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Izračun kontaktnih temperatur v fretinških razmerah

Calculating the Contact Temperature for Lubricated and Dry Fretting Conditions

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Obrabne in torne lastnosti površin v kontaktu so znatno odvisne od kontaktnih temperatur, zato je njihova določitev velikega pomena v vsaki tribološki uporabi. Številni modeli, ki so na voljo v literaturi, uporabljajo precej različne fizikalne, dinamične in geometrijske predpostavke. Posledica tega so velika razhajanja rezultatov za isti računski primer.

Čeprav so ta dejstva splošno znana, so velikokrat pri izračunih spregledana. V predstavljenem prispevku smo analizirali vpliv lastnosti kontaktnih površin med jeklom in silicijevim nitridom v razmerah mejnega mazanja z oljem in nemazanih kontaktov. Predstavljeni so vplivi spremembe termičnih lastnosti, koeficienta trenja in realne kontaktne površine na izračun kontaktnih temperatur. Za analizo smo uporabili deset različnih teoretičnih modelov. Rezultati kažejo velike razlike med posameznimi modeli in še posebej izjemen vpliv lastnosti kontaktnih površin na izračunane temperature.

(Ključne besede: temperature, modeli, izračuni, freting)

The wear and friction properties of tribological interfaces are closely linked to the contact temperature and so a knowledge of this temperature is of great interest for tribological applications. The many different temperature-calculation methods that are available in the literature are based on quite different physical, dynamic and geometric assumptions. As a consequence, large discrepancies in the results can be obtained for the same contact conditions.

Although this is a well-known fact, it is sometimes overlooked. In this paper the effects at a tribological interface between silicon nitride and steel under unlubricated and boundary-lubricated fretting conditions were studied. The effects of a change in the contact's thermal properties, as well as its coefficient of friction and the real contact area on the calculated flash temperature are presented. Ten different ready-to-use theoretical models were selected for the purposes of this investigation. The results show a significant difference between the various models, and in particular, the critical importance of the tribological interface properties on the calculated temperatures.

(Keywords: temperatures, models, calculations, fretting)

0 UVOD

Zaradi premene dela trenja v toploto se pri drsenju na kontaktnih površinah teles temperatura poveča, še posebej pa na dejanski površini, tj. na kontaktih med vršički [1]. Te temperature lahko odločilno vplivajo na obrabne in torne lastnosti tribološkega sistema zaradi sprememb mehanskih, kemijskih in termičnih lastnosti površin.

Za inženirsko prakso je bistvenega pomena čim preprostejša računska metoda, zato so bili razviti številni uporabniško usmerjeni modeli za izračun kontaktnih temperatur. Vendar pa večina

0 INTRODUCTION

The transformation of frictional energy into heat is the cause for the increase in the temperature of sliding bodies in contact, especially at the spot-to-spot contacts, i.e. the real contact area [1]. These temperatures can have a critical influence on the friction and wear characteristics of the contacting surfaces because of the changes in mechanical, chemical and thermal properties of the surfaces.

For engineering/tribological practice an as-simple-as-possible calculating procedure is desired, which has resulted in the development of several readyteh modelov uporablja precej različne fizikalne, dinamične in geometrijske predpostavke o izbranem sistemu. Poleg tega tudi številne površinske lastnosti, ki so v splošnem neznane, bistveno vplivajo na nastalo toploto v tribološkem kontaktu. Na primer, mehanske in toplotne lastnosti materialov se v kontaktih neprestano spreminjajo, še posebej če pride do tribokemijsko povzročenih faznih premen. To nadalje vpliva tudi na porazdelitev torne toplote zaradi različnih lastnosti osnovnega materiala in površine. Številne težave se pojavljajo pri izračunu velikosti in oblike dejanske kontaktne površine ter geometrijskih in termičnih lastnosti obrabnih ali drugih delcev v kontaktu. Spremembe koeficienta trenja, ki neposredno vplivajo na izračun temperatur, ter porazdelitev koeficienta trenja na kontaktni površini sta tudi izjemno pomembna dejavnika pri končnem rezultatu. Vse te neznanke vplivajo na temperature in nasprotno, poleg tega pa vplivajo tudi ena na drugo v številnih povratnih zvezah.

Posledica tega je, da lahko pride do znatnih razlik rezultatov za isti kontaktni problem. V nekaterih pregledanih literaturnih virih ([2] do [5]) je že bilo ugotovljeno, da so izračuni kontaktnih temperatur zaradi torne toplote precej pomanjkljivi in značilno nedodelani, saj se kontaktne razmere spreminjajo s časom in položajem v kontaktu. Čeprav so te ugotovitve znana in sprejeta dejstva, so velikokrat pri obravnavi in komentarju rezultatov spregledane.

Uporabniško usmerjeni modeli so zelo koristno orodje in omogočajo vsaj približno oceno kontaktnih temperatur. Ko pa te modele uporabljamo za ugotavljanje kontaktnih razmer in različnih pojavov, npr. faznih premen, se je treba zavedati številnih omejitev in jih upoštevati pri razlagi rezultatov. Naši rezultati, predstavljeni v tem prispevku in drugje ([6] do [11]), ki se ujamajo tudi z rezultati veliko bolj natančnih modelov [12] ter bolj zapletenih interdisciplinarnih študij [13], kažejo, da so temperature, dobljene z uporabniško usmerjenimi modeli običajno prenizke ter da lahko kontakti na vršičkih, najverjetneje zaradi slabo definiranih razmer na kontaktih med vršički, dosegajo znatno višje temperature.

1 MODELI IN PARAMETRI

Deset modelov, ki smo jih izbrali za izračun dviga kontaktnih temperatur zaradi nastajanja torne toplote, so Archardov model povprečne trenutne temperature z upoštevanjem deformacijskega kriterija in brez njega [14], Archardov model največje trenutne temperature [13], Holmov model povprečne in največje trenutne temperature [5], Tian-Kennedyjev model povprečne in največje trenutne temperature [15], Greenwood-Greinerjev model povprečne trenutne temperature [16] in Ashby-Abulawi-Kongov model

to-use models. However, most of these methods use quite different physical, dynamic and geometric assumptions. Furthermore, a number of interface properties affect the generation of frictional heat in tribocontacts and these are usually unknown—at least in all their details—due to the difficulties in determining them exactly. For example, the mechanical and thermal properties of materials are gradually changing, especially when the interface is tribochemically transformed. This also affects the distribution of frictional heat because of the mismatch in the properties of the surface and the bulk material. Furthermore, extreme difficulties arise in determining the size and shape of the real contact area (spot-to-spot contacts) and the geometric and thermal properties of the wear particles or any other third body within the contact. A change in the coefficient of friction, which enters the temperature calculation to the first power, and its distribution over the contact area is another very important parameter for the final result. All these unknowns affect the temperature and vice-versa, and also influence each other via a number of feedback loops.

As a consequence, a large discrepancy in the results can be obtained for the same contact situation. It has already been shown in many reviews ([2] to [5]) that the frictional heat calculations are quite imperfect because they are typically not well defined and the contact conditions vary greatly in time and place. Although these are broadly accepted and known facts, they are very often overlooked.

Ready-to-use models are a very useful engineering tool and give at least an idea of the possible contact temperatures. However, when these models are used to define certain contact conditions or various phenomena, for example phase transformations, severe limitations must be considered and care in the interpretation of the results must be taken. Our results presented here and elsewhere ([6] to [11]), which are consistent with the more-sophisticated computational models [12] and extensive interdisciplinary studies [13], show that the temperatures obtained by these models are usually underestimated and that some asperity contacts can sustain much higher temperatures than predicted, most probably because of the poorly defined spot-to-spot conditions.

1 MODELS AND PARAMETERS

Ten theoretical models were selected for the calculation of the temperature rise due to frictional heat in the fretting contacts. These are Archard's average-flash-temperature model with and without encountering the deformation critera [14], Archard's maximum-flash-temperature model [13], Holm's average- and maximum-flash-temperature models [5], Tian-Kennedy's average- and maximum-flash-temperature models [15], Greenwood-Greiner's average-flash-temperature model [16] and Ashby-

Preglednica 1. *Prednastavljeni in izmerjeni parametri iz fretinških preskusov*
Table 1. *Preset and measured parameters from fretting wear experiments*

	Pogoji preskusa Test condition					
	D5	D25	D50	L5	L25	L50
okolje environment	nemazano unlubricated	nemazano unlubricated	nemazano unlubricated	mazano lubricated	mazano lubricated	mazano lubricated
amplituda pomika displacement amplitude μm	5	25	50	5	25	50
frekvenca nihanja frequency of oscillation Hz	210	210	210	210	210	210
največja hitrost maximum stroke velocity m/s	0,0067	0,0336	0,0672	0,0067	0,0336	0,0672
pravokotna sila normal force N	88	88	88	88	88	88
koeficient trenja coefficient of friction	0,68	1,18	1,2	0,58	0,85	0,7
polmer kontaktne površine radius of contact area mm	0,175	0,375	0,475	0,140	0,225	0,165

telesne in trenutne temperature [17]. Večina podatkov v tem prispevku je predstavljena kot srednja vrednost izbranih modelov. Skrajšan povzetek osnovnih značilnosti modelov je predsatvljen v literaturi [6].

Vsi parametri, ki smo jih dobili na temelju fretinških testov ([6] in [10]) in smo jih lahko uporabili pri izračunih, so predstavljeni v preglednici 1. Nekatere od teh vrednosti so prednastavljene na samem preskuševališču, nekatere pa so določene s preskusi. Ker nas je zanimal predvsem največji mogoči dvig temperature, smo v izračunih uporabili podatke, izmerjene v trenutku največje vrednosti koeficienta trenja v danih razmerah. Navidezno, nominalno kontaktno površino v določenem trenutku smo določili tako, da smo preskus v danem trenutku zaustavili ter izmerili premer obrabne kotanje in iz nje določili kontaktno površino. Vsak nov preskus je bil izveden na »sveži« in nepoškodovani kontaktni površini.

Nekatere od parametrov, npr. dejanske kontaktne površine, vrednosti materialnih konstant, ki se spreminjajo s temperaturo, koeficient trenja v vsaki točki kontaktne površine ipd., potrebne za izračun temperatur, je zelo težko natančno določiti, tako da njihovih vrednosti ne moremo natančno poznati in jih moramo predpostaviti. Zaradi tega smo v izračunih uporabili splošnejši način, s tem da smo parametre spreminjali v določenem predpostavljenem področju vrednosti. V tem prispevku smo izbrali dva parametra in ju spreminjali, kakor prikazuje preglednica 2. Lastnosti materialov, ki smo jih vzeli iz literaturnih virov [6] in [10] in smo jih uporabili pri izračunu, so podani v preglednici 3.

Abulawi-Kong's bulk- and flash-temperature models [17]. However, for the purposes of this study almost all the data in this paper are presented as the average value of the selected models. A short summary for the models used is presented in literature [6].

All the parameters which could be taken from the fretting experiments ([6] and [10]) and were used in the calculations are presented in Table 1. Some of these are preset as machine-controlled parameters, but some are experimentally obtained values. Since the maximum possible temperature rise was of special interest, the highest coefficient of friction measured in the experiments under certain fretting conditions was selected for the calculations. Nominal contact area at that specific time was determined by stoping the experiment and measuring the wear scar's diameter. Each new experiment was performed with new undamaged contacting surfaces.

Some of the parameters, for instance the real contact area, the material constants as a function of temperature, the coefficient of friction distribution over the contact, etc., needed for the calculations are very difficult to be determined exactly and thus it is difficult to be certain of their true values. Accordingly, Table 2 presents two parameters that were selected for variation in this study. The material properties of the silicon-nitride ceramics and the steel were taken from Refs. [6] and [10], and are presented in Table 3.

Preglednica 2. *Spreminjanje vplivnih parametrov*
Table 2. *Variation of the influencing parameters*

Koeficient trenja Coefficient of friction			0,5	→	1,6	
		20 °C	200 °C	400 °C	600 °C	800 °C
toplotna prevodnost thermal conductivity W/mK	Si_3N_4	30,7	27	23	20	18
	100Cr6	58	52	42	36	33

Preglednica 3. *Podatki o materialih, uporabljenih v izračunih*
Table 3. *Material data used for calculations*

	Gostota Density kg/m^3	Specifična toplota Specific heat J/kgK	Toplotna difuzivnost Thermal diffusivity m^2/s (x10^{-5})	Trdota Hardness HV	Modul elastičnosti Young's modulus GPa
Si_3N_4	3200	710	1,350	1700	3,1
DIN 100Cr6	7865	460	1,665	850	2,1

2 REZULTATI IN OBRAVNAVA

2.1 Vpliv nominalne kontaktne površine in obrabne odpornosti

Večina triboloških testov se izvaja z uporabo kontaktne geometrije kroglice na ravni ploskvi. Zaradi nastajajoče obrabe se, tako kakor drugi parametri, tudi nominalna kontaktna površina neprestano spreminja med preskusom. Pri tem se pojavi vprašanje, katere pogoje, še posebej pa katero nominalno kontaktno površino, naj se pri izračunu upošteva. Če vzamemo nominalno površino na podlagi geometrijskih podatkov teles, bo ta velikost veljala le kratek čas, dokler se ne pojavi obraba. Kasneje postanejo vrednosti povsem netočne. Drug postopek pa je ta, da upoštevamo vrednosti nominalne kontaktne površine, koeficienta trenja, drsne hitrosti idr. v nekem točno določenem času, v katerem so bile te vrednosti izmerjene. Ta način je bil uporabljen v naših izračunih.

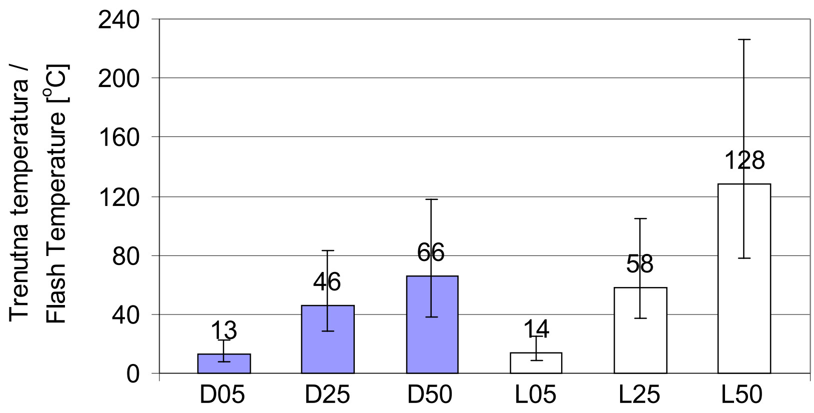
Slika 1 prikazuje povprečno vrednost trenutne temperature na področju celotne kontaktne površine z uporabo osmih modelov in upoštevanjem parametrov iz preglednic 1 in 3. To pomeni, da spreminjanje vplivnih parametrov ni bilo uporabljeno. Archardov model z uporabo deformacijskega kriterija [14], ter Ashbyjev model trenutne temperature [17], nista bila upoštevana v teh izračunih, ker uporabljata drugačno metodologijo za določitev kontaktne površine in tako v tem primeru nista primerljiva s preostalimi modeli. Trenutne temperature v nemazanih razmerah (označene z D) so se gibale med 13°C in 66°C pri najmanjši in največji amplitudi pomika. Vidi se, da se temperature z večanjem amplitude zvišujejo, kar kaže na vpliv povečanja hitrosti. Ker so izračunane temperature razmeroma nizke, tudi ni pomembnejše

2 RESULTS AND DISCUSSION

2.1 Nominal contact area and wear-resistance effect

Most tribological experiments are performed using ball-on-flat testing geometry. It is clear that due to wear, the nominal contact area is changing in such experiments—as do the other conditions. This therefore beggs the question, what are the conditions, especially in the nominal contact area, that should be used in the calculations? If we take the nominal area from the geometric data of our contacting bodies, this will be true only for an extremely limited time, where no wear occurs in the contact. After that, the results of the calculations will become unrealistic. Another possible approach is to calculate the temperature by using the measured nominal contact area, the normal force, the coefficient of friction, the sliding speed, etc., for the specific testing time at which these data were determined. This was the method used for determining the input parameters for our calculations.

Figure 1 shows the average value of the flash temperature over the measured contact area according to eight selected models, using parameters from Table 1 and 3, which means that no variation of influencing factors was employed. Archard's model using deformation criteria [14] and Ashby's flash-temperature model [17] are not included in these results because they use a different method to calculate the contact area. The flash temperatures in unlubricated conditions (denoted as D) ranged between 13°C and 66°C for the lowest and highest displacement amplitude, respectively. It can be seen that the temperature increases with increasing amplitude, which indicates the influence of the increasing sliding speed. Since the temperatures were relatively low, no significant difference between average and maxi-



Sl. 1. *Povprečna trenutna temperatura preko celotne nominalne kontaktne površine v nemazanih in mazanih torno obrabnih razmerah.*
(Znaki raztrosa pomenijo zgornjo in spodnjo izračunano vrednost z različnimi modeli)
Fig. 1. *Average flash temperatures over nominal contact area in unlubricated and lubricated fretting.*
(Scatter bars represent the upper and lower calculated values from different models)

razlike med povprečno in največjo trenutno temperaturo, ki je dosegala le malo do nekaj deset stopinj.

Čeprav se v nekaterih modelih zahtevajo nemazane razmere drsenja, smo za primerjavo izračunali tudi temperature v mazanih fretinških testih (označeni z L na sliki 1). Mazanje je bilo izvedeno na način, da smo pred preskusom kapnili na (kasnejše) mesto kontakta malo olja, po stiku med kroglico in ploščico pa v ta kontakt nismo več dovajali svežega olja. Ker se pri fretinški obrabi zaradi majhnih pomikov kontaktna površina ne odkriva, ostane olje v kontaktu ves čas preskusa. Poudariti je treba, da se naši pogoji mazanja z "oljno kapljo pred testom" povsem razlikujejo od pogojev mazanja z neprekinjenim filmom maziva, za katere veljajo omejitve v enačbah za izračun temperatur. Še več, jasno določena tribokemijska plast in drugi kontaktni parametri, ki so bili dobljeni s številnimi analizami površin, kažejo na kombinacijo mejnega in mešanega mazanja s številnimi "suhimi" kontakti [6]. Torej ne obstajajo razlogi, zaradi katerih bi utemeljeno razlikovali med nastalo tribokemijsko plastjo v naših testih in katerokoli drugo tribokemijsko plastjo v nemazanih razmerah, saj v obeh primerih lastnosti novonastale kontaktne površine niso znane in so drugačne od idealno predpostavljenih v modelu.

Ena izmed pomembnih ugotovitev na temelju teh rezultatov je, da so trenutne temperature, izračunane za mazane razmere, višje kakor pri nemazanih (sl. 1), čeprav so koeficienti trenja pri danih razmerah celo znatno nižji, preglednica 1. Razlog za take rezultate je v manjši nominalni kontaktni površini, izmerjeni v naših preskusih pri mazanih pogojih. To pomeni, da se pridobljena toplota odvaja v telo prek manjše površine, kar posledično pomeni višjo kontaktno

mum flash temperatures was obtained; they varied by a few, or a few tens, of degrees Centigrade.

Although some models demand unlubricated contact conditions, for comparison reasons calculations were also performed using parameters from lubricated contacts (denoted as L in Figure 1). Lubrication took the form of a single drop of oil at the contact position before the start of the experiment: no additional oil was supplied to the contact. Since the contact in fretting remains closed during the experiment, the oil also remained within the contact throughout the test. It must be pointed out here that our "pre-test oil-drop" lubricating conditions were far away from providing a continuously lubricating oil film. Instead, a well-defined tribolayer was formed in the contact and a combination of mixed and boundary lubrication was obtained with many "dry" contacts [6]. Therefore, it is not reasonable to differentiate between our tribochemical layer and any other tribochemical layer obtained under unlubricated conditions because in both cases the interface has unknown and different properties than the ideal conditions assumed in the models.

One of the very important findings from these results is that the flash temperatures calculated for the same displacement amplitude are higher in the lubricated than in the unlubricated conditions (Figure 1), although the coefficients of friction were significantly lower, see Table 1. The reason for such results is in the smaller measured contact area in the lubricated than in the unlubricated conditions obtained in our fretting experiments. This means that the smaller contact through which the heat is conducted under these conditions resulted in a higher contact temperature. This effect was more pronounced than the effect of a higher coefficient of friction during the unlubricated conditions, in contrast to what we would normally expect. This indicates that the wear resistance of the tribological system, which is a consequence of various parameters—

temperaturo. V našem primeru je imel ta pojav večji vpliv na izračunano temperaturo, kakor npr. že omenjeni koeficient trenja, na podlagi katerega bi pričakovali prav nasprotni učinek, pri sicer enakih drugih sistemskih delovnih parametrih. To kaže, da obrabna odpornost tribološkega sistema, ki določa velikost nominalne kontaktne površine in je posledica številnih parametrov, od katerih nekateri sploh ne vplivajo na temperaturo, odločilno vpliva na izračunano temperaturo - preprosto glede na velikost obrabne kotanje.

Iz širine raztrosa rezultatov na sliki 1 lahko ugotovimo, da se rezultati, dobljeni na podlagi različnih modelov, pomembno razlikujejo, približno za trikrat.

2.2 Vpliv dejanske kontaktne površine

Čeprav je splošno znano, da se normalna sila v kontaktu prenaša le prek manjšega dela nominalne površine, se pravi prek kontaktov nekaterih vršičkov, se nominalna površina pogosto uporablja za določitev kontaktnih temperatur. Nekateri modeli vključujejo popravke z uporabo deformacijskega kriterija, npr. Archardov model [14] in Ashbyjev model trenutne temperature [17]. Vendar pa obstaja kar nekaj načinov/modelov za določitev dejanske kontaktne površine in razlike med njimi so precejšnje, predvsem zaradi številnih novih predpostavk, ki imajo neposreden in velik vpliv na končni rezultat.

V našem prispevku smo uporabili splošno priznan kriterij trdote materiala za določitev dejanske kontaktne površine, po katerem je le-ta enaka kvocientu normalne sile s trdoto mehkejšega materiala. Razmerja med tako izračunanimi in izmerjenimi nominalnimi površinami pri danih nemazanih razmerah so bila 1,5%, 2,4% in 10,9% pri amplitudah pomika 50 μm, 25 μm in 5 μm. Te vrednosti za dejanske kontaktne površine smo nato uporabili pri izračunu kontaktnih temperatur v modelih, ki omogočajo neposredni vnos velikosti kontaktne površine v enačbe. Modeli največje trenutne kontaktne temperature niso bili zajeti v tem izračunu, ker niso neposredno primerljivi s pogosto uporabljenima modeloma, ki določata dejansko kontaktno površino na drugačen, lasten način ([14] in [17]).

Slika 2 prikazuje rezultate, izračunane z uporabo modelov srednje trenutne temperature. Razvidno je, da se temperatura znatno spreminja glede na uporabljeno amplitudo pomika in znaša 45 °C, 384 °C in 768 °C pri amplitudah pomika 5 μm, 25 μm in 50 μm. Razlog za take rezultate je delno v povečani relativni drsni hitrosti, delno pa zaradi manjšanja dejanske kontaktne površine z večanjem amplitude. Največje absolutne razlike v izračunanih temperaturah med posameznimi modeli, prikazane z znakom raztrosa na sliki 2, so 577 °C, 294 °C in 37 °C pri amplitudah

many of them which have no impact on the temperature—significantly affects the calculated temperature simply as a result of the extent of the wear scar. Furthermore, since no “equation” can distinguish between the different real contact conditions the theoretical calculations with so few influencing interface parameters (mostly mechanical, i.e. speed, coefficient of friction, contact area) cannot give reliable results because the various surface and chemical effects cannot be presupposed. This is especially true when the maximum contact-temperature rise is of interest and the contact interface is tribochemically transformed.

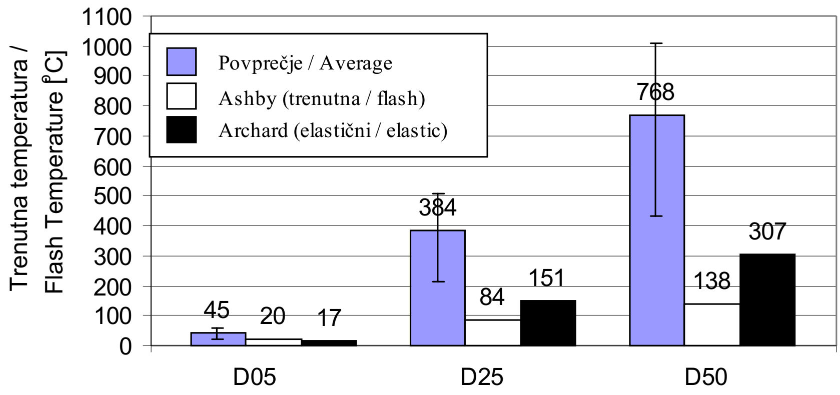
From the scatter marks in Figure 1 we can see that the results according to different models vary significantly: by about a factor of three.

2.2 Effect of the real contact area

Although the nominal contact area is often used for determining the contact-temperature rise due to friction, it is well known that the applied load is carried only over a small part of the contact, i.e. over a few asperity contacts. Some of the models include corrections to take into account the real contact area by employing a level of deformation; for example the frequently-used Archard’s model [14] or Ashby’s flash-temperature model [17]. However, there are several different ways to determine the real contact area and the values can vary quite significantly, mainly due to a lot of necessary assumptions that have a large and direct influence on the result.

In our paper we have used broadly accepted criteria for the real-contact-area determination, i.e. by dividing the normal force by the hardness of the softer material. The ratia between the real and (measured) nominal contact areas for unlubricated conditions were calculated to be 1.5 %, 2.4 % and 10.9 % at 50-μm, 25-μm and 5-μm displacement amplitudes, respectively. These values were then used to calculate the average flash temperature according to models that allow the direct input of the contact area into the equations. The maximum-flash-temperature models were not included in the final calculations because they cannot be directly compared to models that determine the real contact area with their own technique, like Archard’s [14] or Ashby’s flash-temperature models [17].

Figure 2 shows the results obtained from the average-flash-temperature models. It can be seen that the temperatures vary significantly for the different displacement amplitudes used, i.e. 45 °C, 384 °C and 768 °C at 5-μm, 25-μm and 50-μm displacement amplitudes, respectively. This is partially the effect of the increased relative velocity, and partially due to decreasing of the real contact area with increasing amplitude. The maximum absolute differences in temperature calculated by various models were 577 °C, 294 °C and 37 °C at 50-μm, 25-μm and 5-μm displacement amplitudes, respectively.



Sl. 2. *Povprečna trenutna temperatura v nemazanih razmerah z uporabo modelov, ki na tri različne načine določajo velikost dejanske kontaktne površine. (Znaki raztrosa pomenijo zgornjo in spodnjo izračunano vrednost z različnimi modeli)*

Fig. 2. *Average flash temperatures under unlubricated conditions using models with three different ways of determining the real contact area. (Scatter bars represent the upper and lower calculated values with different models)*

pomika 50 µm, 25 µm in 5 µm. To pomeni razlike med posameznimi modeli za približno faktor 2,5. Primerjava z Ashbyjevim in Archardovim modelom trenutnih temperatur, ki določita vsak na svoj, drugačen način kakor pri drugih modelih tudi dejansko kontaktno površino, pokaže, da se zaradi znatno večjih površin temperatura zvišuje znatno manj (sl. 2). Vrednosti dejanskih kontaktnih površin pri teh dveh modelih so 4 do 5-krat višje kakor pri preostalih in znašajo 6,2%, 9,8% in 27,5% pri Ashbyjevem modelu ter 8%, 12,2% in 56,1% pri Archardovem modelu pri amplitudah pomika 50 µm, 25 µm in 5 µm. Prav to je morda tudi razlog, zakaj so temperature pri fretinški obrabi, dobljene s tema dvema modeloma, običajno nižje kakor kažejo velikokrat dobljene fazne premene materialov ([6], [10], [11], [13], [18] do [20]). Vendar pa, podobno kakor pri raztrosu rezultatov med posameznimi modeli povprečne trenutne temperature, se temperature, izračunane po Ashbyjevem in Archardovem modelu tudi razhajajo približno za 2,5 krat.

This equals a variation of about a factor of 2.5. A comparison with Ashby's (flash) and Archard's (elastic contact) flash-temperature models, which calculate the real contact in a different (their own) manner than all the other models in this work shows that due to the considerably higher contact areas, the temperatures are much lower, Figure 2. That is to say, the values of the real contact areas in these two models are 4-to-5 times higher than in others. They are 6.2 %, 9.8 % and 27.5 % in Ashby's model and 8 %, 12.2 % and 56.1 % in Archard's model at 50-µm, 25-µm and 5-µm displacement amplitudes, respectively. This could explain why in fretting the temperatures obtained with these two models are commonly lower than the many-times-observed phase transformations suggest ([6], [10], [11], [13], [18] to [20]). However, in a similar way to the scatter in the average value of the various models used in this study, at higher amplitudes the difference in the flash temperature calculated according to Archard's and Ashby's models is also of about a factor of 2.5.

2.3 Vpliv lastnosti materialov

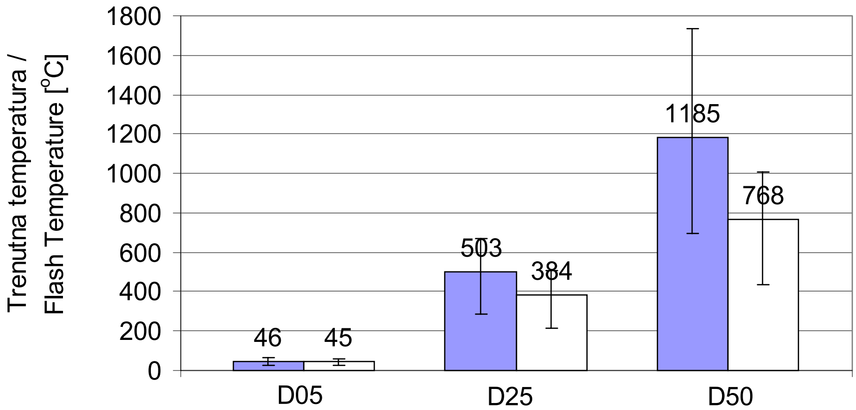
Znano je, da se večina materialnih lastnosti, npr. mehanske, kemijske, električne, pa tudi toplotne, spreminjajo v odvisnosti od temperature. Nekatere med temi pomembno, npr. toplotna prevodnost, za katero je temperaturna odvisnost materialov iz naše raziskave do 800 °C predstavljena v preglednici 2. Torej, z namenom pokazati, kako vplivne so te spremembe, smo v izračunih temperatur izvedli spreminjanje toplotne prevodnosti.

Po rezultatih iz prejšnjega poglavja smo ponovno izračunali trenutne kontaktne temperature, pri čemer smo uporabili vrednost spremenjene toplotne prevodnosti, ustezne za temperaturo, dobljeno v prejšnjem koraku, tj. pri 45 °C, 384 °C in 768 °C pri amplitudah pomika 5 µm, 25 µm and 50 µm.

2.3 Effect of material properties

It is well known that most of the material properties, i.e. mechanical, chemical, electrical, etc., as well as the thermal properties change with the temperature—some of them quite significantly, the thermal conductivity, for example, for which the temperature dependence of the materials used in this research up to 800°C is presented in Table 2. Therefore, for the purposes of showing how important these influencing parameters can be, the variation of the thermal conductivity in the temperature calculation was performed.

Based on the results from the previous section, new average flash temperatures were calculated, using the values of thermal conductivity at the previously calculated temperatures, i.e. 45 °C, 384 °C and



Sl. 3. *Povprečne trenutne temperature v nemazanih razmerah, izračunane s toplotno prevodnostjo v odvisnosti od temperature ter pri 20 °C.*
(Znaki raztrosa pomenijo zgornjo in spodnjo izračunano vrednost z različnimi modeli)
Fig. 3. *Average flash temperatures under unlubricated conditions calculated with thermal conductivity as a function of temperature and at 20°C.*
(Scatter bars represent the upper and lower calculated values with different models)

Slika 3 primerjalno prikazuje rezultate izračunov temperatur, dobljenih z uporabo toplotne prevodnosti materialov pri 20 °C ter z vrednostmi pri že prej izračunanih temperaturah. Vidimo, da z uporabo bolj dejanskih vrednosti za toplotno prevodnost, izračunamo še višje kontaktne temperature. Povprečna vrednost iz modelov srednje trenutne kontaktne temperature znaša 46 °C, 503 °C in 1185 °C pri amplitudah pomika 5 μm, 25 μm in 50 μm. Ustrezno (povprečno) relativno povečanje temperatur je 2%, 32% in 55%. Poudariti je treba, da je pri nekaterih modelih seveda povečanje še znatno večje. V absolutnih vrednostih temperatur to pomeni, da z uporabo modela iz te študije, ki daje najnižjo temperaturo in ne upošteva temperaturne odvisnosti toplotne prevodnosti, ali z uporabo modela, ki daje najvišjo temperaturo in upošteva temperaturno odvisnost toplotne prevodnosti, dobimo pri pogoju D50 razliko za 1300 °C, čeprav so vsi drugi pogoji enaki. To pa kaže na izjemno pomembnost, katere vrednosti materialnih lastnosti upoštevamo v predpostavkah in kako različni so lahko dobljeni rezultati in sklepi o kontaktnih razmerah, samo z uporabo drugačnega modela.

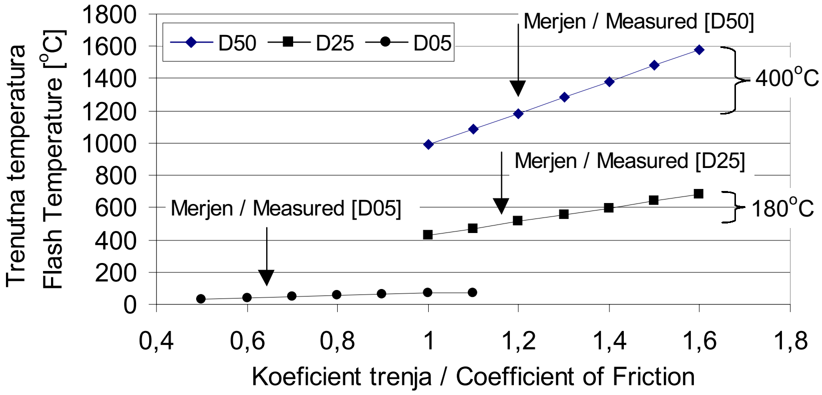
768 °C at 5-μm, 25-μm and 50-μm displacement amplitudes, respectively. Figure 3 shows the results of both sets of calculations, i.e. the temperatures obtained by using the material's thermal conductivity at these previously calculated temperatures, and at 20°C. We can see that the temperatures are even higher when a more realistic value for the thermal conductivity is used. The mean values of the average flash temperatures according to the selected models are 46 °C, 503 °C and 1185 °C for 5-μm, 25-μm and 50-μm displacement amplitudes, respectively. The corresponding relative increases in temperature, which increase with temperature, are 2 %, 32 % and 55 % (average value). However, according to some models the difference is even higher than this. In absolute values this means that when using the models that give the highest and lowest temperatures the difference in temperature at condition D50 is as high as 1300°C for otherwise identical contact parameters. This indicates how important the material properties are and also how different the conclusions can be for the same contact conditions, simply by selecting different models.

2.4 Vpliv koeficienta trenja

Ko se koeficient trenja upošteva pri izračunih, se običajno vzame povprečna vrednost, ki velja za celoten kontakt. Vendar sta v razmerah mešanega ali mejnega mazanja koeficient trenja in s tem nastala toplota in temperatura na nekaterih vršičkih znatno višja od povprečne vrednosti. V skladu s to predpostavko smo trenutne temperature izračunali še z upoštevanjem koeficienta trenja, ki smo ga zgolj za ponazoritev učinka ocenili 30% višje kakor je bil povprečni izmerjeni v preskusih. Rezultati za ta primer so prikazani na sliki 4.

2.4 Effect of the coefficient of friction

When the coefficient of friction is used in the calculations, it is the average value over the whole contact that is usually used. However, in mixed or boundary-lubricated conditions, the coefficient of friction, the heat generated and the temperature in some spot-to-spot contacts can be much higher than the average value. Following this idea, average flash temperatures were calculated based on a speculation regarding the possible coefficients of friction in our experiments. As an example, an up-to-30%-higher coefficient of friction compared to the measured value over the whole contact area is plotted in Figure 4.



Sl. 4. *Povprečne trenutne temperature v odvisnosti od koeficienta trenja na dotikalnih vršičkih*
Fig. 4. *Average flash temperatures as a function of coefficient of the friction at asperity contacts*

Krivulje prikazujejo temperature, dobljene na podlagi srednjih vrednosti s slike 3 (z upoštevanjem temperaturne odvisnosti toplotne prevodnosti), ki so bile najprej normalizirane z izmerjenimi vrednostmi koeficienta trenja (preglednica 1), nato pa preračunane za določeno območje koeficienta trenja. Temperaturna razlika med izmerjenimi povprečnimi vrednostmi koeficienta trenja in preračunanega po tej metodi znašajo pri pogoju D25 približno 180 °C, pri pogoju D50 pa približno 400°C. Pri pogoju D5 so razlike znatno manjše zaradi nižjih temperatur, pa tudi zaradi nižjega koeficienta trenja. Ponovno je treba poudariti, da so razlike pri nekaterih modelih še večje. Nekateri izmed prikazanih rezultatov so seveda nestvarni, saj bi se pri tako visokih temperaturah jeklo lokalno že stalilo, kar torej lahko pomeni tudi zgornjo mejo možnih kontaktnih temperatur. V naših analizah s spektroskopijo z Augerjevimi elektroni in transmisijsko mikroskopijo smo dejansko dobili plast debeline 200 do 300 nm, ki ustreza talini ([6] in [21]). Poleg tega so tudi ločene študije kemijske reaktivnosti med jeklom in keramiko pokazale, da so za nastale reakcije med tribološkim procesom potrebne temperature prek 1000°C ([22] in [23]).

Iz naših rezultatov izhaja, da bi z uporabo modelov, ki dajejo najvišje ali najnižje temperature in/ali z uporabo zelo različnih predpostavk, uporabljenih v teh modelih, dobili razlike v temperaturah tudi prek 1800 stopinj. Še več, z uporabo izključno modelov največje trenutne temperature bi bile te razlike še bolj izrazite. Vseeno pa je treba taljenje jekla vzeti za zgornjo možno mejo kontaktnih temperatur.

The curves represent the temperatures obtained according to the mean values from Figure 3 (with the new thermal conductivity k(T)) that were first normalised by the measured overall coefficient of friction (Table 1) and afterwards recalculated for the selected range of the coefficient of friction. Between the measured and the highest value of the coefficient of friction presented here, the temperature difference is about 180°C at condition D25 and about 400°C at condition D50. At condition D05 the difference is less significant because of the lower temperature and also because of the lower coefficient of friction. It must be stressed that with some models even higher values can be obtained. Some of these results are, of course, unrealistic, because the general contact conditions would change at such temperatures and melting of the steel would occur, which is therefore the upper limit of the possible temperature. In fact, based on our AES and TEM results, a 200 to 300 nm thick interface layer was found, which indeed corresponded to the melt ([6] and [21]). In addition, separate studies on the chemical reactivity between steel and ceramics also showed that temperatures above 1000°C are necessary for the observed reactions during tribological processes ([22] and [23]).

Again, it must be pointed out that when the models that give extreme temperatures and/or extremely different conditions are encountered, the calculated average flash temperatures can differ by more than 1800 degrees Centigrade. Furthermore, if the maximum-flash-temperature models were used, the differences would be even higher because these effects are much more pronounced at higher temperatures. However, the melting point of the steel can be used as the upper limit for the validity of such an analysis.

3 SKLEP

Iz predstavljenih izračunov lahko povzamemo, da parametri, ki smo jih spreminjali v tej raziskavi, tj. toplotna prevodnost v odvisnosti od temperature in koeficient trenja glede na položaj v kontaktu, znatno vplivata na izračunane trenutne

3 CONCLUSION

Based on our results we can conclude that the parameters varied in this research, i.e. the thermal conductivity and the coefficient of friction, significantly affect the calculated flash temperatures. The same conclusion can be drawn for another unknown temperature. Enak sklep velja tudi za izjemno pomemben vhodni parameter, ki je tudi neznan in ga je treba pri izračunu predpostaviti, to je dejanska kontaktna površina. Prav tako pomemben za izračun trenutnih temperatur pa je tudi teoretični model. Iz naših rezultatov je razvidno, da so razhajanja med posameznimi modeli pri enakih vhodnih podatkih za več sto stopinj. V konkretnem primeru smo dobili s kombinacijo uporabljenega modela in vhodnih parametrov razlike tudi do 1800 stopinj, čeprav je šlo za dejansko enake kontaktne razmere. Tako velike razlike med posamičnimi modeli in dopustna ohlapnost pri izbiri vhodnih parametrov torej kažejo, da je treba upoštevati številne omejitve in biti dovolj kritičen pri uporabi in upoštevanju dobljenih vrednosti trenutnih kontaktnih temperatur z izbranimi enačbami in modeli.

but necessarily assumed input parameter for any calculation, the real contact area. Another extremely important factor for the obtained results is the selection of the theoretical model. From our calculations it can be seen that the differences between various models can be as high as several hundreds of degrees for the same contact conditions and input parameters. By employing different theoretical models and input parameters, the calculated temperature in our work could vary by as much as 1800 degrees Centigrade. Such large differences between different models and such loosely defined input parameters imply that severe limitations in accuracy must be considered and care in the interpretation of the results must be taken when ready-to-use models are used.

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