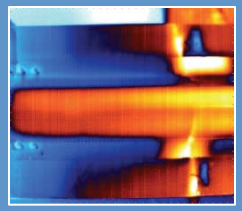

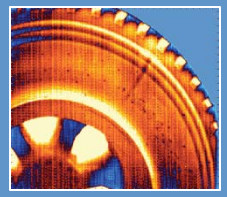

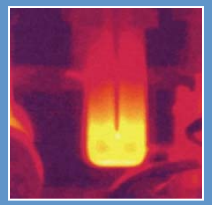

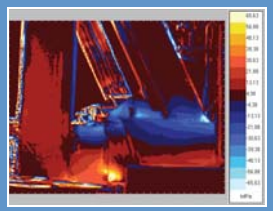

Utilizzo dei metodi termici per la diagnosi non distruttiva di materiali compositi

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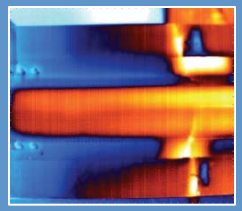

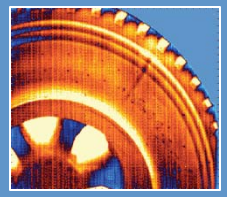

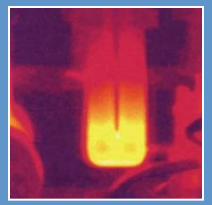

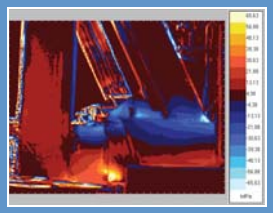

Introduzione

Il crescente utilizzo di materiali innovativi quali i materiali compositi nei più svariati campi di applicazione, ha focalizzato l'attenzione dei ricercatori sullo sviluppo di nuove tecniche di controllo non distruttivo, rapide, automatizzabili, poco costose, non "nocive".

Le Tecniche Termografiche rappresentano uno strumento molto utile per l'analisi non distruttiva dei materiali. In particolare:

- possono essere applicate direttamente sul componente
- in fase di produzione, funzionamento e manutenzione
- sono automatizzabili
- possono essere di supporto alle tecniche NDT tradizionali

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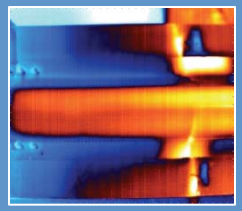

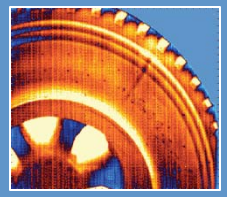

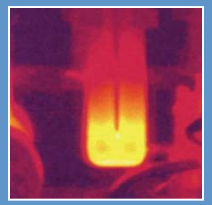

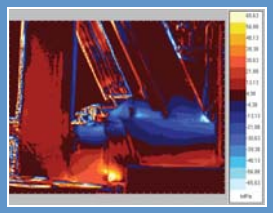

La Termografia

La termografia è una tecnica sperimentale che permette di valutare la temperatura superficiale di un oggetto. La misura di temperatura è possibile grazie a sensori che rilevano a distanza l'energia elettromagnetica emessa da qualsiasi oggetto con temperatura superiore a 0 °K nel campo di lunghezze d'onda dell'infrarosso termico 3-14[μm].

Principali Vantaggi :

1)Tecnica che non richiede contatto fisico con gli oggetti
2)Tecnica a campo intero che permette di ottenere in modo immediato l'immagine termica
3)L'indagine qualitativa dell'immagine ottenuta è di facile interpretazione
4)Non richiede l'utilizzo di radiazioni pericolose

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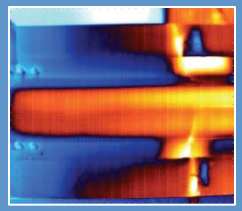

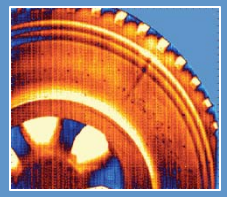

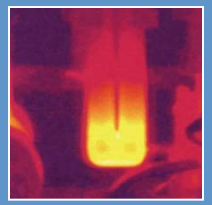

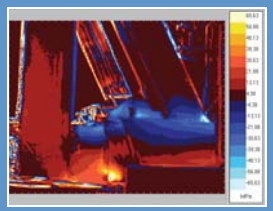

Termografia stimolata e non stimolata

L'individuazione di anomalie termiche con l'indagine termografica è possibile solo se di conduce l'indagine durante una fase di transitorio termico.

Termografia non stimolata:

L'indagine termografica è resa possibile dalle stesse condizioni di esercizio del componente in esame, che comportano, a seconda dei casi, una generazione o una rimozione di calore.

Termografia stimolata:

L'indagine termografica è resa possibile grazie all'utilizzo di una sorgente esterna di calore in grado di provocare il transitorio termico.

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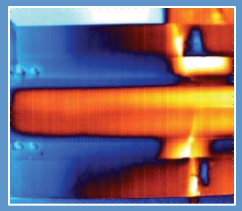

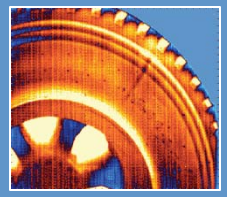

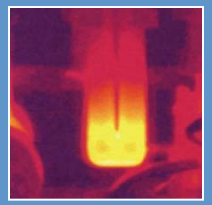

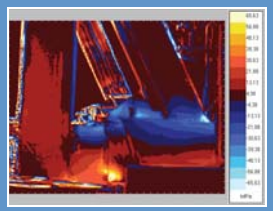

Termografia stimolata e non stimolata

Tecniche termografiche

- Pulsata
- Lock-in
- PPT
- TSA

Sorgente di eccitazione

- Meccanica
  - Ultrasuoni
  - Carichi dinamici
- Elettrica, Elettromagnetica
  - Ottica
  - Microonde
  - Correnti indotte
- Calore per conduzione o convezione

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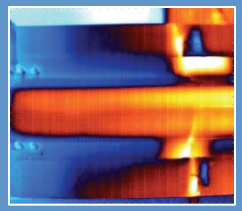
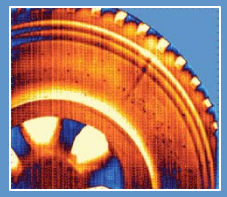
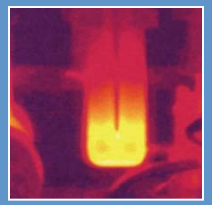
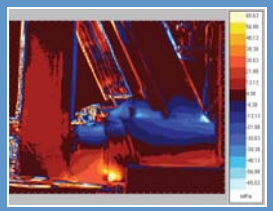








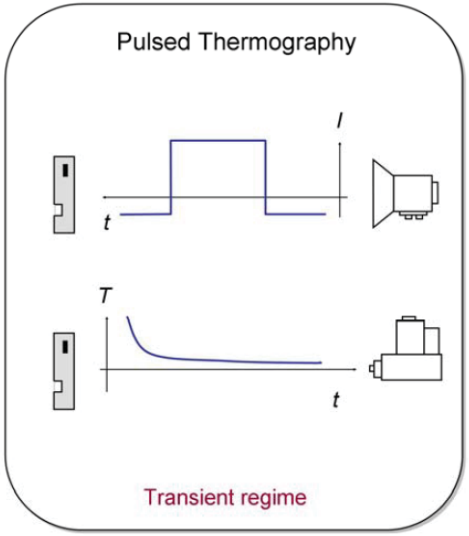
Tecniche NDT

La tecnica Pulsata

Tale tecnica comporta il riscaldamento del provino per un definito intervallo di tempo seguito dalla registrazione della curva di decadimento della temperatura dello stesso.

Segnale sorgente

Risposta termica del materiale



La presenza di un difetto superficiale riduce la diffusione del calore così che, osservando la temperatura superficiale, il difetto appare come un’area a temperatura differente rispetto all’area non difettata. Infatti la riduzione di diffusione causata dalla presenza di un difetto subsuperficiale si tramuta in “accumulo di calore” e da qui in poi la più alta temperatura si riscontrerà nella zona del difetto.

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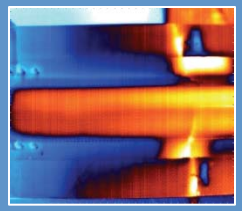

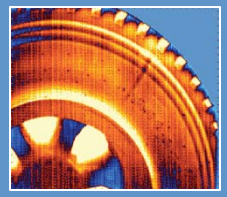

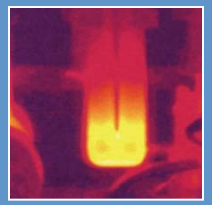

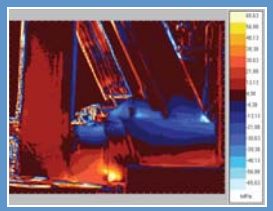

Pulsed Thermography

Analisi dei dati

I difetti più profondi sono osservati dopo e con un ridotto contrasto termico. Un interessante relazione lega (in prima approssimazione) il tempo di osservazione con il quadrato della profondità dei difetti subsuperficiali mentre la perdita di contrasto *c* è proporzionale al cubo della profondità .

$$t \sim z^2 / \alpha \qquad c \sim 1/z^3$$

Una regola largamente usata dice che *il raggio del più piccolo difetto ispezionabile dovrebbe essere almeno uno a due volte più grande della sua profondità sotto la superficie.*

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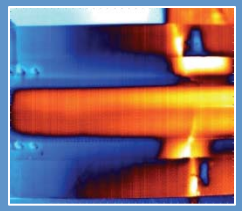
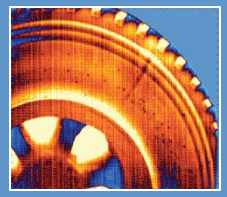
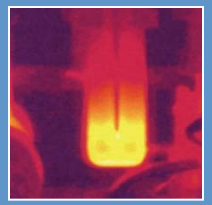
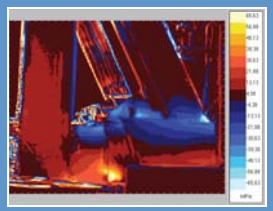




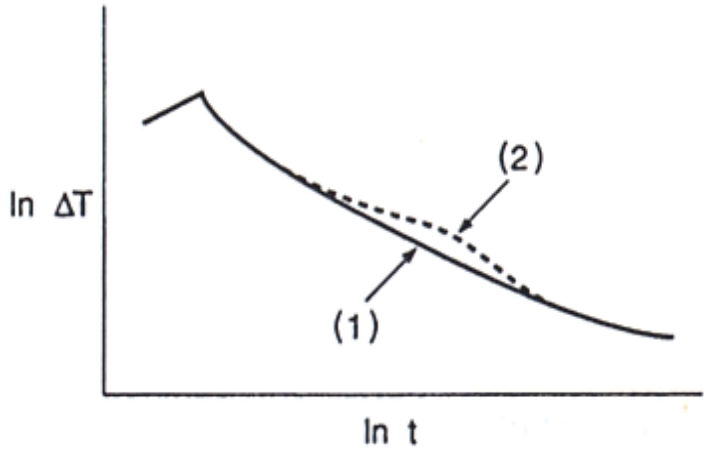




Pulsed Thermography

Analisi dei dati

Se si riporta l'andamento della variazione di temperatura superficiale nel tempo in una scala doppio logaritmica, si ottiene per una zona priva di difetti (1), una decadimento che ha pendenza pari a (-1/2) nella parte centrale.



Se è presente un difetto in profondità (sub-superficiale) (2), il decadimento della variazione di temperatura risulta "deviare" rispetto alla condizione omogenea priva di difetti.

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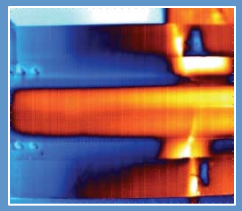
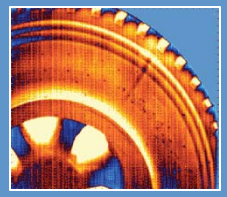
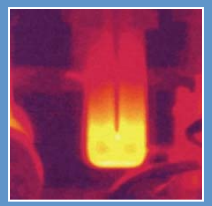
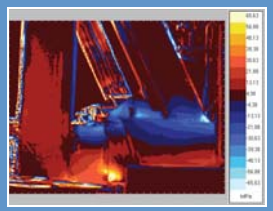


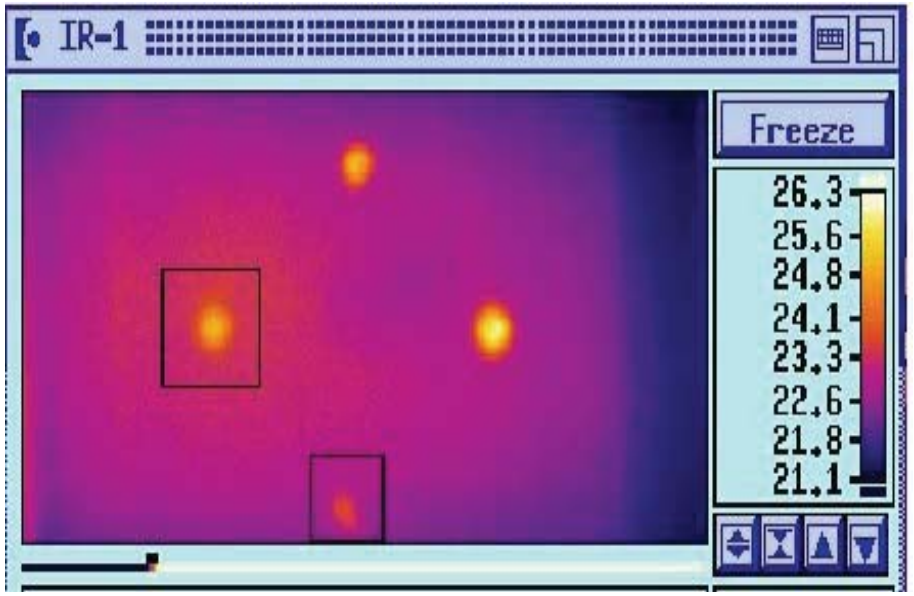






Termografia stimolata: Applicazioni

Tecnica Pulsata: valutazione di difetti in materiali compositi. Prove su provini campione con difetti simulati.



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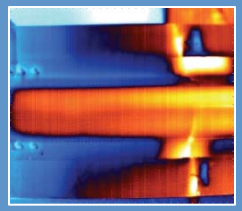

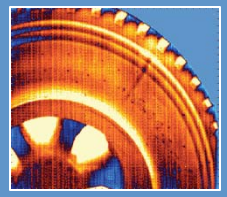

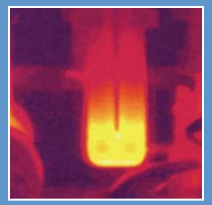

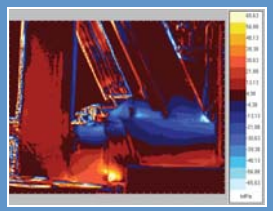

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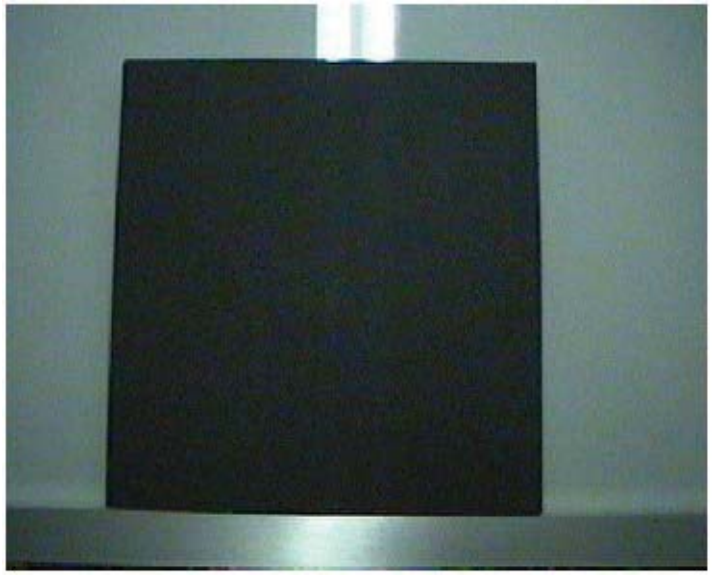

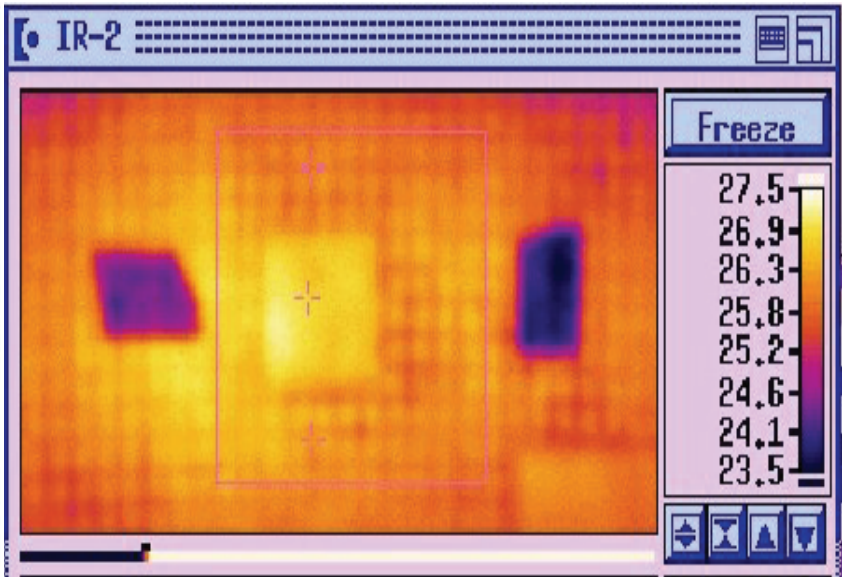

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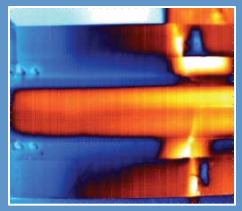
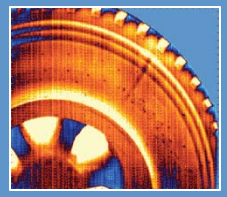
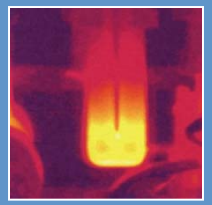
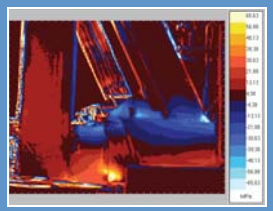


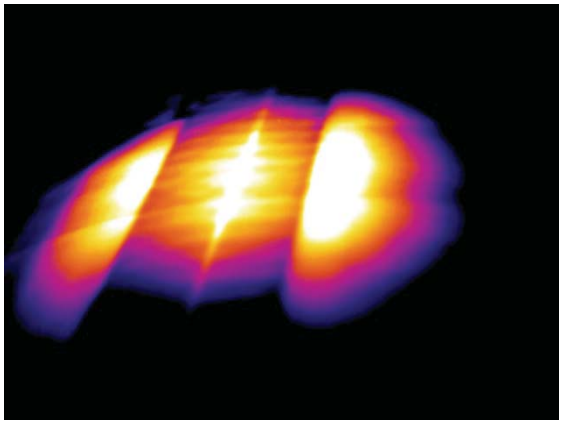


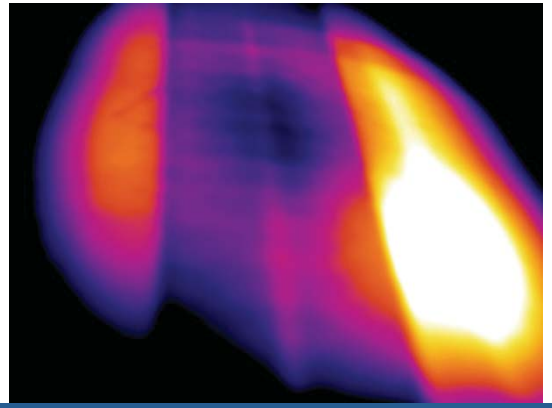




Termografia stimolata: Componenti GFRP

Indagine sulla struttura interna di una pala eolica





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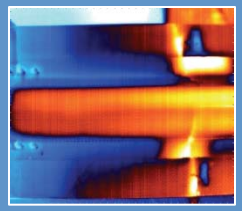
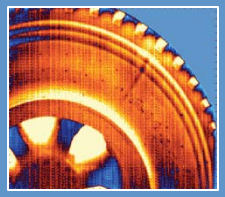
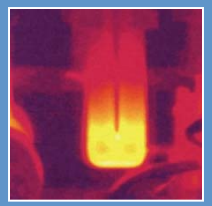
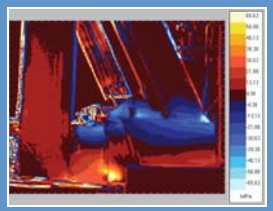
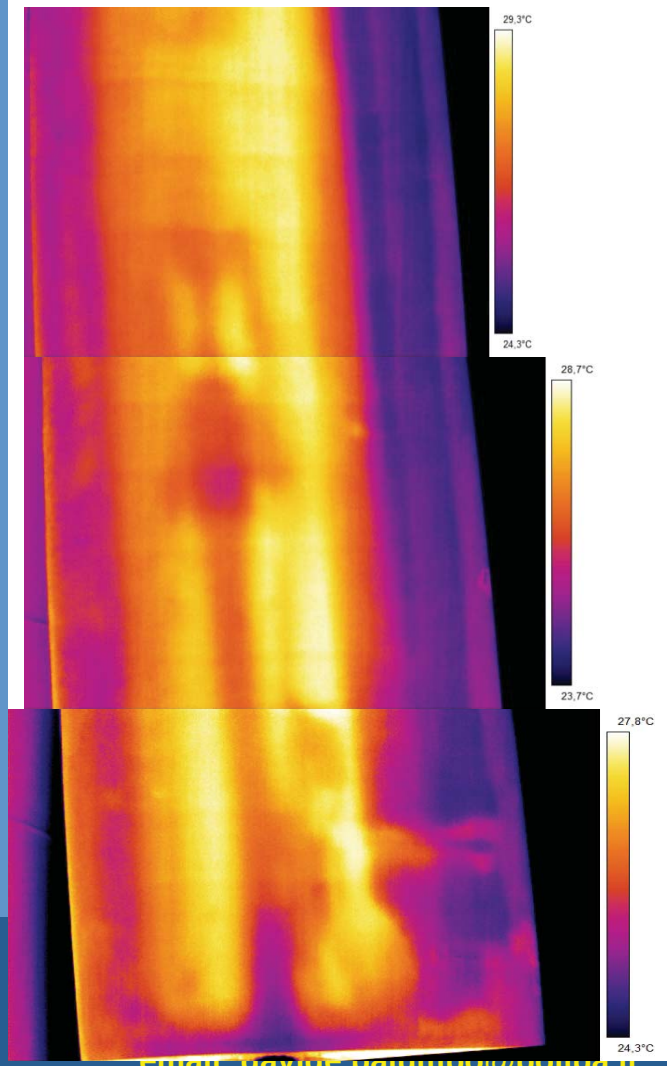








Termografia stimolata: Componenti GFRP



Indagine sulla struttura di una pala eolica con tecnica termografica

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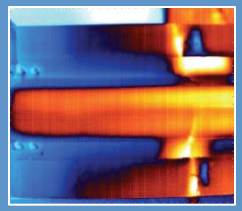
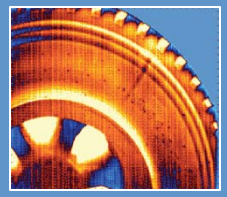
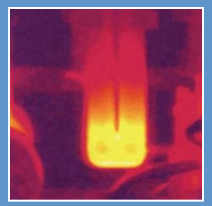
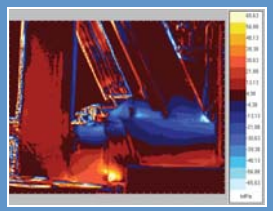








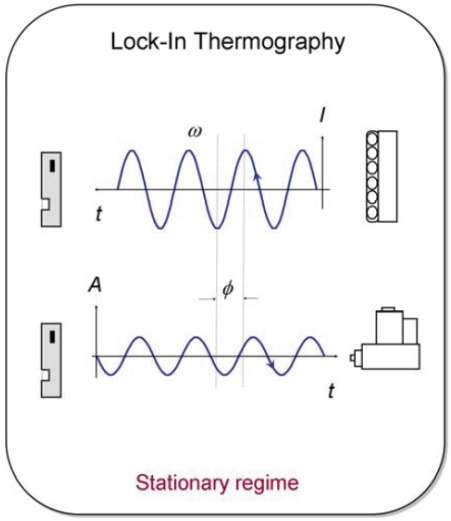
Tecniche NDT

La tecnica Lock-in

La termografia lock-in è basata su onde termiche generate all'interno del provino analizzato mediante una sorgente di calore esterna, in regime stazionario.

Segnale sorgente

Risposta termica del materiale



La risposta termica del materiale viene rilevata da una termocamera. Tramite algoritmi di processing dei dati è possibile ottenere informazioni sull'ampiezza e la fase del segnale termico. Le zone difettate, caratterizzate da proprietà termiche differenti, originano una risposta termica differente rispetto alle zone sane, misurabile in termini di *variazione di fase del segnale termografico* .

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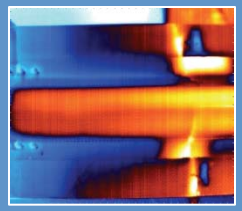
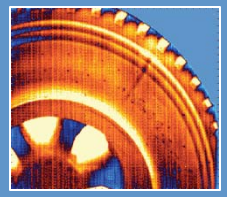
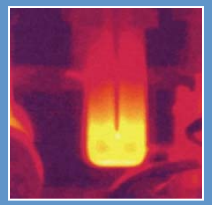
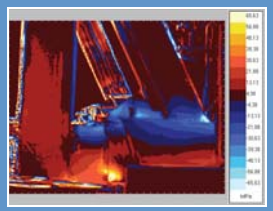
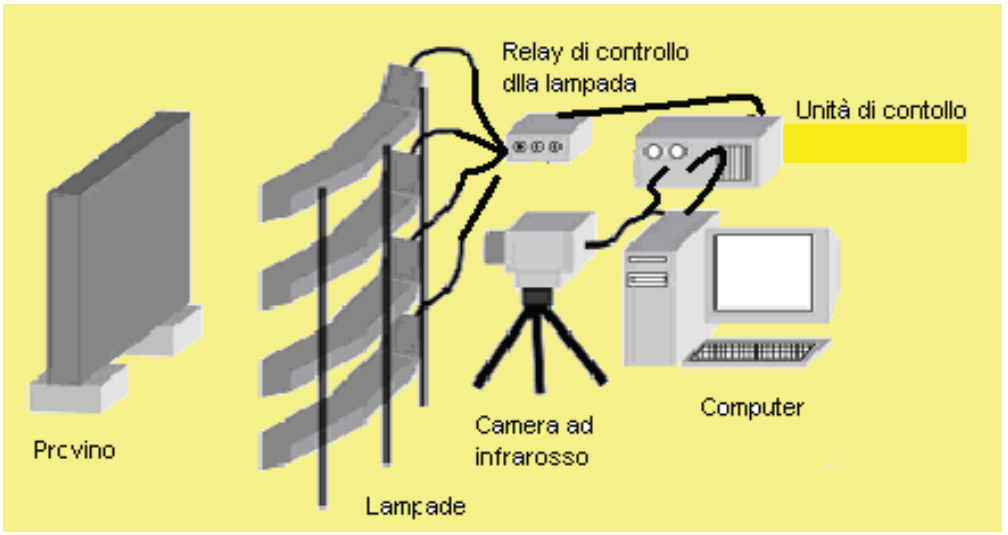








LOCK-IN THERMOGRAPHY (set up di prova)



Il set up tipico di prova, prevede l'utilizzo di:

-Sorgente/i di eccitazione (lampade alogene, laser, ecc)

-Scheda di acquisizione per il controllo della/e sorgente/i di eccitazione

-Termocamera e software per acquisizione dati (sequenze IR)

-Computer con software di controllo scheda di acquisizione

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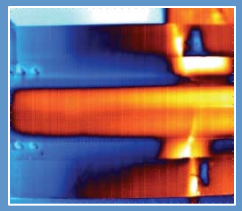

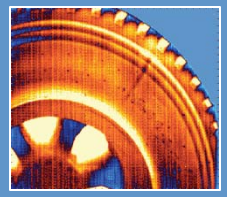

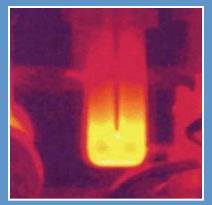

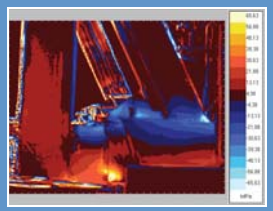

LOCK-IN THERMOGRAPHY

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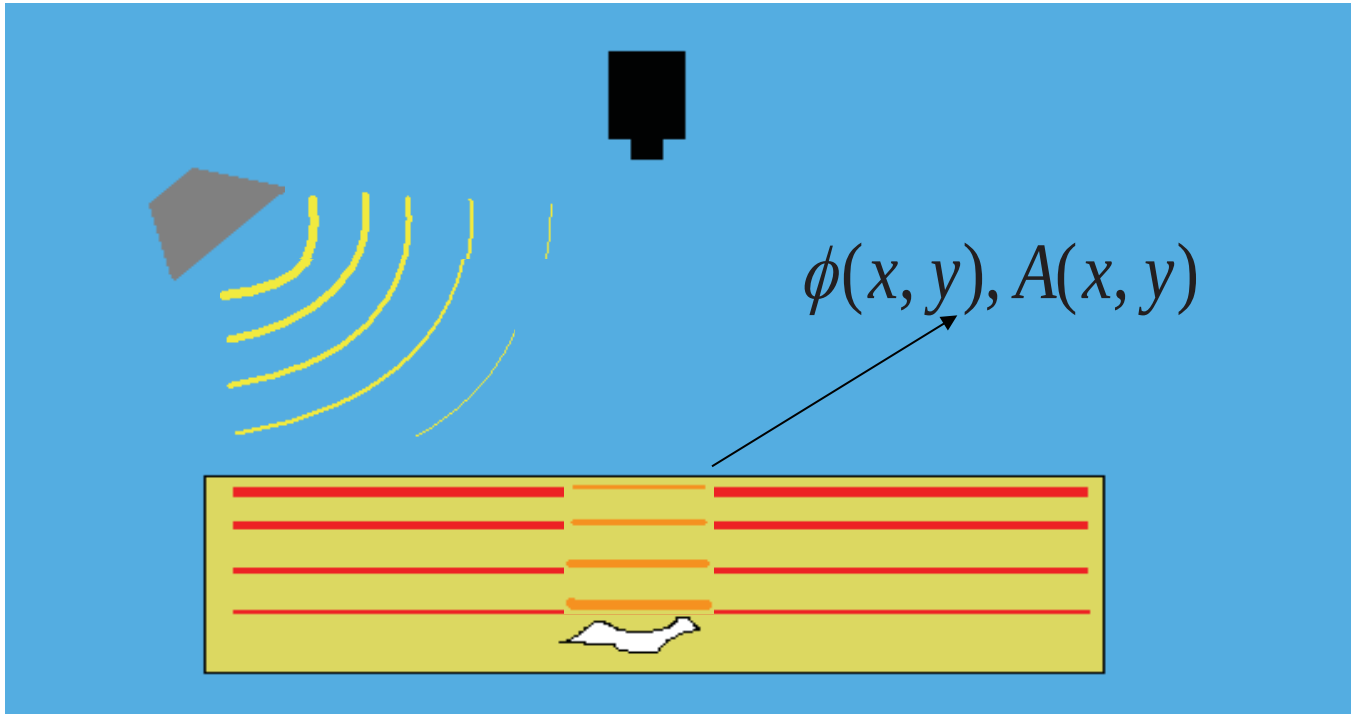

L’onda termica si diffonde all’interno del materiale fino a quando incontra un ostacolo (difetto) che ne impedisce la normale diffusione. La risposta termica del materiale, sotto forma di onde termiche che si ottengono in corrispondenza di un difetto, risulterà differente in termini di fase e ampiezza rispetto alle zone ‘’sane’’ del materiale.

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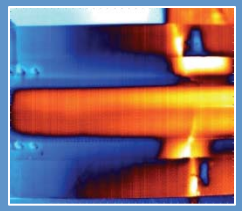

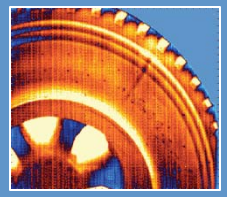

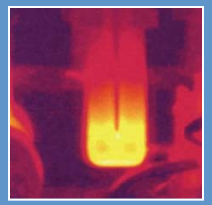

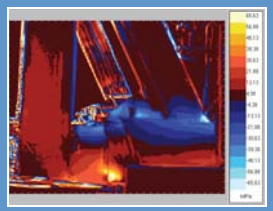

LOCK-IN THERMOGRAPHY

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Grandezze fisiche fondamentali

$$\mu = \sqrt{\frac{2\alpha}{\omega}}$$

lega la profondità di ispezione con la frequenza di eccitazione della sorgente

$$\alpha = \frac{k}{\rho C_p}$$

Indica la capacità di un materiale di diffondere calore al proprio interno

α = diffusività termica;

ω=2πf = pulsazione dell'onda di eccitazione;

μ = lunghezza di diffusività termica;

k = conducibilità termica;

ρ = densità del materiale;

C_p = calore specifico a pressione costante;

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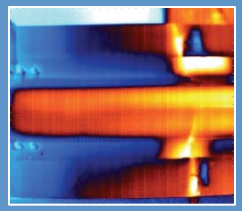

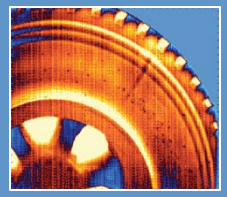

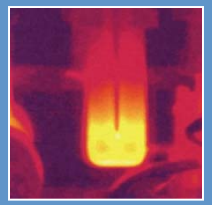

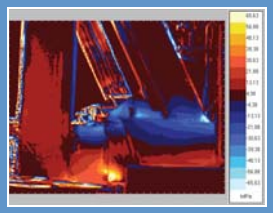

LOCK-IN THERMOGRAPHY

La lunghezza di diffusione termica e la fase possono fornire informazioni a riguardo della profondità di penetrazione *x* raggiunta all'interno del materiale :

$$\varphi(x) = \frac{2\pi x}{\lambda} = \frac{x}{\mu}$$

φ = fase dell'onda;

x = profondità di penetrazione;

λ = lunghezza d'onda;

Dato che la lunghezza di diffusione termica è inversamente proporzionale alla frequenza, frequenze alte restringono l'analisi a regioni prossime alla superficie, mentre onde termiche a bassa frequenza propagano a profondità maggiore ma più lentamente .

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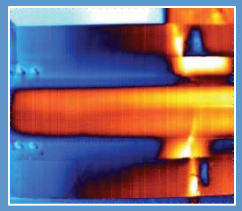
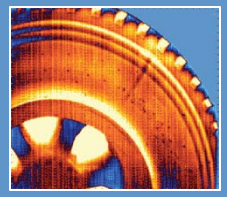
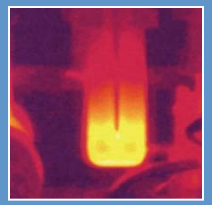
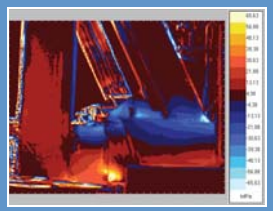


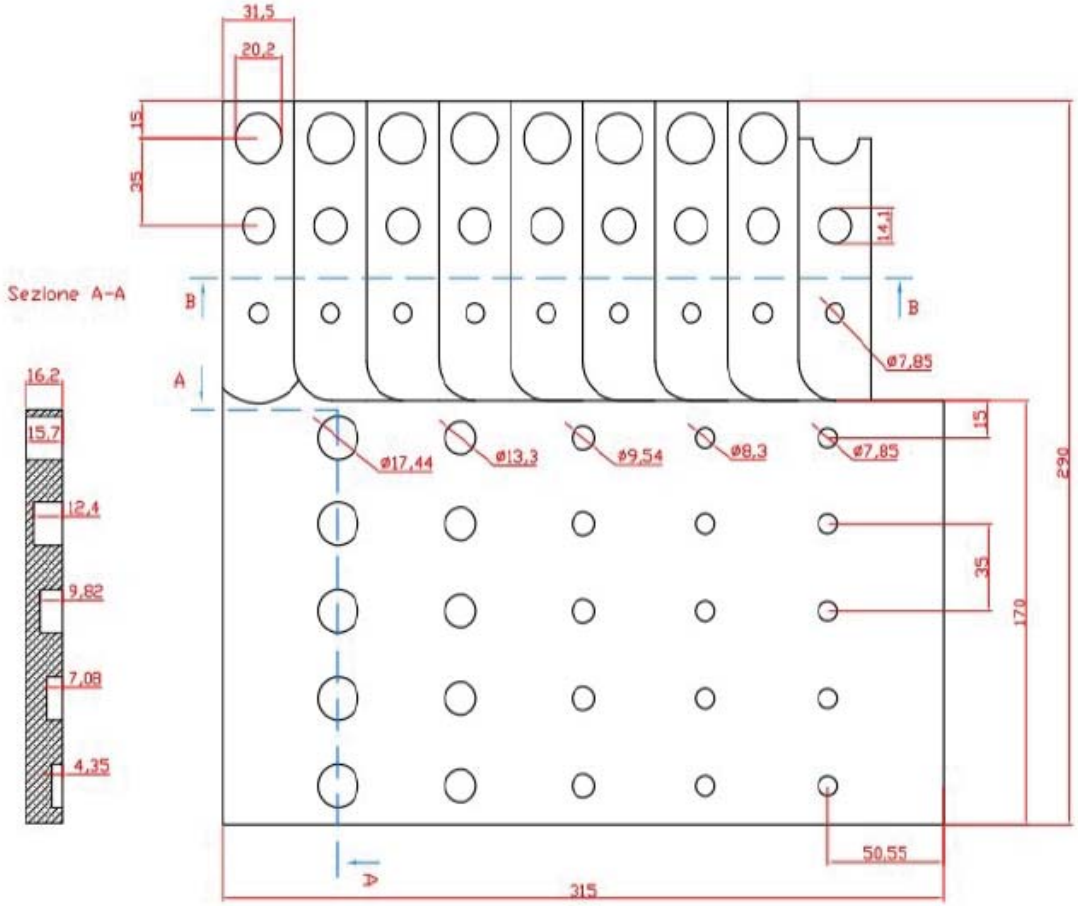






OPTICAL LOCK-IN THERMOGRAPHY

Applicazioni: provino campione in GFRP



Provino campione con difetti simulati con fori ciechi di differente diametro e a differenti profondità

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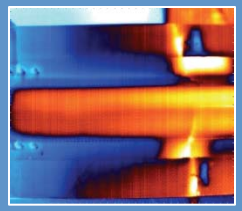
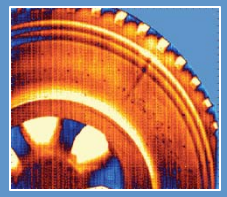
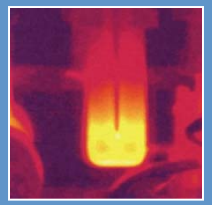
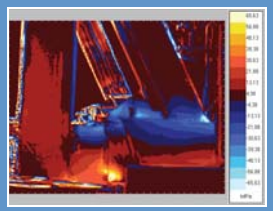




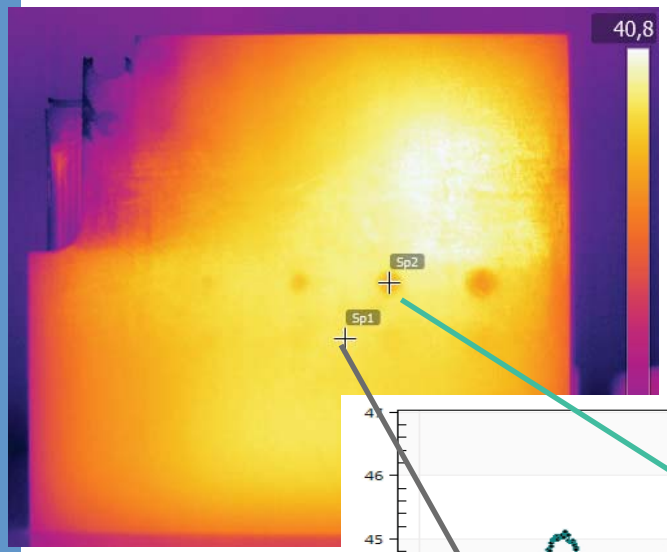




OPTICAL LOCK-IN THERMOGRAPHY

Applicazioni: provino campione

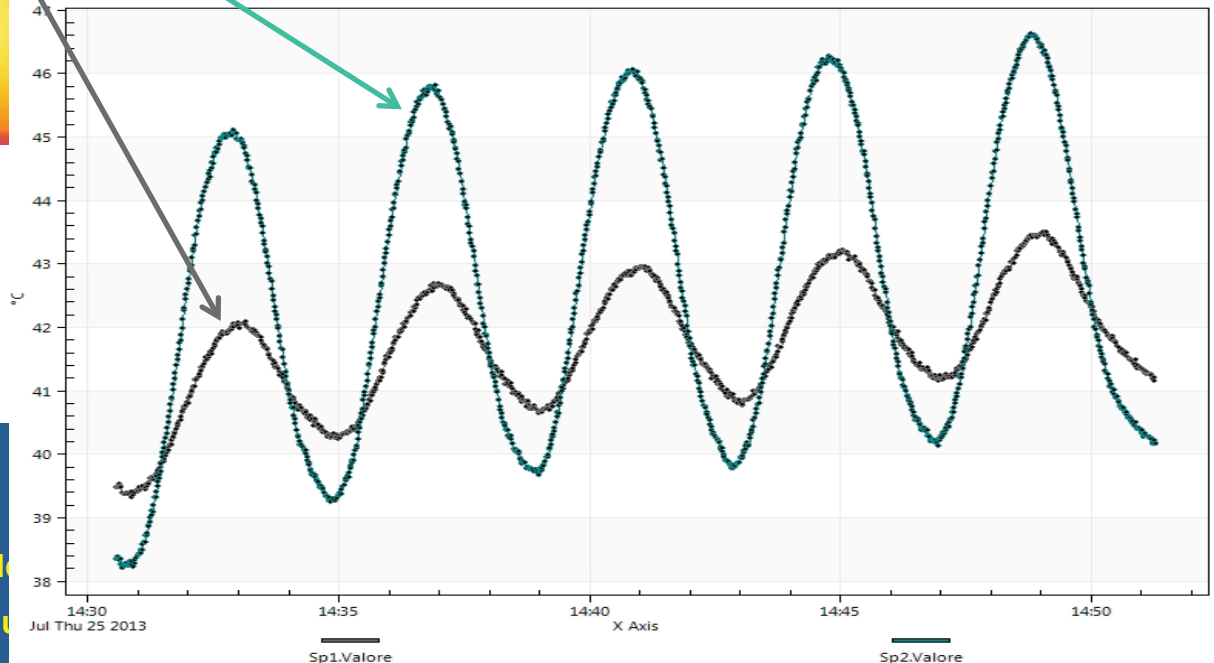
Valutazione della risposta termica del materiale base privo di difetti e del difetto



Periodo 240 s

difetto

materiale base



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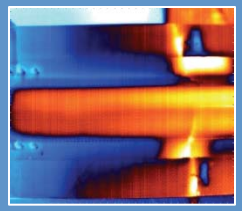
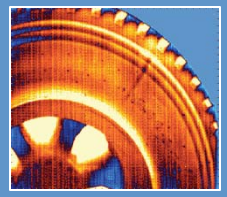
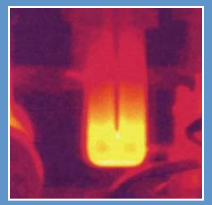
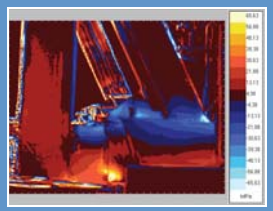






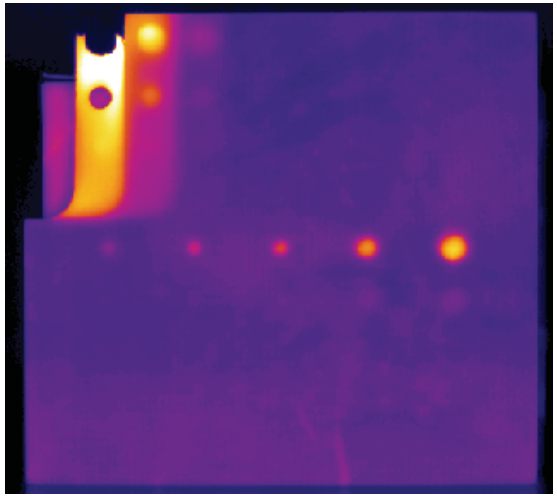


OPTICAL LOCK-IN THERMOGRAPHY

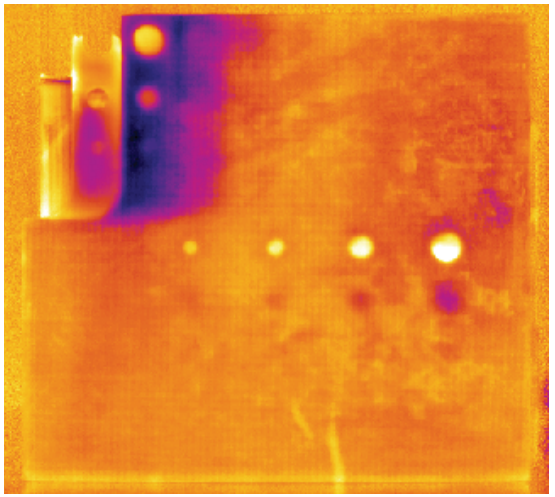
Applicazioni: provino campione

Valutazione della risposta in ampiezza ed in fase del segnale

ampiezza



fase



Pixel per pixel attraverso opportuni algoritmi di calcolo, possono essere ricavate le informazioni in ampiezza (ΔT) ed in fase (φ) del segnale.

In questo modo si ottengono delle “mappe” di ampiezza e fase che forniscono un informazione a campo intero che permette di identificare la posizione di eventuali difetti e/o variazioni geometriche.

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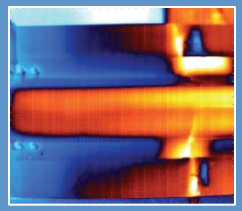
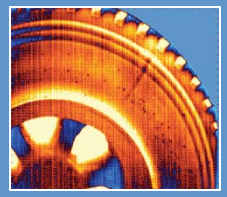
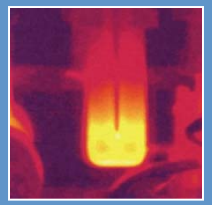
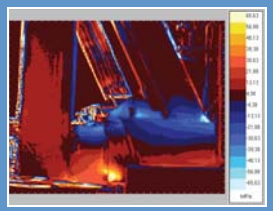
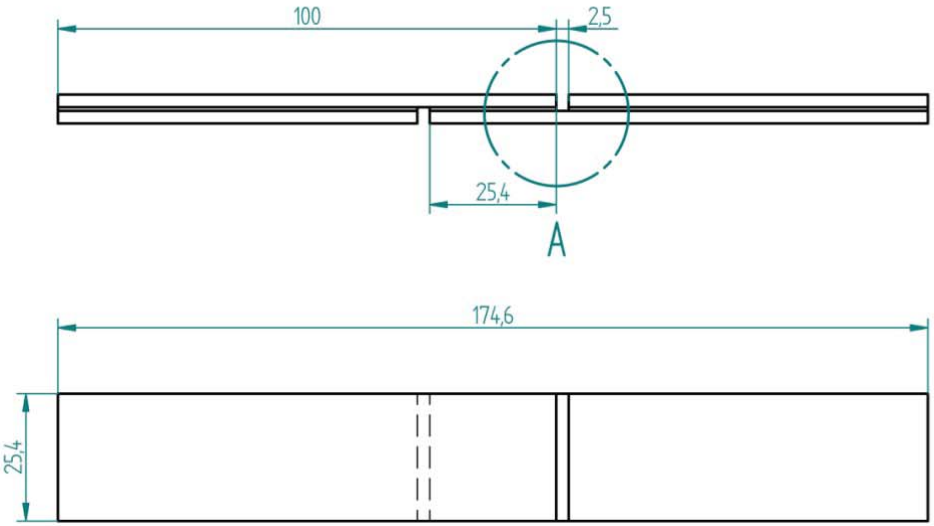


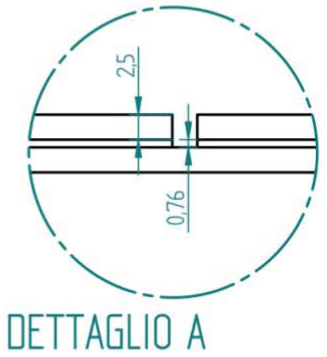






Riduzione dell'errore nella caratterizzazione dei materiali





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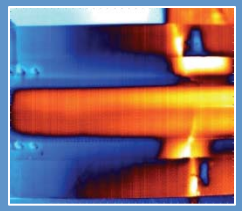
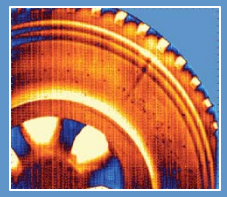
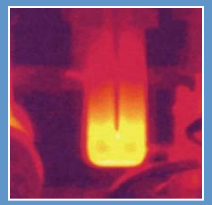
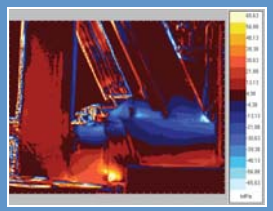
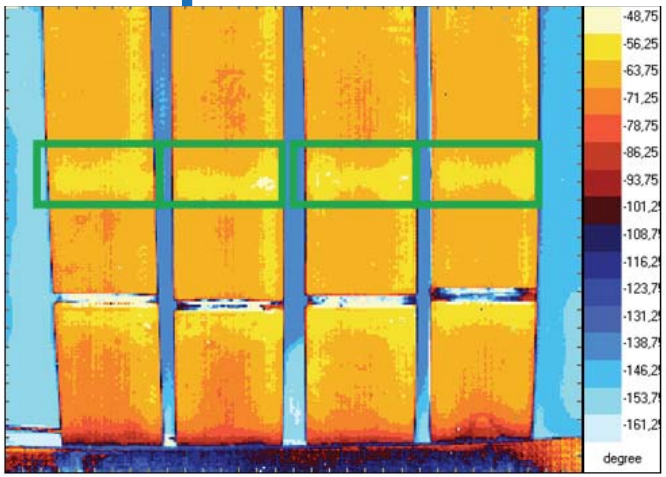


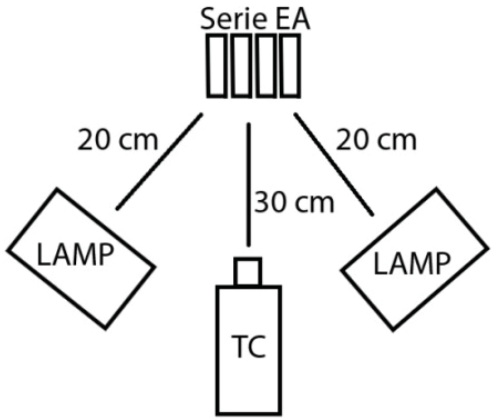




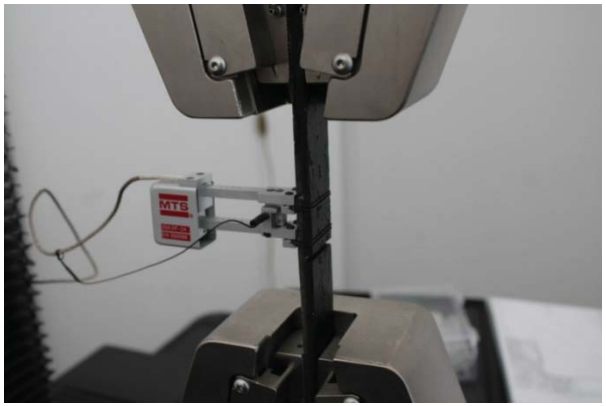


Esclusione rapida dei provini danneggiati





Periodo 160 s - 2 frame/s - 3 periodi - 1120 frame - onda sinus.



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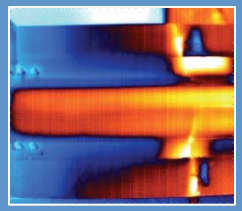
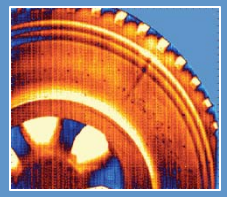
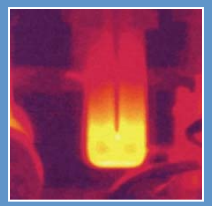
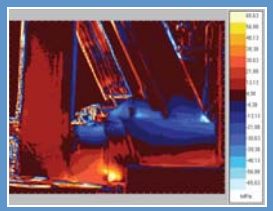


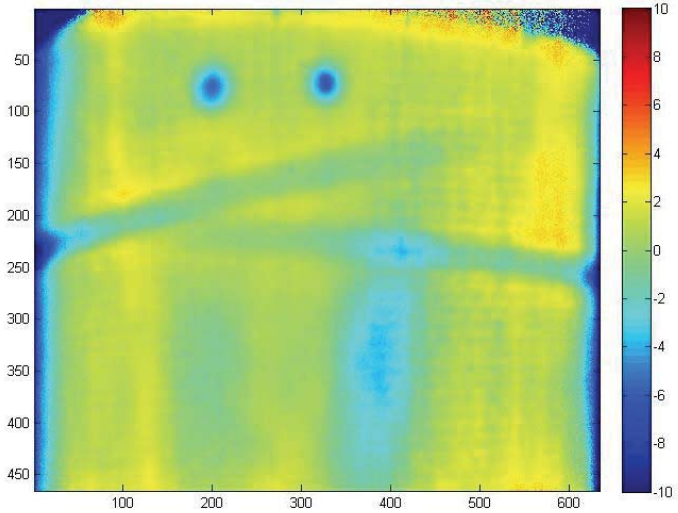






Termografia stimolata: Componenti GFRP

Tecnica Lock-in: valutazione di difetti in materiali compositi



Radice di pala di un generatore eolico.

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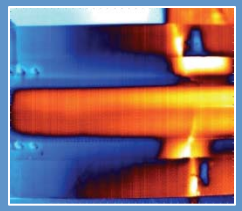
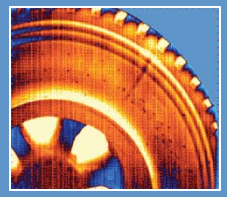
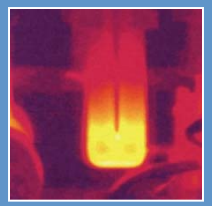
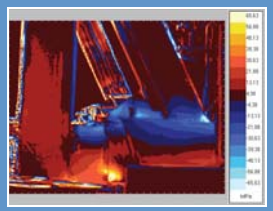


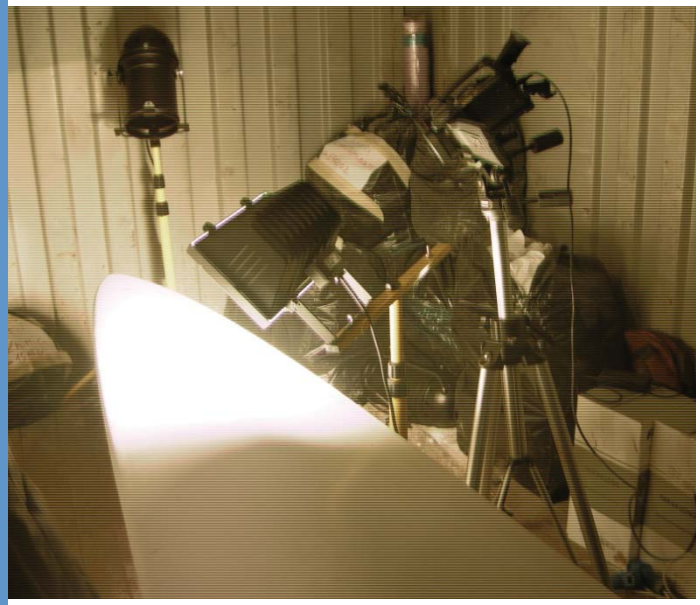


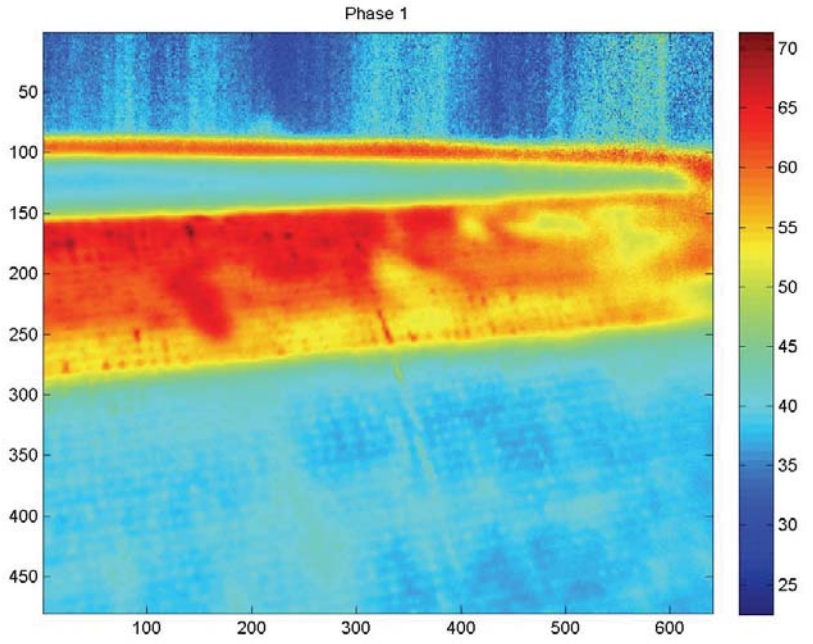




Termografia stimolata: Componenti GFRP

Indagine sulla struttura di una eolica pala con tecnica termografica Lock-in





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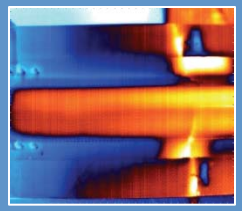
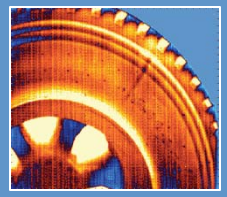
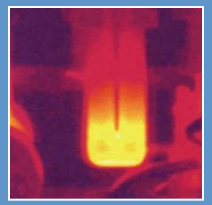
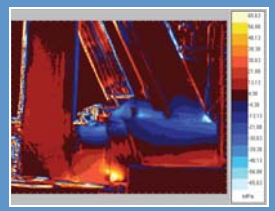


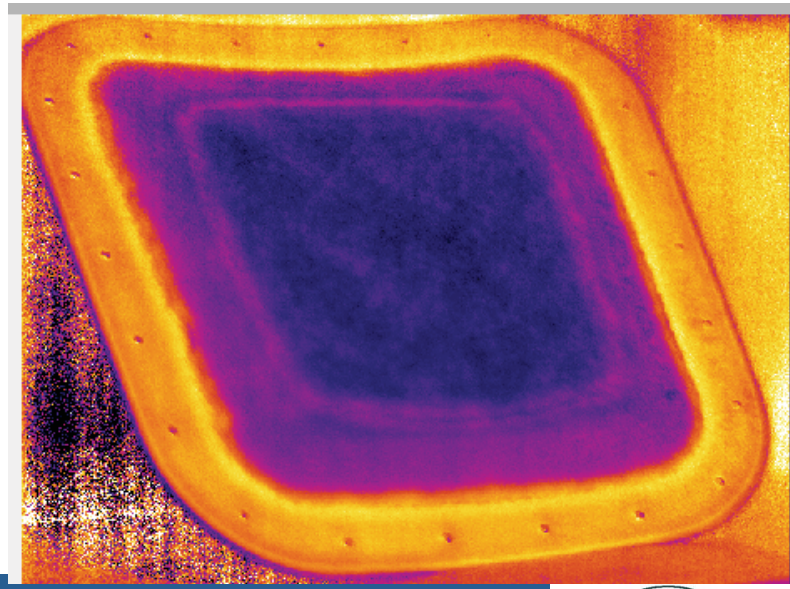






Termografia stimolata: Componenti CFRP

Prova termografica lock-in, periodo 30 secondi, immagini di fase, possibilità di valutare la struttura interna del componente



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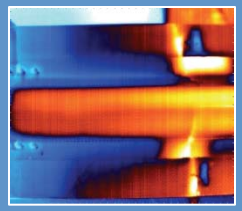
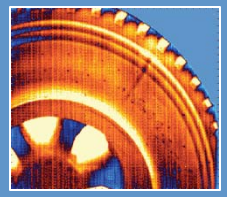
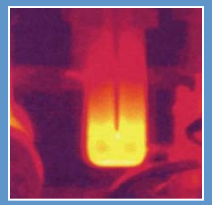
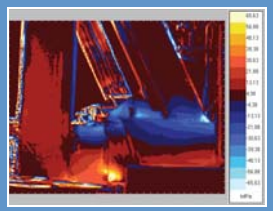


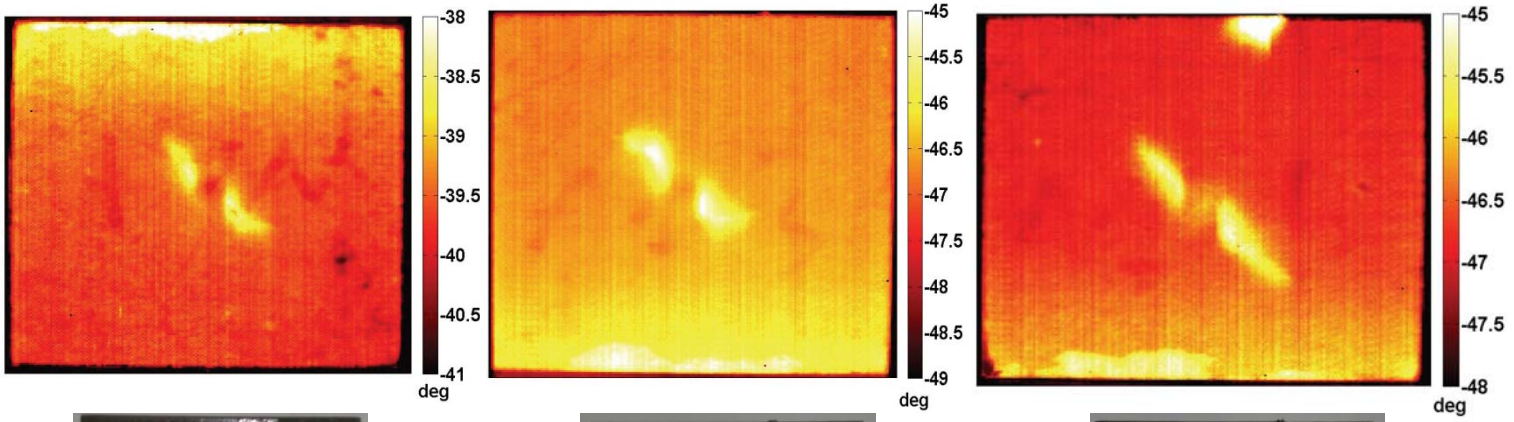


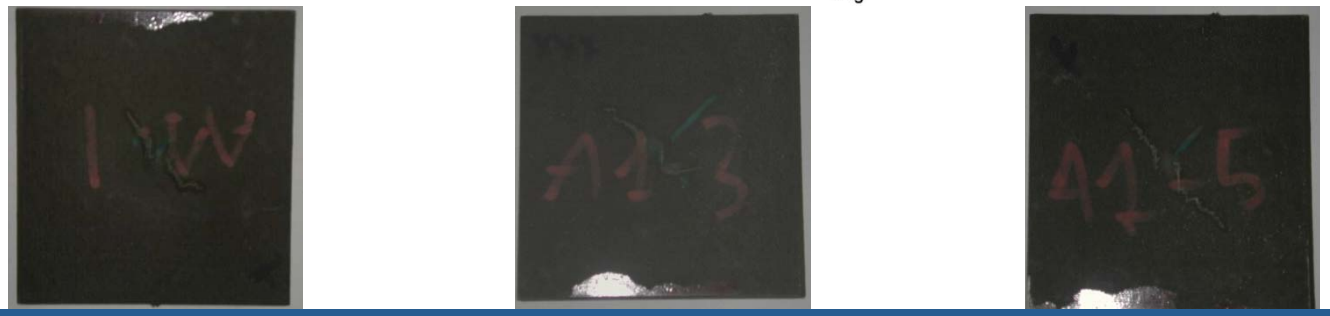




Termografia stimolata: Componenti CFRP

Tecnica Lock-in: valutazione di danni da impatto su componenti sandwich.





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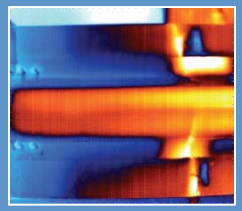
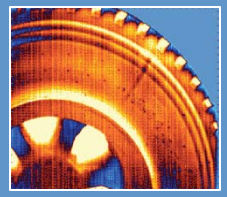
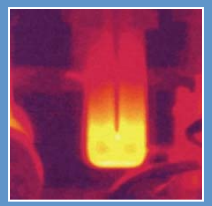
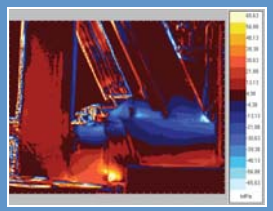


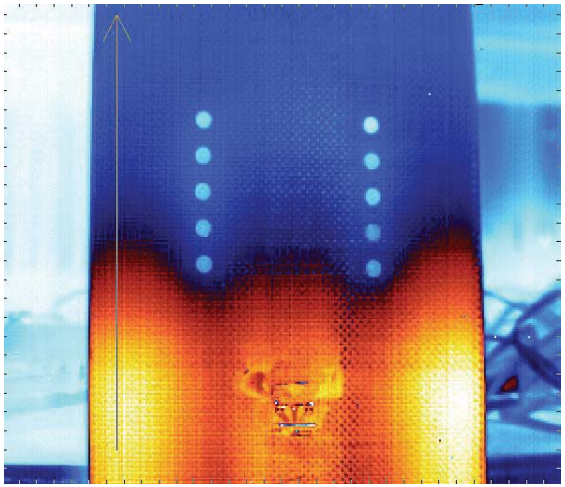


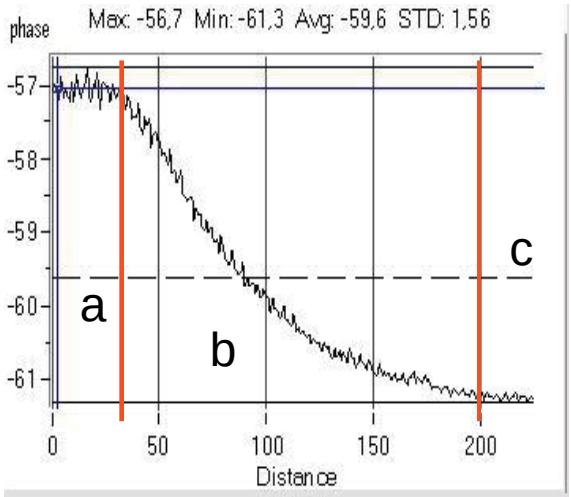


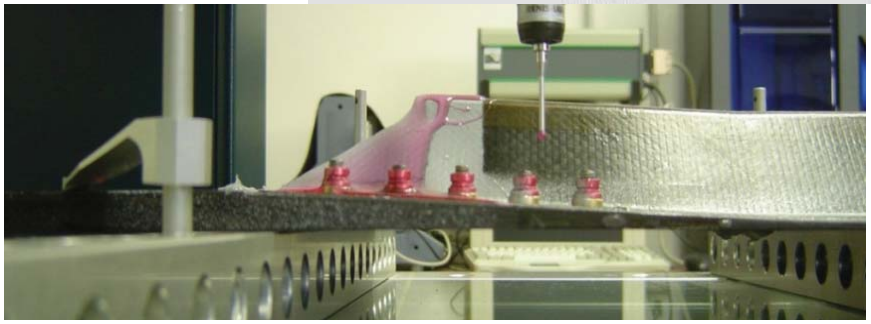


Altre applicazioni su CFRP

Termografia lock-in utilizzata per la misura degli spessori di materiali compositi.







a,c = aree a spessore costante;

b = area in cui lo spessore varia linearmente

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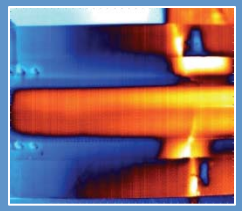
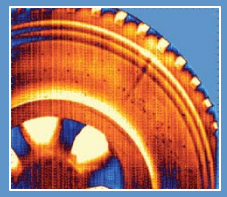
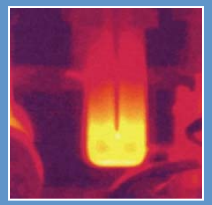
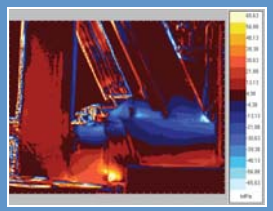




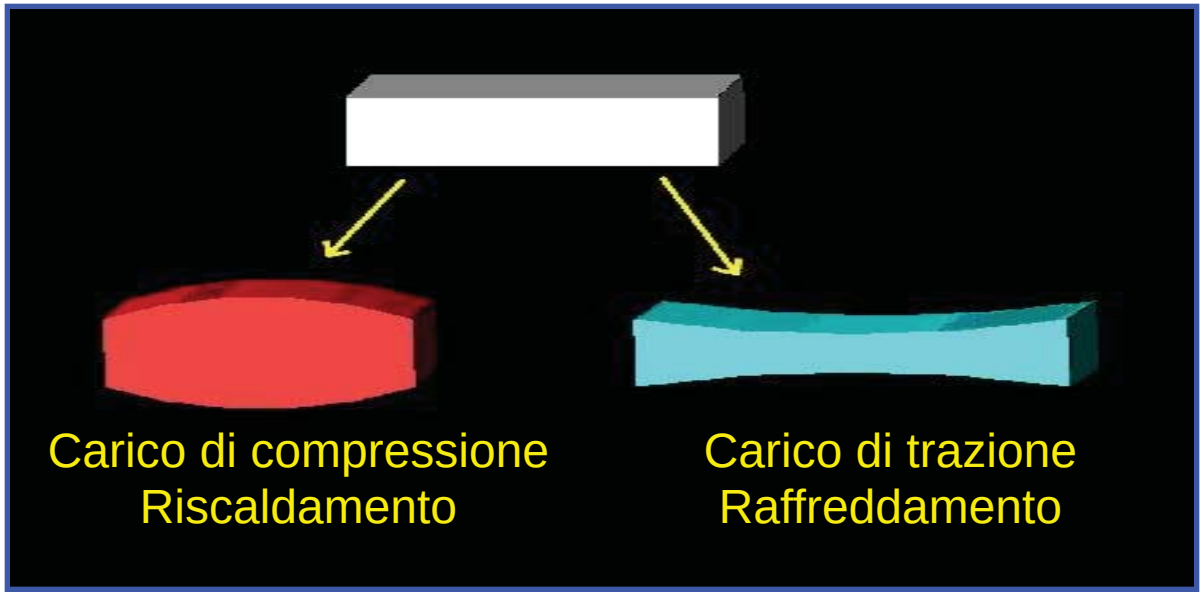




Analisi termoelastica delle sollecitazioni

I fluidi, così come i solidi, variano la propria temperatura se soggetti a una variazione di volume dovuta ad un carico applicato.

Tale fenomeno fisico è chiamato effetto termoelastico.



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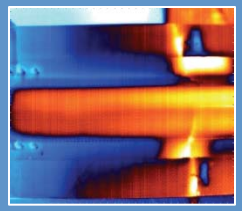

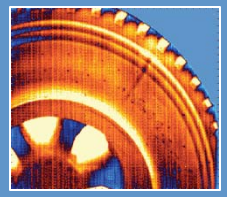

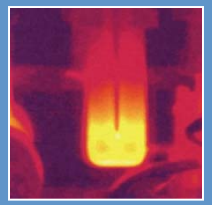

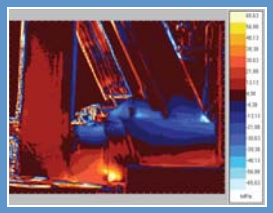

Analisi termoelastica delle sollecitazioni

Trascurando le variazioni del modulo di Young *E* e di Poisson *v* con la temperatura ed esprimendo il calore specifico a deformazione costante in termini di calore specifico a pressione costante si ottiene:

$$\Delta T = -\frac{\alpha}{\rho C_P} T(\Delta\sigma_1 + \Delta\sigma_2)$$

con K_0 costante termoelastica del materiale espressa come $K_0 = \alpha / \rho * C_P$ dove C_P è il calore specifico a pressione costante, α è il coefficiente di dilatazione termica lineare e ρ è la densità del materiale.

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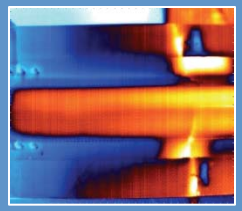
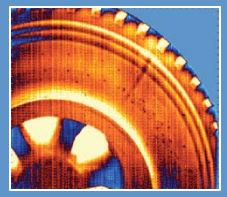
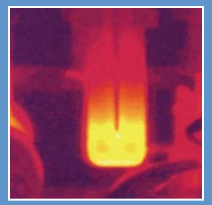
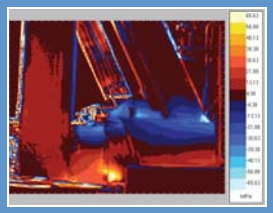


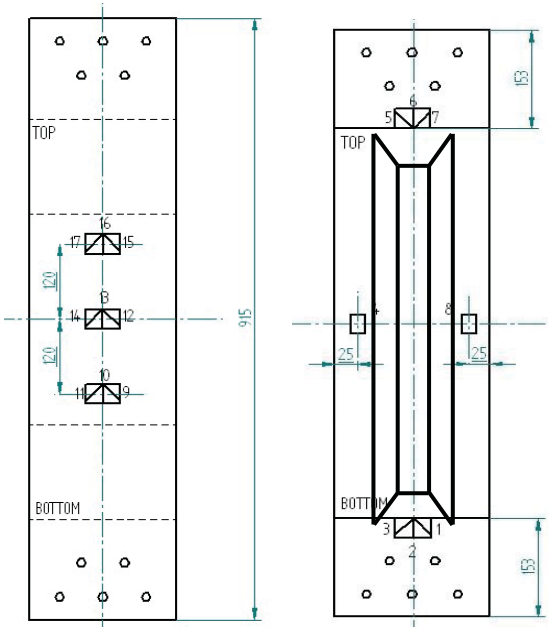






Analisi termoelastica delle sollecitazioni

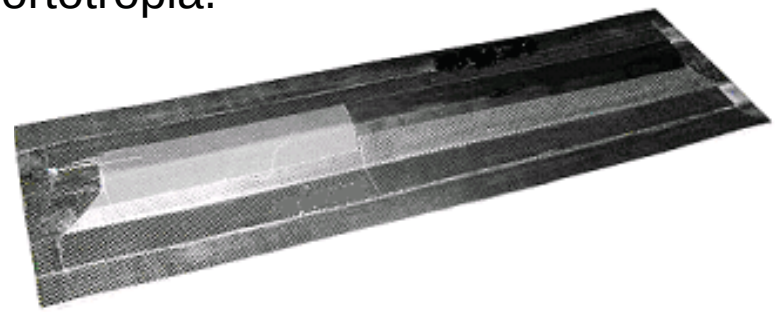
Analisi su materiali compositi: Applicazione su 2 Stringer aeronautici



Equazione termoelastica per materiali ortotropi

$$\Delta T = -\frac{T}{\rho C_p}\left(\alpha_1\sigma_1 + \alpha_2\sigma_2\right)$$

α_1 e α_2 coefficienti di dilatazione termica nelle 2 direzioni di ortotropia.



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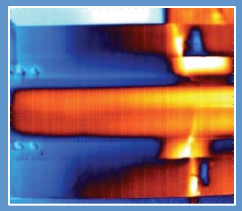
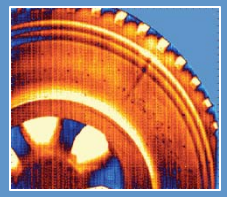
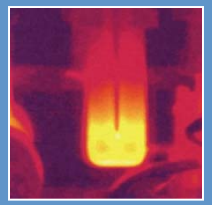
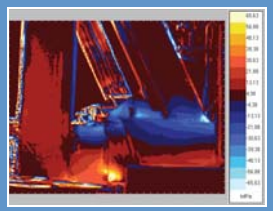








Analisi termoelastica delle sollecitazioni

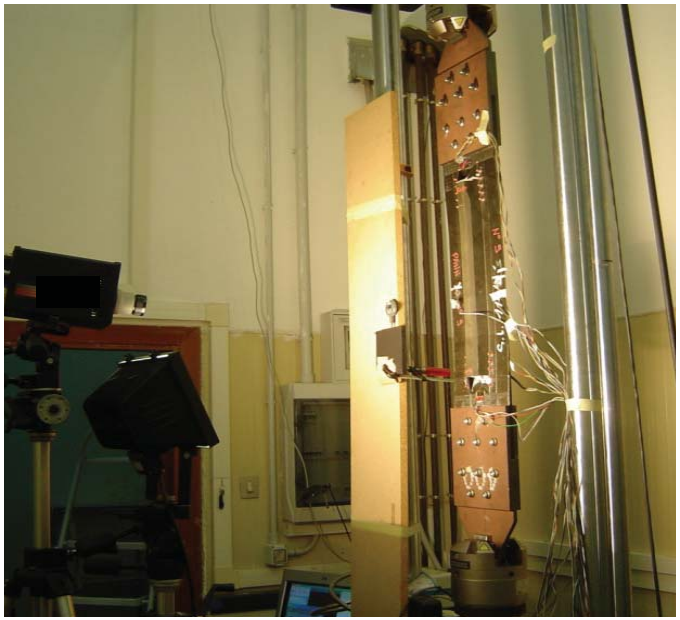
Analisi su materiali compositi: Applicazione su 2 Stringer aeronautici

Stringer testati con un carico dinamico sinusoidale ad ampiezza costante.

Contemporanea analisi durante la prova con tecnica TSA e tecnica Lock-in.

TSA eseguita durante le prove di fatica.

Termografia lock-in eseguita a macchina di carico ferma in intervalli regolari.



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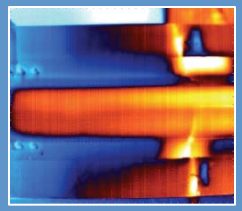
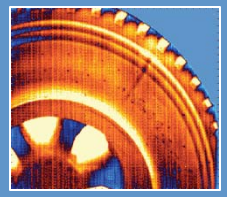
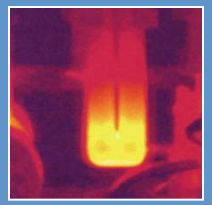
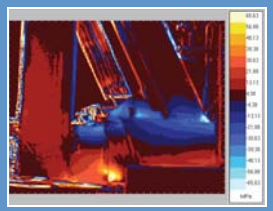
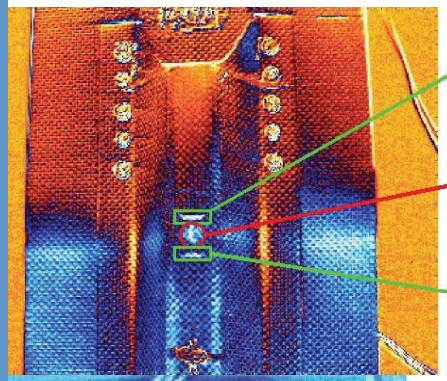



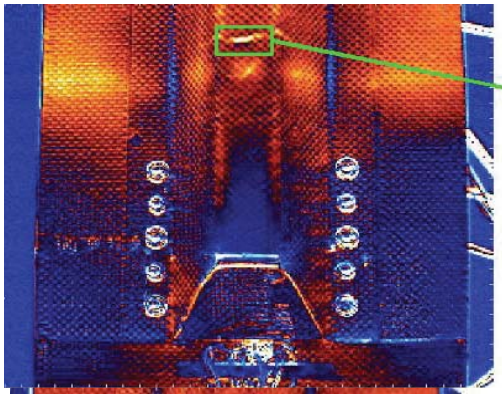



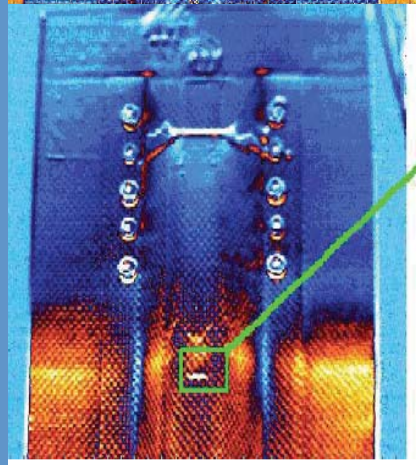
Analisi termoelastica delle sollecitazioni

Analisi su materiali compositi: Applicazione su 2 Stringer aeronautici

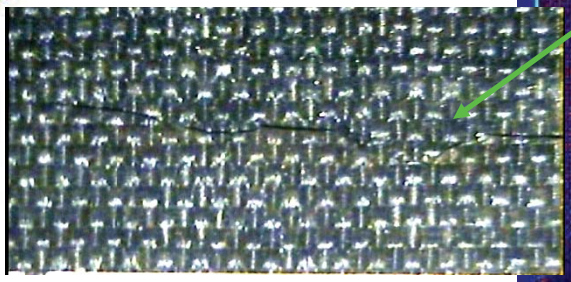


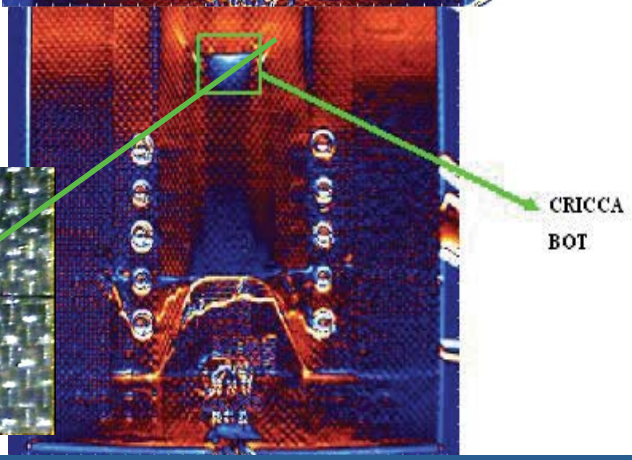
Stringer 7





Stringer 9





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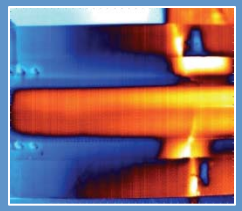
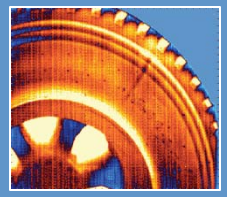
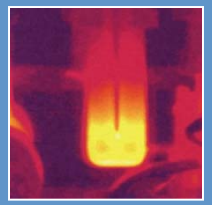
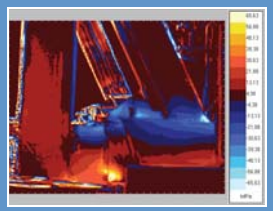




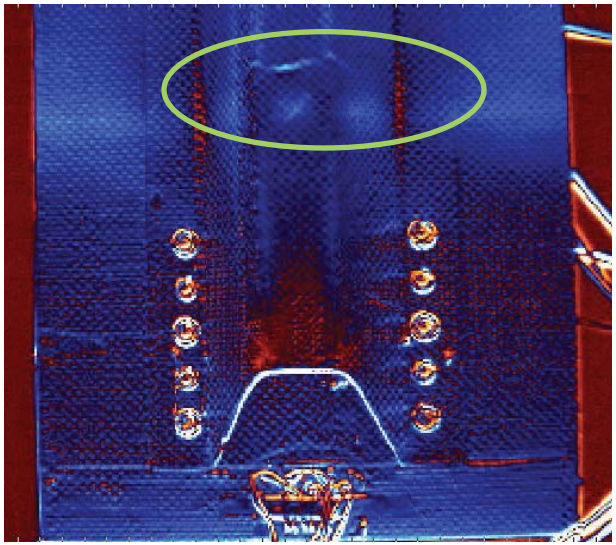




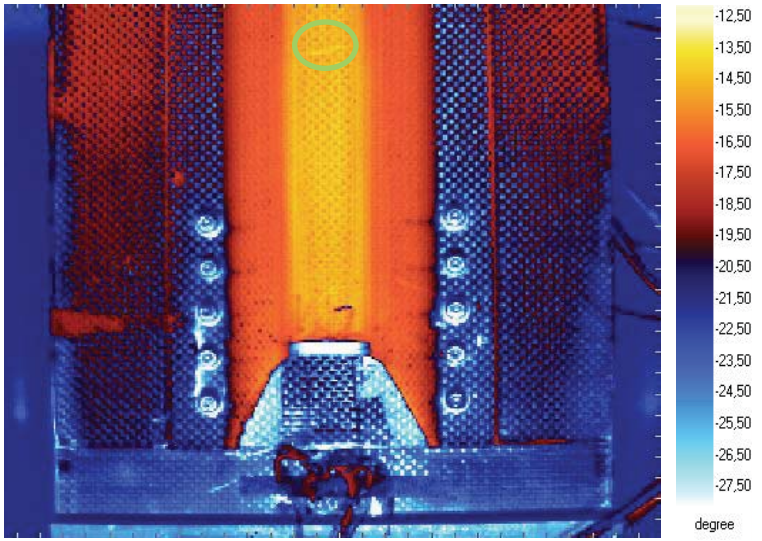
Analisi termoelastica delle sollecitazioni

Analisi su materiali compositi: Applicazione su 2 Stringer aeronautici

L'analisi termoelastica oltre a fornire una mappa qualitativa delle sollecitazioni, consente di individuare i difetti superficiali e subsuperficiali come le cricche.



TSA



Lock-in

Confronto tra TSA e termografia lock-in sullo Stringer 7 (cricca sul rinforzo)

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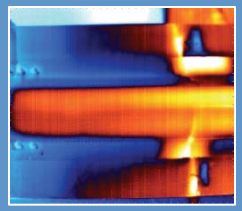
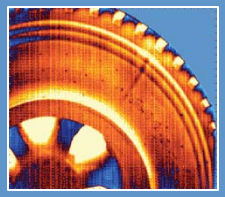
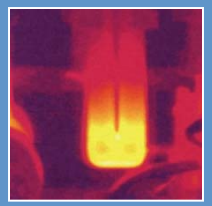
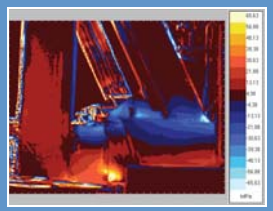
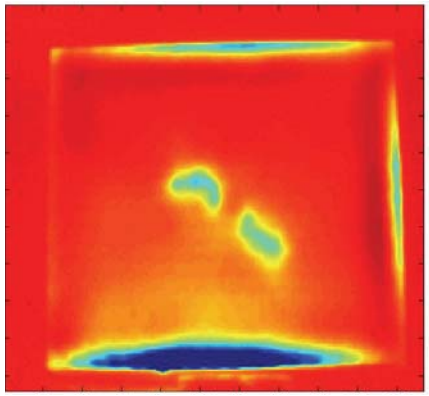
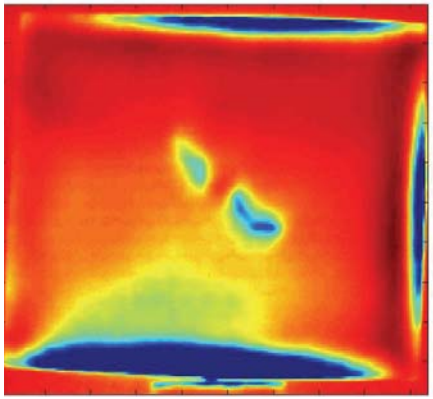
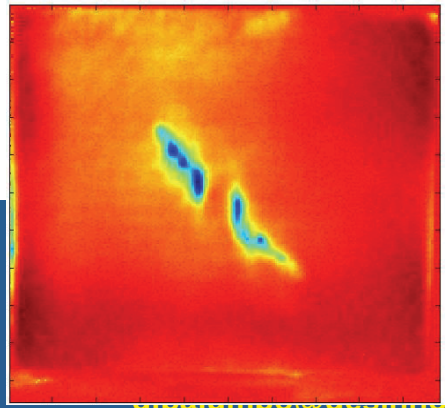
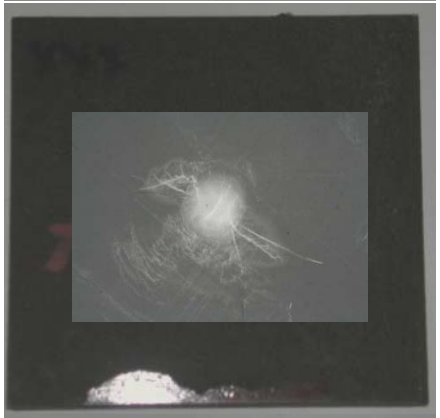
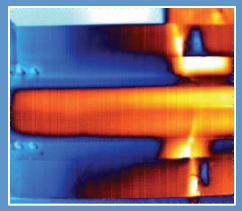



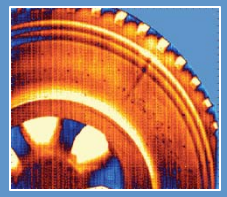



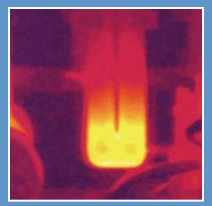




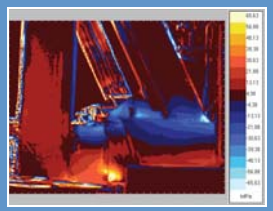


X-ray









Spin Off

Padiglione A

Fiera RAMSPEC

La Diagnostic Engineering Solutions srl (DES srl) nasce nel 2011 come spinoff del Politecnico di Bari con la mission di industrializzare e commercializzare i risultati di quasi vent'anni di attività del Laboratorio di Diagnostica Strutturale e Metodi Termici per la Meccanica Sperimentale del DMMM con oltre 2.2M€ di attività di ricerca nel corso degli ultimi 5 anni.

- Software
- Sistemi hardware per NDT
- Corsi NDT certificati
- Testing e procedure di prova
- Controllo ed ottimizzazione di processo

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