x 45.2 mm (600 cm^3)
Compression Ratio	12:1
Valve Train	DOHC 16 Valve
Cooling System	Liquid Cooled
Lubricating System	Forced Pressure, Wet Sump
Fuel System	Carburetor, Constant Velocity
Ignition System	Full Transistorized Ignition
Drive Train	Multi-plate, Wet
Transmission	6 Speed
Primary Reduction	1.863:1
Gear Ratio 5th	1.2:1
Gear Ratio 6th	1.086:1

Lubrication is achieved by a pressured oiling system that supplies oil from the crankcase sump to the cylinder head, crankshaft, and transmission areas.

Before a test is started, all critical, wear-related engine hardware such as piston, cylinders, cam lobes, and transmission gears are measured to allow comparison at the completion of the test for wear assessment.

The test engine is then assembled and installed in a test cell that includes a completely automated data acquisition and control system that controls throttle, oil temperature, coolant temperature, and engine speed. The test engine can be seen in Figure 1.

Additionally, fuel consumption, exhaust CO level, exhaust temperatures, humidity, spark plug temperature, and air temperature are recorded.

To minimize the possibility of cross-contamination of oil from engine build to test sample, a series of flushes are performed whereby several oil changes using the test oil are flushed through the engine. After a 3-hour break-in period, the cylinder head valve lash, cylinder compression, and crankcase blowby are measured. The oil is changed one last time and the engine is fitted with a new oil filter.

The durability test consists of 200 hours of engine operation at full throttle. The engine speed is 9600 rpm. The oil temperature is 125^{o}C and the cooling water temperature is 100^{o}C. It should be pointed out that 200 hours of engine operation at full throttle represents about 23,000 miles of driving without an oil change The first portion of the test is run in top gear, or 6th, while the last 20 hours are run in 5th gear. Throughout the course of the test, the engine is periodically inspected to verify valve clearance and to monitor oil consumption. The variations in valve clearance as well as oil addition amounts are recorded. Should there be signs of gear wear as evidenced by significant gear whine, inspections of the transmission gears can be accomplished by removing the engine oil pan. In severe cases, the test would be terminated based on the condition of the gears.

At the completion of the test, the engine is removed from the test stand and carefully disassembled. Critical parts are then inspected, rated, and measured. The wear of the transmission gears is quantified by estimating the area (square millimeters) of pitting on each gear tooth and then summing those values for each gear. Both 5th and 6th gears are rated, on both mainshaft (drive) and countershaft (driven) sides.

RESULTS AND DISCUSSION

The first test run in this engine, with oil A from Table 1, had to be terminated after 100 hours due to severe gear whine. Inspection of the gears showed the severe gear wear. The wear seen in Figures 2 and 3 represent the average gear wear from the evaluation of Oil A .

This test run for 100 hours was equivalent to 11,500 miles of driving at full throttle without changing oil. This test is designed as a severe durability test and this result was deemed unacceptable. Another oil formulation had to be considered. From a chemical perspective, additional gear protection may be obtained from conventional

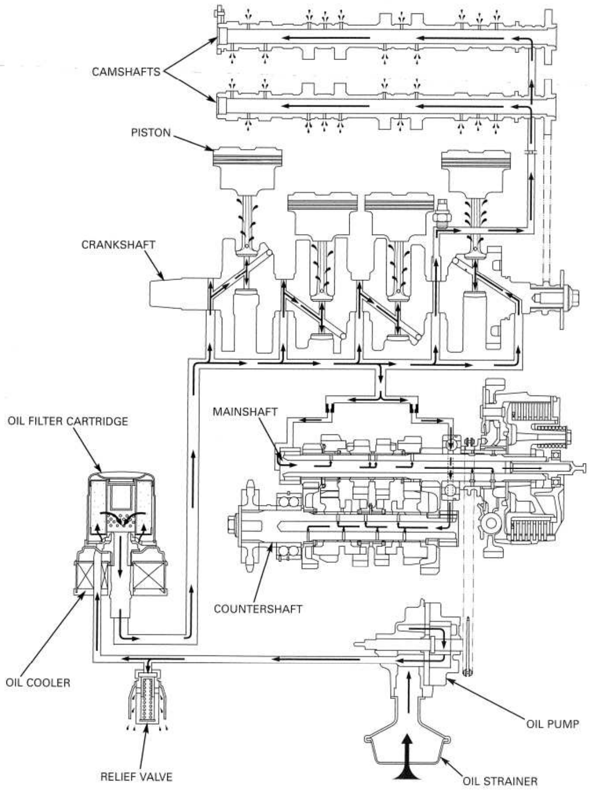
Zinc Dithiophosphate (ZDP) but this option was not available due to the %P limitation of API SJ. The second approach was based on increasing the base oil film thickness by formulating to a higher viscosity oil within the 10W-30 viscosity grade.

The second test run in this engine, with Oil B from Table 1, ran slightly longer but again had to be terminated, this time after 120 hours due to severe gear whine. Again inspection of the gears showed excessive wear as seen in Figures 4 and 5.

This test run for 120 hours was equivalent to 13,800 miles of driving at full throttle without changing oil. While the test duration was longer, this was still unacceptable because the test oil was not able to complete the test.

This engine operates under very high load, severe conditions in order to simulate high speed full throttle high speed driving. From study of the lubrication system diagram for this engine shown in Figure 6, it is apparent that there are several locations within the engine that subject the engine oil to very high shear conditions as well.

Figure 6: Lubrication system diagram (2)



As engine oil passes through these high shear areas, it may undergo permanent shear thinning, effectively reducing the oil film thickness. In an engine operating under severe load, the resulting oil film thickness may not be sufficient to provide gear wear protection. In order to evaluate this theory, Oil C shown in Table 1 was formulated and evaluated in this test. This oil contains a low molecular weight, very shear stable viscosity modifier, not typically used in passenger car oils. If the viscosity modifier does not shear thin during the test, the oil film strength will be maintained, and the gears may be protected from wear and pitting to allow the test to complete. When this oil was tested, the test did indeed run to completion, a full 200 hours or the equivalent of 23,000 miles, under very severe conditions without changing the oil. The gears, as well as the remainder of the engine, were evaluated and found to be satisfactory. The gears from this test are shown in Figures 7 and 8.

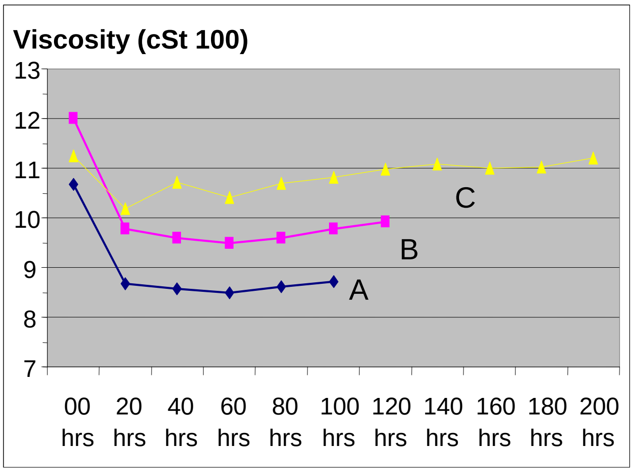
The results of these three tests are summarized on Table 3. In this table, the amount of surface area affected by gear pitting is summarized for each of the candidates.

Table 3: Summary of engine test results

	Oil A	**Oil B**	**Oil C**
Total test hours	100	120	200
Total test miles	11,500	13,800	23,000
Main shaft pitting (sq mm)	103	172	129
Counter-shaft pitting (sq mm)	44	113	86
Total gear pitting (sq mm)	147	285	215

The used oils from each test were evaluated in order to determine if the shear stability theory was valid. The used oil data is shown graphically in Figure 9.

Figure 9: Used oil analysis from the engine tests



It is clear that Oil C sheared the least and maintained the oil film thickness needed to allow this test to run to completion without encountering the gear pitting issues seen earlier by candidates A and B. After the initial shear thinning, the slight increase in viscosity of all candidate oils can be attributed to oxidative thickening.

This data has been previously reported (3). A surface analysis study of the gears by X-Ray Photoelectron Spectroscopy (XPS), recently conducted at Case Western Reserve University using a PHI 5600 spectrometer, provides additional data supporting this theory.

Table 4: Depth of the anti-wear film by XPS

	Oil A	**Oil B**	**Oil C**
	Depth of anti-wear film (Å)		
Zn	800	900	200
S	800	800	400
P	1200	1200	500

The tribochemical film thickness is 800Å -1200Å for formulations A and B. Formulation C, which contained a shear stable VM, formed a 200Å -500Å reaction layer of anti-wear film. The differences in reaction layer thickness appear to be related to the performance of the VM. The minimized shearing of Oil C results in maintaining the fluid film (elastohydrodynamic) thickness to support the applied load thereby reducing multiple asperity contacts. Ultimately, this leads to lower temperatures in the contact zone and hence less reactivity of the additives with the gear surface. Conversely, the shearing of the viscosity modifier in Oils A and B leads to thinner fluid films, and more surface asperity contact, raising the temperature in the contact zone, and ultimately more reactivity of the additives with the gear surface. The result is a thicker tribochemical film formation.

SUMMARY

While there is a constant push to develop more fuel efficient oils for passenger car applications, these same oils become less suitable for motorcycle applications. It is known that highly friction modified oils developed to enhance fuel economy in passenger car engines can cause clutch slippage. It is also known that oils of viscosity grades lower than 10W-30 can cause gear pitting issues when used in motorcycles. This paper demonstrates that even 10W-30 oils developed for passenger car applications may cause gear pitting issues when motorcycles are run under heavy load severe service conditions. Today's 10W-30 engine oils formulated for passenger car applications are typically formulated with non-shear stable viscosity modifiers. In motorcycle engines, however, shear thinning of the viscosity modifier combined with low viscosity and low phosphorus oils may lead to gear pitting issues under severe service conditions as demonstrated in this paper.

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621.434-144.4	4-taktni motor motorkotač	4-stroke motorcycle engine
621.892.097.2	motorno ulje	engine oil
629.118.6	motorkotač	motorcycle
620.191.36	pitting	pitting
62-585.12	zupčanički prijenosnik mjenjača	speed change gear

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