Single Crystal Technologies in Power Generation Equipment

M. Konter

Single crystal (SX) components enable significant increase in gas turbine inlet temperature, pressure ratio and reduce consumption of cooling air. SX parts in power generation equipment are not only significantly larger than those in the aircraft turbines, but also serve at different conditions, such as much longer time at maximum temperature. New manufacturing processes, such as LMC, GCC or constructed blading enable economical production of large SX blades and vanes. SX alloys design is optimized for manufacturability and long term structure stability. SX technologies today are not limited any more to the casting technique. Various processes with solidification rate from very slow (TLP brazing) to very high (laser cladding) are employed for different applications. Epitaxial brazing provides up to 80% of the base alloy life and allows repair of SX components and manufacturing of large constructed SX parts. Epitaxial laser cladding restores geometry of ex-service blades and vanes. Single crystal coatings have potential to significantly extend life of fatigue loaded parts. Here attention should be paid not only to control over the heat flux, but also over epitaxial nucleation in two-phase systems, such as gamma-beta.

Parole chiave: impieghi in temperatura, superleghe

WHY POWER GENERATION TURBINES NEED SINGLE CRYSTAL COMPONENTS

The main drivers in industrial gas turbine (IGT) design are fuel efficiency and reliability in operation. In the past material technology for power generation gas turbines has followed the aircraft technology, being 15 – 20 years behind /1/. During the last decade dramatic competition in the power equipment sector has boosted technology to the level achieved in the aviation turbines less than decade before (fig. 1, /2/). In modern IGT the gas turbine inlet temperature exceeds 1300°C, efficiency requirements limit the amount of compressor air available for cooling, and the life target for highly loaded front stages components is 25'000 - 50'000h at metal temperature above 900°C. To satisfy these requirements, latest IGT employ advanced cooling schemas, thermal barrier ceramic coatings and single crystal blades and vanes.
Single crystal (SX) components for industrial gas turbines are significantly larger and heavier compared to the aircraft parts. This certainly reflects in manufacturing yield and in component costs. Very high costs of IGT SX components gives a permanent character to the question, does our industry really need them. Each new turbine design needs a benchmark of SX against conventional and directionally solidified (DS) parts. Nevertheless, most of IGT producers are using SX components in front stages. Examples are GE H-frame, Siemens V84.3A and Alstom GT24/26 machines.
High costs of SX technology is a driver but not the single reason why, being fully established in aircraft industry, SX needs permanent benchmarking for IGT. One of important advantages of SX over conventional material is stability against so-called "thin wall" factor. At wall thickness below 1 mm conventionally cast material shows catastrophically high reduction in high temperature creep life due to through going grain boundaries and grain boundaries sliding. In large IGT components wall thickness is usually above 1.5 mm and maximum metal temperature is below the limit of grain boundary sliding.
The driving force to use SX technology in IGT is an excellent resistance of properly oriented single crystals to thermo-mechanical fatigue (TMF). In <001> direction E – modulus is one half of those for conventionally cast material, which reduces thermally–induced stress and extends TMF life in many times. The main advantage of SX over DS parts is an absence of grain boundaries in platform areas and better control over orientation. Since most of IGT blades and vanes are rather TMF than creep life limited, in many cases SX technology is the only way to achieve life target.
Application of SX parts must be supported by specific manufacturing, reconditioning and repair technologies, and by consideration of IGT – specific material requirements.

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SINGLE CRYSTAL ALLOYS

Single crystal IGT blading is cast Ni-based superalloys, often Re-containing. Re is not only very effective solid solution and γ/γ' interface strengthener, but it also extends stability of precipitation hardening γ' phase to higher temperatures. CMSX-4 /3/, MK-4/4/ and Rene' N5 /5/ are examples of such high strength high oxidation resistant aircraft type alloys used in power generation turbines. Other class of IGT SX materials are derivatives from traditional power generation alloys, such as IN-792SX, PWA 1483 and CMSX-11 /6/. These Re-free so-called "first generation" single crystal superalloys have lower temperature capability, but are significantly less expensive and demonstrate good phase stability during operation and a balance between oxidation and corrosion resistance.
The modern trend in IGT alloy development reflects the specific power generation requirements: IGT components serve at base load temperature much longer than those in aircraft engines, though the peak temperature is lower (fig.2). As a consequence, stability of alloy structure and properties in long term high temperature operation gains in importance compared to ultimately high strength at very high temperature, which was a dominant optimisation parameter in aerospace alloy design.

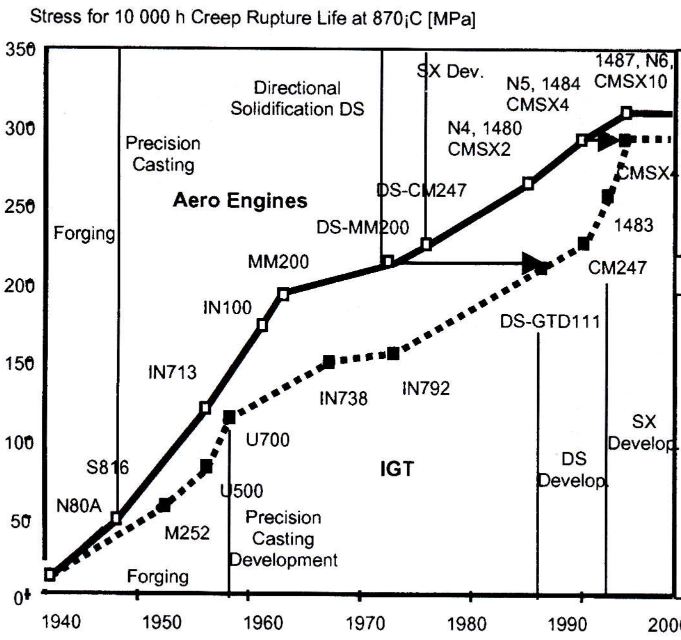

Fig. 1. Progress in aero- and IGT blade material.

Fig. 1. Progresso nei materiali per turbile aeree e IGT.

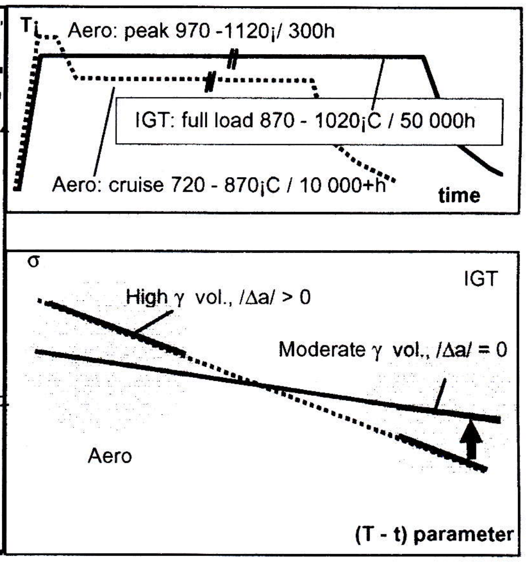

Fig. 2. Specific IGT service conditions and trends in blade alloy development.

fig. 2 Condizioni di servizio specifiche di IGT e tendenze nello sviluppo di leghe per turbine.

Extension of IGT blading material life over the level achieved today, requires alloys with very high level of γ and γ' solid solution strengthening but probably lower precipitate volume fraction and more stable γ-γ' structure (low lattice mismatch). Notably, γ/γ' lattice mismatch causes an additional strengthening, and this is often used in commercial superalloys. However, the lattice mismatch as well as very high γ' volume fraction promote formation of rafted structure /7/, especially detrimental when γ' becomes a continuos phase. Though the detrimental effect of rafting and γ/γ' inversion on creep properties is being disputed /5/, and several publications show no reduction in creep properties due to these types of degradation, ductility and TMF life deteriorate. For the other hand, cooled high temperature IGT components cast in alloys with relatively high Ti and low Al content, such as IN-792 derivatives suffer from internal oxidation and nitridation if not internally coated. Overall, oxidation resistance of IGT alloys plays a very important role and being promoted by clean processing, desulfurisation and addition of rear-earth elements /8/.
Next generation IGT blade alloys most probably will combine high oxidation and fatigue resistance of aircraft materials with significantly increased resistance to structure degradation. Alloys with higher resistance to rafting and γ/γ' inversion, namely those ones with moderate γ' volume fraction and low lattice mismatch, fit better to IGT requirements. Their temperature capability, oxidation and creep resistance has to be further improved compared with commercial alloys of "corrosion resistant" class, such as CMSX 11 and IN 792 SX.

RECONDITIONING OF SINGLE CRYSTALS

Service life of conventionally cast blades and vanes being usually extended by rejuvenation heat treatment after first 20' – 30'000 hours of operation. During this treatment the coarsened γ' is fully or partially dissolved and newly precipitated in a fine form. Sometimes this step is combined with a hot isostatic pressure treatment (HIP) to close voids and micro-cracks accumulated during the service. Single crystal components, which locally accumulate more than 1-2% strain, are sensitive to recrystallisation after solutioning of γ' phase, which leads to loss of properties. For the same reason it is impossible to HIP the SX parts.
The difficulty to find heat treatment which does not result in recrystallisation and from other hand transforms degraded ex-service γ' phase back to cubical morphology is described elsewhere / ../. Fortunately, rafted morphology of γ' phase is thermodynamically unstable in isothermal unloaded condition, and our experiments on ex-service blades have shown, that a combination of stress relief steps and an isothermal stage below γ' solvus temperature restores the cubical morphology, though coarser than in initial condition. Coarse cubic γ' structure possess creep and fatigue properties significantly higher then those of the inverse γ' matrix, but still lower than of material with initial structure. Virgin SX material properties, therefore, can be only partially restored with rejuvenation treatment. However, even the partial rejuvenation gives additionally more than 50% of an initial component life.

SINGLE CRYSTAL CASTING

Large IGT single crystal components cause very high manufacturing costs using traditional SX casting technology. Fig. 3a illustrates the current Bridgman process. The mould with molten metal moves gradually from the heating chamber to the cooling chamber separated by baffle. Heat is removed by radiation in vacuum from the mould towards water - cooled chamber walls. Good isolation between the cooling and the heating zones provided by the baffle results in vertical temperature gradient, which provides directional solidification of the component. When the temperature gradient in primary growth (vertical) direction is high enough, no grain defects occurs. This is usually a case when relatively small aircraft components are cast. For massive IGT

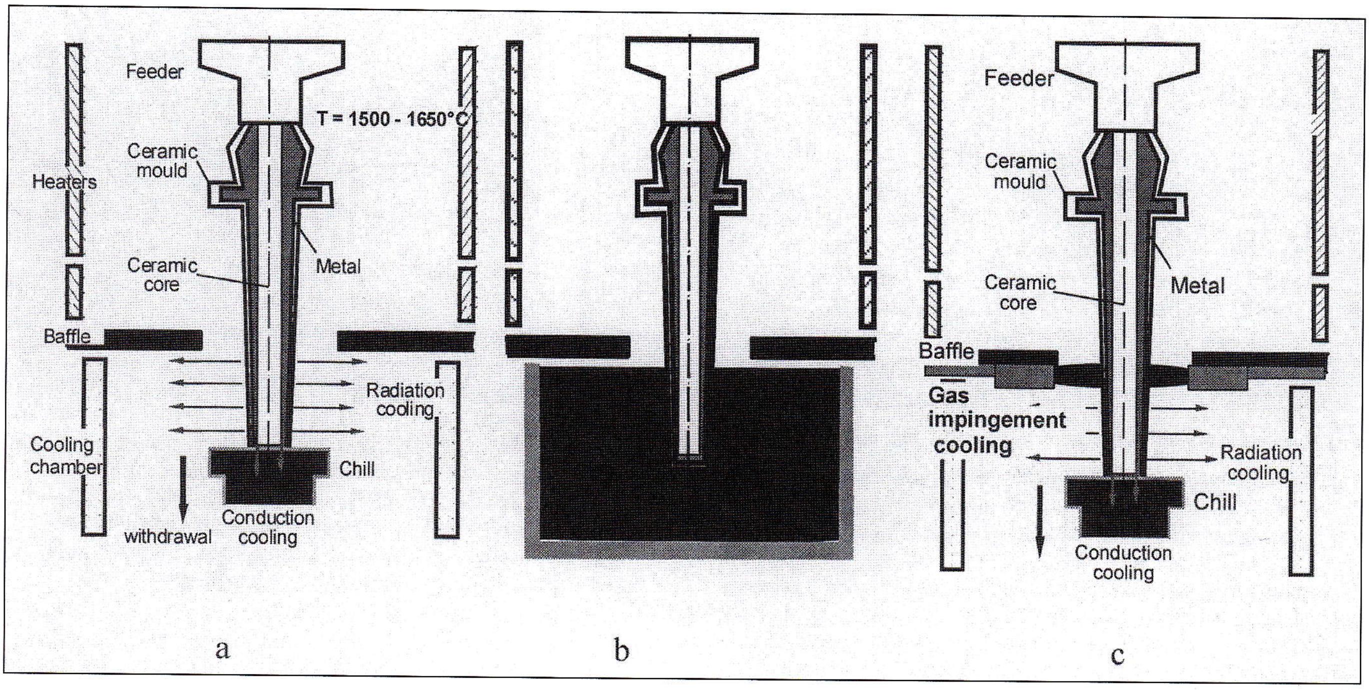

Fig. 3. Bridgman (a), Liquid Metal Cooling (b) and Gas Cooling (c) casting processes.

Fig. 3. Processi di colata Bridgman (a), con raffreddamento di metallo liquido (b) e raffreddamento a gas (c).

parts heat radiation in vacuum is on the limit of capability to extract significant amount of heat and therefore to provide sufficient temperature gradient. When the temperature gradient is low, too high as well as too low solidification rate result in various casting defects, such as freckles, columnar grains and porosity.

Several measures are being currently implemented to increase SX yield of large components. Computer simulation of solidification process is used both by vendors to optimise casting process parameters and by turbine producers as a part of design for manufacturing. Latest versions of computer codes allow prediction of casting stresses and formation of low angle grain boundaries.

More radical is development of single crystal casting techniques with high cooling rate, such as liquid metal cooling (LMC), fig. 3b /9/ and gas cooling casting (GCC) process, fig.3c /10/. In LMC process the mould is immersed in the bath with liquid tin or aluminium. Advantage of this process, besides higher temperature gradient, is the fact, that in the bath elements of the mold see no heat input from the adjoining parts, and therefore mold size (number of blades per mold) is limited only by mold strength and by size of equipment. Limits of the process are effectiveness and stability of the aluminium bath in Al process and shell cracking (tin poisoning of superalloy) in the tin process. In GCC process gas impingement cooling is provided below the baffle in addition to the "standard" cooling by radiation. The process is as effective as LMC, easy to control, but the cluster size is limited similarly to the conventional process by heat input from adjoining mold elements.

Another way to increase casting yield is alloy design for castability. The density balance between the liquid metal in the mushy zone and the bulk liquid metal above the liquidus line significantly reduce metal convection during solidification. This prevents formation of freckles and increases tolerance to the inclination of solidification front with respect to formation of secondary grains. Balance of elements such as Hf and C controls metal-mould reaction (wrinkles, surface scale etc.) and further reduce freckling / 11/. Addition of grain boundary active elements increases tolerance to the low angle grain boundaries misfit from 5 – 6° to 9 – 12° and above.

SINGLE CRYSTAL BRAZING FOR MANUFACTURING AND REPAIR

Problems with casting of large internally cooled SX components keep interest to alternative manufacturing technologies. One example is a concept of so-called "constructed blade", when parts of the blade are cast separately and than joint together. Already in seventies there were trials on diffusion welding of two SX blade halves with open cooling configuration. Drawbacks of this technology were absence of adequate non-destructive testing (NDT) technique and very high requirements to precision in parts geometry to fit together.

Today advanced NDT methods and application of transient liquid phase (TLP) brazing allows to produce at least prototypes of very heavy blades with complex cooling geometry. TLP brazing, giving more flexibility to joining process usually results in equiaxed or eutectic cellular structure. However, only SX structure of the braze zone, epitaxial to the base material can provide "as-cast" life of component. Even higher demand for epitaxial SX brazing comes from repair needs.

Epitaxial closure of cracks in base metal and re-build of blade tip area can extend service life of SX components (in combination with rejuvenation heat treatment and re-coating) by additional 80%.

Principles of directional solidification known from casting help to develop the epitaxial SX brazing process. Using constitutional undercooling equations /12/ temperature gradient and velocity of solidification front can be described in terms of concentration gradient and diffusivity of alloying elements. Diffusion modelling enables to define a composition of braze alloy, which at chosen temperature produces an epitaxial single crystal joint for commercial SX superalloys (fig.4).

Next important step after solidification is homogenisation heat treatment, which binds melting point depressants into stable, widely spread precipitates with fine morphology. Wrongly precipitated boron- and silicon-reach phases, for example with plate-like morphology, embrittle the material. Fine nano-size particles in a contrast do not reduce neither ductility nor strength of the base alloy.

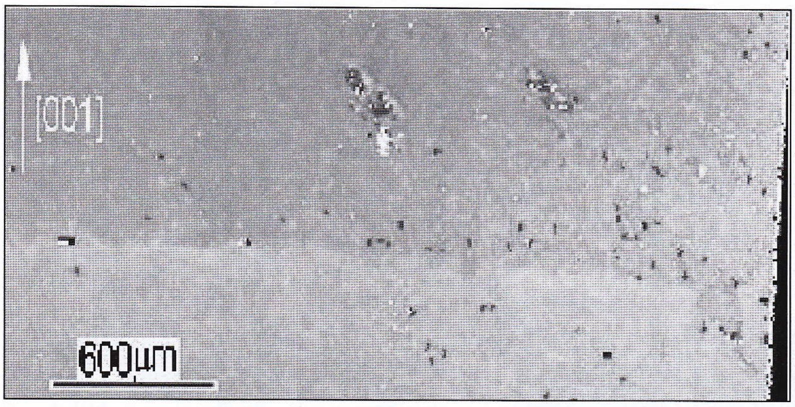

Fig. 4. Kikuchi crystal orientation map of SX brazed joint.

Fig. 4. Mappa orientativa del cristallo di Kikuchi di un giunto SX brasato.

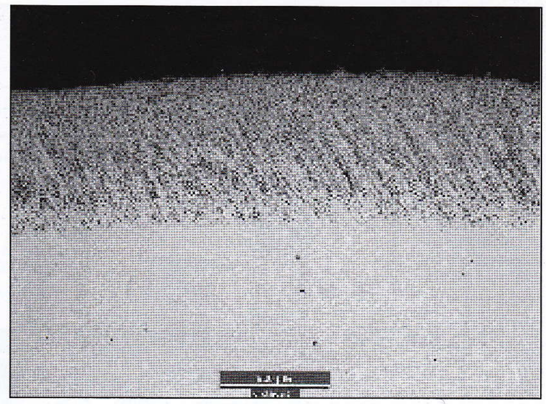

Fig. 5. Laser cladded SX coating.

Fig. 5. Rivestimento SX mediante placcaturea laser.

SINGLE CRYSTAL COATING

A great variety of coating compositions and technologies are used in industrial gas turbines. On first stages many IGT manufacturers use vacuum plasma sprayed (VPS/LPPS) MCrAlY coatings, often with air plasma sprayed (APS) thermal barrier coating (TBC) as a best compromise of temperature capability, life and costs. Other used systems are aluminide, i.e. PtAl protective coatings and electron beam physical vapour deposition (EB PVD) TBC. Recent advances in HVOF /13/ and PVD (cathodic arc, /14/) processes promise to give better quality at lower costs compared to plasma spray. The most typical coating failure mode in advanced gas turbines is thermal-mechanical fatigue. Improvement in metallic coatings therefore goes in direction better interface, lower porosity, controlled thickness, phase structure which combines high oxidation resistance with good ductility and toughness.

All the listed processes, however, are not able to produce coating comparable in TMF life with the SX substrate, which possess twice as low elastic modulus compared to the conventional equiaxed grain structure of fine grain coatings. Single crystal coating /15/ just by nature of directional solidification has very low porosity and, being epitaxial to the base metal, almost an ideal interface. Absence of grain boundaries significantly reduces diffusion of oxygen and sulphur inside the coating layer.

Single crystal epitaxial coating in principle can be grown using vapour deposition technique, the process applied in electronic industry. This method however is too slow for thickness needed in IGT applications (up to 0.4 mm). Laser cladding technique /16/ provides capability comparable to those of VPS process. Laser cladding process has very high solidification rate and produces fine dendritic structures, epitaxial to the substrate (fig.5). During and after solidification clad has high level of thermal stresses, and right stress relief heat process is important. Not less important is alloy selection, as due to mentioned solidification stresses, process is susceptible to hot tearing (solidification cracking). Coatings with properly selected chemistry provide, however, defect free layer even at high process velocity.

SUMMARY

Application of single crystal components in power generation turbines requires specific solutions not only with respect to base alloys and casting process, but also in rejuvenation, repair, joining and coating methods. The full spectrum of SX technologies is developed for lifetime support of single crystal components. Single crystal techniques described in the paper vary from epitaxial TLP brazing process with very slow solidification rate through high gradient casting technologies such as GCC and LMC to rapid solidification laser cladding of epitaxial coatings.

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ABSTRACT

TECNOLOGIE DI PRODUZIONE DI MONOCRRISTALLI DESTINATI A IMPIANTI PER LA PRODUZIONE DI ENERGIA

I componenti costituiti da un monocristallo (SX) permettono nelle turbine a gas un significativo aumento della temperatura d'ingresso e del rapporto di pressione oltre ad una riduzione del consumo di aria di raffreddamento. Negli impianti per la produzione di energia questi componenti monocristallini non devono avere solamente dimensioni significativamente maggiori rispetto a quelle degli analoghi componenti per impieghi aereonautici, ma devono essere anche in grado di operare in condizioni di servizio molto diverse, come ad esempio maggiori tempi di esercizio alle massime temperature.

I nuovi processi di produzione, quali LMC (Liquid Metal Cooling), il GCC (Gas Cooling Casting) o "constructed blading" permettono di produrre in modo economico pale e ugelli per grandi turbine in SX. La progettazione di componenti in leghe atte a costituire monocristalli viene ottimizzata in termini di fabbricabilità e di stabilità a lungo termine della struttura.

Oggi, per la produzione di monocristalli non si è più limitati dalle tecniche di colata, vengono utilizzati vari processi che consentono velocità di solidificazione che vanno da quella molto lenta della brasatura TLP a quella molto elevata della placcatura laser scelte di volta in volta in funzione delle diverse applicazioni. La brasatura epitassiale aumenta fino all' 80% la vita in esercizio della lega e permette di produrre e di riparare componenti SX anche di grandi dimensioni.

Il rivestimento epitassiale mediante laser ristabilisce anche la geometria di palette e ugelli dopo servizio. I rivestimenti monocristalli hanno la potenzialità di prolungare significativamente la vita di parti sottoposte a fatica sulla quale vita influiscono non solo parametri termici (flusso termico, gradienti di temperatura) ma anche parametri metallurgici, essenzialemnte legati alla nucleazione epitassiale dei sistemi bifase, quali i gammα-beta.

L'applicazione di componenti monocristalli nelle turbine per la produzione di energia richiede dunque soluzioni specifiche non soltanto con riferimento alle leghe basse ed al processo di fusione, ma anche nei metodi di recupero, riparazione, giunzione e rivestimento. La gamma completa di tecnologie SX permette la gestione di tutta la durata in vita dei componenti monocristalli. Le tecniche SX descritte nella presente memoria vanno dal processo di brasatura epitassiale TLP a solidificazione molto lenta alle tecnologie di colata ad alto gradiente quali GCC e LMC e alla placcatura rapida solidificazione a mezzo laser di rivestimenti epitassiali.