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THERMOELASTIC STRESS ANALYSIS FOR STRUCTURAL INTEGRITY ASSESSMENT

TERMOELASTIČNA ANALIZA NAPONA U PROCENI INTEGRITETA KONSTRUKCIJE

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Ključne reči
- termoelastična analiza napona
- opseg faktora intenziteta napona
- kombinovani oblik naponskog stanja
- prslina

Izvod

U radu su predstavljeni rezultati termoelastične analize napona u određivanju opsega faktora intenziteta napona na vrhovima zareza i prslina u uslovima naponskog stanja usled kombinovanog opterećenja

UVOD

Termoelastičnost se zasniva na principu da su, pri adijabatskim i reverzibilnim uslovima, za konstrukciju opterećenu ciklično i izloženu temperaturskim promenama, ove promene proporcionalne sumi glavnih napona. Ove varijacije temperature mogu se izmeriti osetljivim infracrvenim detektorom, čime se dobija izgled cikličnog polja napona na površini konstrukcije. Izraz za prvu invarijantu napona u oblasti vrha prsline se može izvesti preko jednačina naponskog polja i može se upotrebiti za određivanje faktora intenziteta napona. Veličina faktora intenziteta napona dobijena termoelastičnom analizom je jednaka rasponu faktora intenziteta napona, ΔK, koji se javlja na vrhu prsline kao rezultat dejstva cikličnog opterećenja. Na ovaj način je omogućeno eksperimentalno određivanje stvarne sile rasta prsline, umesto preko maksimalnog i minimalnog faktora intenziteta napona, kao u slučaju drugih eksperimentalnih metoda.

Premda su izvedene precizne analize za otvaranje prslina i zareza, postignut je samo ograničeni napredak u određivanju faktora intenziteta napona za prsline u kombinovanim uslovima naponskog stanja primenom termoelastičnih metoda, /1–4/. Najskorije publikovani podaci u ovoj oblasti /2/ pokazuju dobro slaganje teorije i eksperimenata za ΔK_{I} i ΔK_{II} kod centralnih zareza i prslina, kao i kod ivičnih zareza. Međutim, kod ivičnih prslina u uslovima kombinovanog opterećenja, neslaganje teorije i eksperimenta dostiže 30%. Većina publikovanih podataka odnosi se na prsline u uslovima dominantnog I tipa opterećenja, a jedini dostupni podaci u uslovima dominantnog opterećenja tipa II ukazuju na razliku između teorije i eksperimenta od 40%, /1/. Iako je poznato da većina prslina u uslovima kombinovanog opterećenja u inženjerskim komponentma pretežno raste kao prsline I tipa, u slučajevima lopatice turbine ili zamornog

Keywords
- thermoelastic stress analysis
- stress intensity factor range
- mixed mode stress state
- crack

Abstract

The paper presents the results of thermoelastic stress analysis investigations for determining the range of stress intensity factors at the tip of notches and cracks loaded under mixed mode conditions.

INTRODUCTION

Thermoelasticity is based on the principle that under adiabatic and reversible conditions, a cyclically loaded structure experiences temperature variations that are proportional to the sum of principal stresses. These temperature variations may be measured using a sensitive infrared detector and thus the cyclic stress field on the surface of the structure may be obtained. An expression for the first stress invariant in the region of the crack tip can be derived from stress field equations and used to determine the stress intensity factors. The stress intensity factor value obtained from thermoelastic analysis is equal to the range of the stress intensity factor, ΔK, that occurs at the crack tip due to the applied cyclic load. This allows the actual crack driving force to be experimentally determined rather than being inferred from maximum and minimum stress intensity factors, which is the case with other experimental techniques.

Although accurate analyses have been performed for opening mode cracks and slots, only limited progress has been made for the determination of stress intensity factors for mixed-mode cracks using thermoelastic techniques, /1–4/. The most recently published data on the subject /2/ shows good agreement between theory and experiment for both ΔK_{I} and ΔK_{II} for central slots and cracks, and edge slots. However for mixed-mode edge cracks the differences between theory and experiment were up to 30%. The majority of the published data has been for cracks under predominantly mode I loading and the only data for predominantly mode II loading showed a difference between theory and experiment of up to 40%, /1/. Although it is known that the majority of mixed-mode cracks found in engineering components eventually propagate as mode I cracks, in some cases such as turbine blades and rolling contact fatigue in rails, mixed-

kontakta kotrljanja po šinama, dominantan je kombinovani oblik opterećenja. Stoga je ova oblast istraživanja značajna i potrebna su dalja ispitivanja.

U svim objavljenim eksperimentima generisani su uslovi kombinovanog tipa opterećenja na vrhu prsline primenom zategnute ploče sa oštrim zarezom ili sa prslinom pod uglom u odnosu na pravac opterećenja. Dvoosno opterećenje uzorka nije razmatrano. Analiza naponskih polja primenom termoelastičnosti često je otežana činjenicom da je do nedavno bilo jedino moguće primeniti termoelastičnost u istraživanjima parametara vrha prsline samo kod stacionarnih prslina, zbog ograničenja termoelastičnih instrumenata sa jednom mernom tačkom kao što je SPATE (analiza naponskog polja toplotnom emisijom). Novi instrumenti kao DeltaTherm sadrže mrežu detektora i omogućavaju snimanje termoelastičnih podataka u realnom vremenu.

EKSPERIMENTALNA PROCEDURA I REZULTATI

Razvoj softvera i opreme

U svrhu što efikasnijeg procesiranja prikupljenih podataka, neophodno je bilo prvo direktno povezati prikupljene podatke sa termoelastičnih senzora radi njihove obrade u računskom algoritmu Tomlinson *et al*, /1/. U toj metodi se koristi Njutn-Rafsonovu iteraciju u kombinaciji sa pristupom najmanjih kvadrata radi fitovanja jednačina koje opisuju naponsko polje oko vrha prsline termoelastičnim podacima, a na bazi pristupa Muskelišvili. Proračun faktora intenziteta napona zahteva da se ti podaci nalaze u oblasti dominirane singularnošću vrha prsline, unutar polja linearno elastičnih napona, izvan oblasti u blizini vrha prsline gde su dominantni lokalna plastičnost i troosni naponi, a uz moguće provođenje toplote. Takođe je uočeno da su podaci izdvojeni sa bokova prsline nedovoljno opisani jednačinama naponskog polja, pa se moraju maskirati, /1/. Stoga je interfejs napisan u *Visual Basic*-u kako bi se podaci SPATE i DeltaTherm mogli unositi, a zatim operator bira oblasti za maskiranje, gde su podaci nevažeći za određivanje faktora intenziteta napona. Selektuje se mreža od približno 100 tačaka u važećoj oblasti podataka oko vrha prsline, a zatim se ovi direktno unose u algoritam za rešavanje ΔK_{I} i ΔK_{II}. Interfejs za DeltaTherm je napisan u saradnji sa druga dva projekta u kojima se takođe upotrebljava algoritam Tomlinson *et al*, EPSRC Grant No GR/M 577125, kao i u okviru Izvršnog projekta zdravlje i sigurnost "Integritet u repariranim zavarima". Ispravnost procedure sa interfejsom je ispitana određivanjem faktora intenziteta napona u tipu opterećenja otvaranjem i izrazitom I tipu kombinovanog opterećenja na ivičnim zarezima, kod kojih se algoritmom postižu precizni rezultati, uz korišćenje SPATE podataka, /6/, kao i kod prslina opterećenih otvaranjem korišćenjem podatke DeltaTherm, /7–9/. Ova istraživanja su pokazala da su interfejs i algoritam robusni i da je metoda ponovljiva i ne zavisi od operatora, /8/. Predloženo je da se eksperimenti izvode pod kontrolisanim uslovima, upotrebom dvoosne mašine za ispitivanje, kojom se proizvode realne prsline kombinovanog opterećenja, umesto prslina dobijenih u uslovima I tipa opterećenja, /2/. Ova mašina omogućava kontrolisanje ugla rasta prsline i sprečava

mode loading continues to dominate. Therefore this area of research is of importance and further testing is required.

All published experiments generate the mixed-mode conditions at a crack tip with the use of tensile loading of a plate containing a sharp slot or crack at an angle to the direction of loading. Biaxial loading of a sample has not been considered. The analysis of crack tip stress fields using thermoelasticity has been hampered also by the fact that, until recently, it has only been possible to use thermoelasticity to investigate crack tip parameters of stationary cracks, due to the limitations of single-point thermoelastic instruments such as SPATE (Stress Pattern Analysis by Thermal Emission). New instruments such as DeltaTherm, which contain an array of detectors, enable thermoelastic data to be recorded in real time.

EXPERIMENTAL PROCEDURE AND RESULTS

Software and equipment development

In order for the processing of subsequent data to be as efficient as possible it was first necessary to interface directly the data collection from the thermoelastic sensors to be utilised with the calculation algorithm of Tomlinson *et al*, /1/. In this method Newton-Raphson iteration combined is used with a least squares approach to fit the equations describing the stress field around the crack tip, based on Muskhelishvili's approach, to the thermoelastic data. The calculation of stress intensity factors requires data to be within the area which is dominated by the crack tip singularity, within the linear elastic stress field, and outside the area close to the crack tip where localised plasticity and triaxial stresses dominate, and heat conduction is possible. It has also been found that data selected from the flanks of crack are not well described by the stress field equations and must be masked, /1/. The interface was therefore written in Visual Basic to enable both SPATE and DeltaTherm data to be input and then the operator selects areas to be masked where the data are invalid for the determination of the stress intensity factors. An array of approximately 100 data points are selected from the valid region of data around the crack tip and these are subsequently input directly to the algorithm to solve for ΔK_{I} and ΔK_{II}. The interface with DeltaTherm was written in collaboration with two other projects which were also using the Tomlinson *et al* algorithm, EPSRC Grant No GR/M 577125 and also a Health and Safety Executive Project, "Integrity of Repair Welds". The success of the interfacing procedure was tested by determining stress intensity factors from opening mode and predominantly mode I mixed-mode edge slots for which the algorithm is known to give accurate results, using SPATE data, /6/, and opening mode cracks using DeltaTherm data, /7–9/. These studies showed that the interface and algorithm were robust and that the technique was highly reproducible and operator independent, /8/. It was proposed that the experiments be performed under controlled conditions using a biaxial testing machine to produce true mixed-mode cracks rather than those grown under mode I conditions, /2/. The use of this machine would enable firstly the angle of crack growth to be controlled and secondly the prevention of crack propagation

širenje prsline tokom prikupljanja podataka sa SPATE. Računarski deo sistema mašine je unapređen pre ispitivanja, čime je ciklično opterećenje kontrolisano PC-jem preko softvera *Labview*.

Određivanje faktora intenziteta napona na zarezima sa kombinovanim opterećenjem

Iako je cilj projekta bio istraživanje primene termoelastičnosti u određivanju zamornih prslina u uslovima dvoosnog opterećenja, odlučeno je da se tačnost predložene metode prethodno testira na oštrim zarezima. Smatralo se bitnim da se eliminišu svi faktori kojima se mogu uneti greške u rezultate, a iz ranijih radova je poznato da se kod zamornih prslina može pojaviti zatvaranje, a to ima efekt smanjenja izračunate vrednosti ΔK, /12/. Da bi se sprečio uticaj tih efekata na tačnost metode, podaci su prvo sakupljeni oko oštrog zareza, umesto oko zamorne prsline. Uzorci su izrađeni od čelika 150M36, krstastog oblika, sa centralnim zarezom pod uglom od 45°, dužine $2a$ = 6 mm, dobijenim elektro-erozijom. Jedna strana uzorka je polirana da bi se eventualni rast prsline mogao lako pratiti na optičkom mikroskopu. Druga strana je uzorka je nabrizgana tankim slojem crne mat boje da bi se povećala emisivnost i dobio jednolik termoelastični signal. Opterećenje je izvedeno preko dvoosne mašine za ispitivanje od 100 kN tipa Denison Mayes. Oblik talasa i odzivi davača opterećenja su praćeni preko dva osciloskopa, a referentni signal je uzet sa jednog davača opterećenja.

Upotrebljeno je sinusno opterećenje frekvencije 8 Hz i odnosa opterećenja, R = 0, duž dve ose uzorka da bi odnosi $\Delta K_{II}/\Delta K_I$ imali približne vrednosti 0; 0,5; 1; 1,5; 2; i 2,5. Zatim je uticaj promene odnosa opterećenja ispitan izborom $\Delta K_{II}/\Delta K_I$ = 0,5 i opterećivanjem uzorka sa R = 0,1; 0,2; 0,3; 0,5 i 0,7. Pri svakom izboru opterećenja su snimljeni termoelastični podaci oko vrha zareza preko sistema DeltaTherm 1550.

Svaka mapa termoelastičnih podataka je integrisana za 3,25 minuta i jedna tipična mapa je prikazana na sl. 1. Termoelastični signal je kalibrisan korišćenjem dve ortogonalne merne rozete, postavljene u oblasti uniformnog napona na poliranoj strani uzorka, a primenom standardne kalibracione metode, /1/. Signal je kalibrisan na jednakim intervalima u toku programa ispitivanja, jer svaka promena temperature okoline može da promeni konstantu kalibracije. Rasponi faktora intenziteta napona, ΔK_I i ΔK_{II}, su određeni iz svakog skupa podataka metodom zasnovanom na pristupu Muskelišvili. Obezbeđeno je prikupljanje podataka unutar singularne dominantne zone, a izvan nelinearne zone na vrhu prsline izazvane plastičnošću i provođenjem toplote, i to iscrtavanjem krive y u funkciji $1/S_{max}^2$, /13/, gde je S_{max} maksimalni termoelastični signal na liniji na rastojanju y paralelno prslini, uz prihvatanje podataka samo iz linearne oblasti.

Zarez je dalje proširen na $2a$ = 12, 18, 24 i 30 mm, a ista procedura je ponovljena za svaku od ovih dužina zareza. Na sl. 2 su prikazani rezultati ovih ispitivanja i upoređeni sa faktorima intenziteta napona dobijenim prema teoriji koju su razvili Bold *et al*, /14,15/.

during data collection using SPATE. The computing system of the machine was upgraded prior to the commencement of testing enabling the cyclic load to be controlled via personal computer using Labview software.

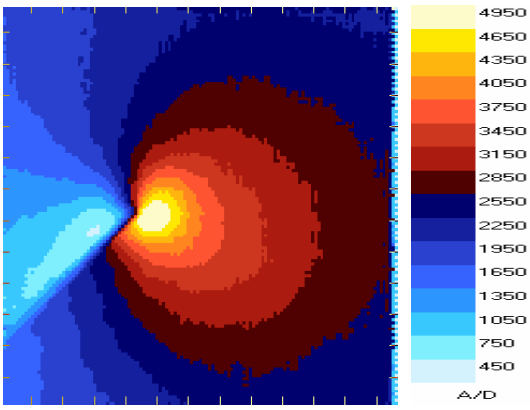
Determination of stress intensity factors from mixed-mode slots

Although the aim of the project was to investigate the use of thermoelasticity in the determination of fatigue cracks under biaxial load, it was decided that the accuracy of the proposed method should be tested initially using sharp slots. It was considered important to eliminate any factors which may introduce errors into the results and from previous work it had been found that fatigue cracks may exhibit crack closure and this had the effect of depressing the value of ΔK calculated, /12/. So in order to prevent these effects on technique accuracy, data was first collected from around a sharp slot rather than a fatigue crack. The specimens were made from 150M36 steel and were of a cruciform shape with a central spark-eroded notch inclined at 45º, of length $2a$ = 6 mm. One side of the specimen was polished to enable any crack growth to be easily monitored using an optical microscope. The other side of the specimen was sprayed with a thin coat of matt black paint to increase emissivity and to obtain a uniform thermoelastic signal. The load was applied using a 100 kN Denison Mayes Biaxial Testing Machine. The shape of waveforms and response of the load cells were monitored using two oscilloscopes and the reference signal was taken from one of the load cells.

A sine load was applied at a frequency of 8 Hz and a load ratio, R = 0 along the two axes of the specimen in order to give the ratios of $\Delta K_{II}/\Delta K_I$ approximately values of 0, 0.5, 1, 1.5, 2, and 2.5. Then the effect of changing the load ratio was investigated by setting $\Delta K_{II}/\Delta K_I$ = 0.5 and loading the specimen at R = 0.1, 0.2, 0.3, 0.5 and 0.7. At each load setting thermoelastic data was recorded around the notch tip using a DeltaTherm 1550 system.

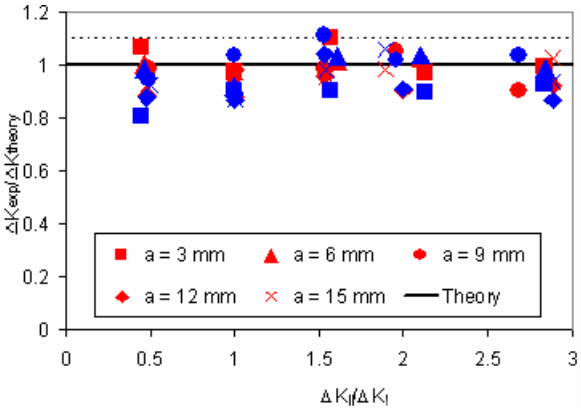
Each thermoelastic data map was integrated over 3.25 minutes and a typical map is shown in Fig. 1. The thermoelastic signal was calibrated using two orthogonal strain gauge rosettes, located in an area of uniform stress on the polished side of the specimen, using a standard calibration method, /1/. The signal was calibrated at regular intervals throughout the test programme since any change in ambient temperature can change the calibration constant. The stress intensity factor ranges, ΔK_I and ΔK_{II}, were determined from each set of data using a method based on the Muskhelishvili approach. It was ensured that the data were collected within the singularity dominated zone, and outside the non-linear zone at the crack tip caused by plasticity and heat conduction, by plotting a graph of y versus $1/S_{max}^2$, /13/, where S_{max} is the maximum thermoelastic signal from a line at a distance y parallel to the crack, and only taking data from the linear region.

The notch was further extended to $2a$ = 12, 18, 24 and 30 mm, and the same procedure repeated at each of these notch lengths. The results of these tests are shown in Fig. 2 compared to stress intensity factors determined from the theory developed by Bold *et al* /14,15/.

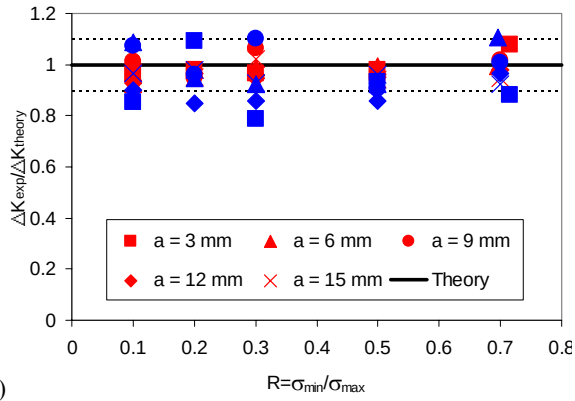


Slika 1 (levo). Tipična termoelastična raspodela za kombinovano opterećeni zarez, $\Delta K_{II}/\Delta K_I = 1{,}0$; rezolucija = 8,67 piksela/mm; dimenzija slike = 256 × 256 piksela

Figure 1 (left). Typical thermoelastic pattern from a mixed mode notch, $\Delta K_{II}/\Delta K_I = 1.0$; Resolution = 8.67 pixels/mm; Image size = 256 × 256 pixels.



a)



b)

Slika 2. Grafički prikaz normalizovanog faktora intenziteta napona za zareze u zavisnosti od (a) porasta odnosa $\Delta K_{II}/\Delta K_I$ i (b) porasta odnosa R. crveni simboli = ΔK_I, plavi simboli = ΔK_{II}

Figure 2. Graphs of the normalised stress intensity factor for notches versus (a) increasing applied $\Delta K_{II}/\Delta K_I$ and (b) increasing R ratio. Key: red symbols = ΔK_I, blue symbols = ΔK_{II}.

Prema sl. 2a eksperimentalni podaci za ΔK_I i ΔK_{II} se dobro slažu sa teorijskim procenama, sa prosečnom razlikom između eksperimenta i teorije od 4,5% za ΔK_I i 6,5% za ΔK_{II}. Rezultati su precizniji kod dužih zareza, međutim kod najkraćeg zareza, oblast u kojoj je moguće prikupiti važeće podatke je bila relativno mala i ovo se smatralo razlogom za nedovoljno poklapanje sa teorijom. Veće razlike pri manjem odnosu K_{II}/K_I u rezultatima II tipa opterećenja se mogu objasniti činjenicom da je vrednost K_{II} mala kod dužih prslina. Rezultati za porast odnosa R (sl. 2b) pokazuju da su prosečne razlike između eksperimenta i teorije 4,1% i 8,8% za ΔK_I i ΔK_{II}, respektivno.

Ova serija ispitivanja je pokazala da se faktori intenziteta napona mogu precizno izračunati preko termoelastičnih podataka u uslovima opterećenja I tipa i dominantnog kombinovanog II tipa. Ovim radom se sugeriše da su greške u ranijem radu /1/ na ivičnim zarezima u uslovima dominantnog opterećenja tipa II, možda nastale zbog ograničenja u sistemu SPATE 8000 za prikupljanje podataka ili pak u numeričkim rešenjima sa kojima su upoređivane.

Određivanje faktora intenziteta napona na zamornim prslinama pri kombinovanom opterećenju

Urađena je serija ispitivanja za određivanje faktora intenziteta napona kod zamornih prslina u uslovima stvarnog kombinovanog opterećenja primenom termoelastičnosti. Pretpostavlja se da nema ranije objavljenih podataka ovog tipa. U cilju sprečavanja grananja rastuće prsline, primenjen

From Fig. 2a the experimental data for both ΔK_I and ΔK_{II} compare well with theoretical estimations showing an average difference between experiment and theory of 4.5% for ΔK_I and 6.5% for ΔK_{II}. The results appear more accurate for the longer slits, however for the shortest slit the area in which valid data could be collected was relatively small and this was thought to be the reason for the less favourable comparison with theory. The larger discrepancy for the low K_{II}/K_I ratio may be accounted for in the mode II results, by the fact that the value of K_{II} was small in relation to the longer cracks. From the results for increasing the R ratio (Fig. 2b), the average differences between experiment and theory were 4.1% and 8.8% for ΔK_I and ΔK_{II}, respectively.

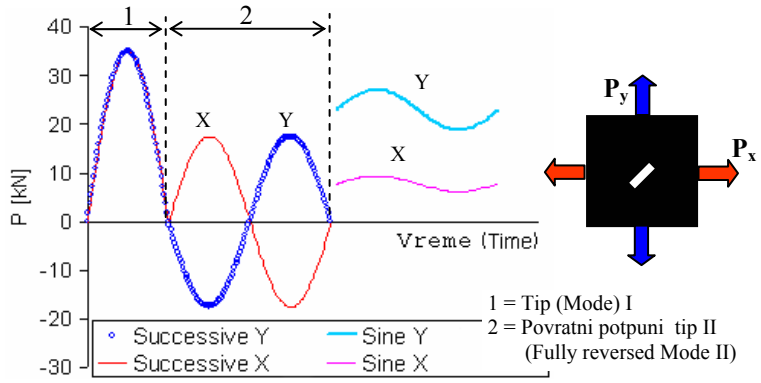
Overall, this series of tests showed that accurate stress intensity factors may be calculated from thermoelastic data under both mode I and mode II dominant, mixed-mode loading conditions. This work suggests that errors encountered in previous work /1/ for predominantly mode II edge slots may have been due to the limitations of the SPATE 8000 system data collection or the numerical solutions against which they were compared.

Determination of stress intensity factors from mixed-mode fatigue cracks

A series of tests were performed to determine the stress intensity factors from fatigue cracks under true mixed-mode loading using thermoelasticity. It is believed that no data of this type has been published previously. In order to prevent

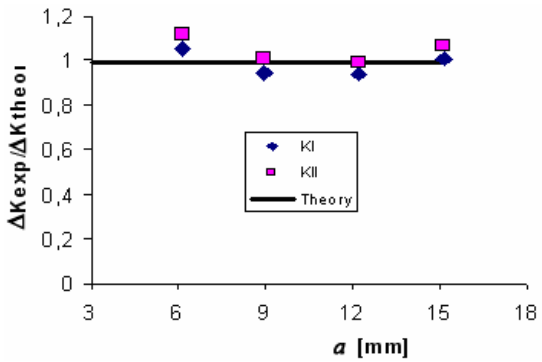
je sukcesivni ciklus opterećenja, Bold *et al* /14/. U ovom ciklusu, dovodi se opterećenje I tipa i zatim rasterećuje pre nego što se dovede potpuni povratni ciklus opterećenja tipa II, kao što je prikazano na sl. 3. Bilo je pokušaja da se snime termoelastični podaci pod uslovima ovog ciklusa opterećenja, međutim, primećeno je da je za uspešno prikupljanje podataka vrlo bitan i referentni signal za korelaciju toplotne emisije.

branching of the propagating crack, a successive load cycle developed by Bold *et al* /14/ was applied. In this cycle, a mode I load is applied and removed before the fully reverse mode II cycle is applied, as shown in Fig. 3. An attempt was made to record thermoelastic data under this load cycle, however it was found that the reference signal required for correlation with the thermal emission was crucial to successful data collection.



Slika 3. Sukcesivni ciklus opterećenja za rast prsline, $\Delta K_{II}/\Delta K_I = 1$; $R = 0$; i primer sinusnog ciklusa opterećenja upotrebljenog za prikupljanje podataka, $R = 0{,}7$; $\Delta K_{II}/\Delta K_I = 0{,}45$

Figure 3. The successive load cycle for crack growth, $\Delta K_{II}/\Delta K_I = 1$; $R = 0$; and an example of the sine load cycle used for data collection, $R = 0.7$; $\Delta K_{II}/\Delta K_I = 0.45$.



Slika 4. Faktori intenziteta napona ΔK_I i ΔK_{II} u zavisnosti od porasta dužine prsline. $\Delta K_{II}/\Delta K_I = 0{,}45$ i $R = 0{,}7$

Figure 4. The stress intensity factors ΔK_I and ΔK_{II} with increasing crack length. $\Delta K_{II}/\Delta K_I = 0.45$ and $R = 0.7$.

Referentni signal se koristi za filterisanje pozadinskog infracrvenog zračenja koje se emituje, ali ne usled cikličnog opterećenja. Najčešći referentni signal korišćen u termoelastičnim ispitivanjima je sinusnog talasnog oblika preko kojeg se direktno izračunava promena u sumi glavnih napona. Posle konsultacija sa proizvođačima sistema DeltaTherm, Stress Photonics Inc., zaključeno je da se softverom DeltaVision ne može prepoznati sukcesivni referentni signal opterećenja za korelaciju toplotnog signala. Rešenje ovog problema je bilo u izazivanju rasta prsline sa sukcesivnim opterećenjem, a zatim snimanjem termoelastičnih podataka pri manjem opsegu sinusnog opterećenja, na pr. na sl. 3, time obezbeđujući da do porasta prsline ne dolazi pri skupljanju podataka. Ovim rešenjem predloženo istraživanje mogućnosti metode da prati širenje prslina pri kombinovanom opterećenju nije moglo da se izvede u ovoj fazi, ali su proistekli zaključci zasnovani na širenju prslina pri dejstvu opterećenja I tipa.

Izazvane su zamorne prsline kod dvoosnih epruveta i faktori intenziteta napona su određeni primenom iste procedure, istih inkremenata porasta dužine prsline, kao i odnosa opterećenja opisanih u prethodnom odeljku *Određivanje faktora intenziteta napona na zarezima sa kombinovanim opterećenjem*. Namera je bila pokušati sprečiti zatvaranje prslina pri njihovom rastu, ali nije ostvareno zbog sukcesivnog ciklusa opterećenja pri $R = 0$, gde je teško bilo sprečiti zatvaranje prsline /14,15/. Međutim, pri snimanju podataka pri većim odnosima R bilo koji uticaj zatvaranja prsline na vrednosti faktora intenziteta napona je minimiziran usled opterećivanja prsline u potpuno otvorenom delu ciklusa. Na sl. 4 su prikazani rezultati eksperimenta sa porastom dužine

The reference signal is used to filter out any background infrared radiation which is emitted not due to the cyclic load. The most common reference signal used in thermoelastic tests is the sine wave from which it is straightforward to calculate the change in the sum of principal stresses. After consultation with the manufacturers of the DeltaTherm system, Stress Photonics Inc., it was concluded that the DeltaVision software could not recognise the successive load reference signal for correlation with the thermal signal. The solution to this problem was to grow the crack under successive loading and then record thermoelastic data under a reduced sine load range, e.g. in Fig. 3, ensuring that the crack did not grow during data collection. This solution meant that the proposed investigation of the ability of the method to monitor propagating cracks under mixed-mode loading could not be achieved at this stage, however, conclusions based on the propagation of mode I cracks have been drawn.

Fatigue cracks were grown in the biaxial specimens and then the stress intensity factors were determined using the same procedure, crack length increments, and load ratios outlined in the previous section *Determination of stress intensity factors from mixed-mode slots*. It had been intended to try and prevent crack closure whilst growing the cracks, but this had not been possible since for the successive load cycle at $R = 0$ closure it was difficult to prevent /14,15/. However, when recording data at higher R ratios any effect of crack closure on the values of stress intensity factors is minimised since the crack is being loaded in the fully open part of the cycle. Figure 4 shows results of the experiment with increasing crack length for $\Delta K_{II}/\Delta K_I = 0.45$

prsline, za $\Delta K_{II}/\Delta K_I = 0{,}45$ i $R = 0{,}7$. Prosečne razlike između eksperimenta i teorijskih predviđanja od 4,3% i 5% su ostvarene za ΔK_I i ΔK_{II}, respektivno, a što je uporedivo sa tačnošću dobijenom na uzorcima sa zarezom.

Određivanje faktora intenziteta napona na rastućim prslinama

Kao što je već rečeno u prethodnom odeljku *Određivanje faktora intenziteta napona na zamornim prslinama pri kombinovanom opterećenju*, nije bilo moguće snimiti razumljive termoelastične podatke na rastućim prslinama u uslovima kombinovanog opterećenja zbog neodgovarajućeg sukcesivnog referentnog signala opterećenja. Međutim, moguće je bilo snimiti podatke na rastućoj prslini pod dejstvom tipa I opterećenja, u okviru studije zavarenog spoja /7/. U sistemu DeltaTherm postoji rešetka sa 256 × 256 ili 256 × 320 infracrvenih detektora, sa kojima se može posmatrati zamorni rast prsline u praktično realnom vremenu. Jedina prepreka u prikupljanju podataka u realnom vremenu je intenzitet šuma u slici, koji nastaje zbog prirode površine materijala i pomeranja komponente pri cikličnom opterećenju. Ovaj šum se može minimizirati integrisanjem slike duž određenog broja ciklusa, međutim, kada prslina raste tada je broj ciklusa ograničen na onaj broj u okviru kojeg se ne uočava promena u raspodeli napona.. U izvedenom eksperimentu /7/, prslina se širila maksimalnom brzinom od 0,0001 mm/ciklus sa frekvencijom od 16 Hz, a termoelastični podaci su integrisani na 30 sekundi. Podaci su i dalje sa znatnim šumom, pa su zato pre bilo koje kvantitativne analize usrednjeni filterom 3 × 3. Iz podataka je bilo moguće odrediti faktore intenziteta napona, čime je ukazano na mogućnosti metode za proučavanje rasta prsline.

ZAKLJUČCI

Pokazana je da je nova metoda upotrebljiva na zarezima i prslinama opterećenim kombinovano i dvoosno, kao i na rastućim prslinama I načina. Algoritmi koji su razvijeni se unose u komercijalno dostupan softver, a uskoro će se objaviti novosti i u industrijskim primenama.

ZAHVALNOST

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and $R = 0.7$. An average difference between experiment and theoretical predictions of 4.3% and 5% was obtained for ΔK_I and ΔK_{II}, respectively, which is comparable to the accuracy obtained for notched specimens.

Determination of stress intensity factors from propagating cracks

As stated in the previous section *Determination of stress intensity factors from mixed-mode fatigue cracks*, it was not possible to record meaningful thermoelastic data from propagating mixed-mode cracks due to the unsuitability of the successive loading reference signal. However, it was possible to record data from a propagating mode I crack in a study on the welded specimen /7/. The DeltaTherm system has a 256 × 256 or 256 × 320 array of infrared detectors, which provide the means to observe near real time fatigue crack growth. The only limitation to real time data collection is the amount of noise in the image which can be due to the nature of the surface of the material and the movement of the component during cyclic loading. This noise can be minimised by integrating the image over a number of cycles, however, if the crack is propagating then the number of cycles is limited to the number over which the stress pattern cannot be observed to change. In the experiment carried out /7/, the crack propagated at a maximal rate of 0.0001 mm/cycle at a frequency of 16 Hz and the thermoelastic data was integrated over 30 seconds. The data was still quite noisy, therefore, prior to any quantitative analysis the data was smoothed using a 3 × 3 mean filter. The stress intensity factors were able to be determined from the data and thus indicated the potential of the technique for crack propagation studies.

CONCLUSIONS

The new technique has been shown to work on mixed-mode biaxially loaded notches and cracks, and mode I propagating cracks. Developed algorithms are incorporated in commercially available software and further publications on industrial applications will be presented shortly.

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