Benefits from using high thermal conductivity tool steels in the hot forming of steels

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Hot stamping is a fairly novel technology where tool steels play a capital role, they strongly influence the properties of the obtained component, the die has a strong contribution to investment and maintenance costs and above all, the influence on produced component cost is unusually high. This is so because productivity is a capital cost factor in this technology, and tool material together with cooling strategy has a great effect on attainable cycle time. In stationary regime, the heat has to be transported from the produced piece to the cooling fluid as fast as possible. Here the cooling strategy and even more the tool material thermal conductivity are the determinant factors, taking for granted that the sheet-tool contact and the cooling fluid turbulence are sufficient. Moreover the thermal conductivity of the tool material influences the aggressiveness of the cooling strategy that can be employed, since it's one of the main determining factors in the thermal shock resistance. The tribological behaviour of the tools is strongly dependant on the sheet coating employed. AAAIn this work the requirements on press hardening dies have been precisely determined through simulation and experimentation. Then several hot work tool steels have been developed with extreme thermal conductivity and with the wear resistance adapted to every specific sheet coating. In the evaluation of these tool steels it has been seen that the predicted tool material requirements were indeed the necessary ones.

KEYWORDS: hot stamping, press hardening, hot forming, closed die forging, die casting, thermal conductivity, hot work tool steel, productivity, cycle time, thermal fatigue

INTRODUCTION

Light construction while maintaining or improving response under extremely high dynamic loads is continuously gaining relevance in the transport industry due to stricter regulations and consumer environmental and security awareness. Under these premises the so called AHSS and UHSS , which present greatly increased mechanical resistance often with a loss of toughness and malleability lower than expected, have seen a rapid raise in their implementation. Precisely the increased strength that make this new generation of sheet steels so interesting, are also one of the greater drawbacks hampering their broader application, the main reasons being spring-back and tooling costs. One way to circumvent the problematic of spring-back and extreme die wear inherent to the forming of materials presenting simultaneously high yield strength and elastic modulus was devised in Sweden some thirty years ago: high resistance steels could be formed in the austenitic state and then die quenched to attain the desired properties, provided they had sufficient hardenability. The so called "Press hardening" or "Hot Forming" could be considered the maximum limit of light construction with steel in the automobile industry since mechanical strengths in excess of 1400 MPa are normally achieved in fairly complex geometries. In Fig. 1 a typical production line, the cooled dies and some pieces coming out of the furnace can be observed. As can be presumed, investment costs are quite high for this technology and thus the attainable productivity has a big influence on the production cost.

Determining the optimal tool steel for a given application implies a very deep knowledge of the requirements set upon the tooling. This knowledge is commonly gathered through phenomenological modelling, simulation, laboratory experimentation, and subsequently experience gathered in field applications. The knowledge obtained on the most relevant failure mechanisms in real field dies is definitely the most conclusive and relevant to further optimize the tooling solutions employed but also the less available when facing a new application.

The introduction of press hardened martensitic steel components has brought along some new challenges for the tool steels employed both in the hot forming operation and cutting in the already hardened state. In this work some new tool steels that have been developed to optimize the tooling for hot forming are presented. When developing the tool steels, the complete tooling solution was considered as a whole. Under tooling solution was considered: the tool steel, the die construction (including die design), the coating on the die, the process parameters (die usage), and the reparability of the tool (die maintenance).

As is often the case, the driving force to determine the optimum property combination of the developed tool materials, was the minimization of the produced pieces' cost. As has been mentioned, "Press hardening" is an investment intensive technology, and the required tooling is quite complex (necessary cooling, complex adjusting....).Therefore attainable productivity, die durability, cost of die maintenance and die costs were the observed variables.

In Hot Forming, the attainable productivity is mainly associated with the time required to extract the heat from the sheets after forming. In Fig.2, it can be observed the heat extraction path, from the sheet to the cooling water circulating within the dies. Being a

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FIG. 1
Hot Stamping line, dies, and pieces coming out of the furnace (indirect process) at VOLKSWAGEN AG Kassel's plant.
Linea di stampaggio a caldo, stampi e pezzi in uscita dal forno (processo indiretto) presso lo stabilimento VOLKSWAGEN AG di Kassel.

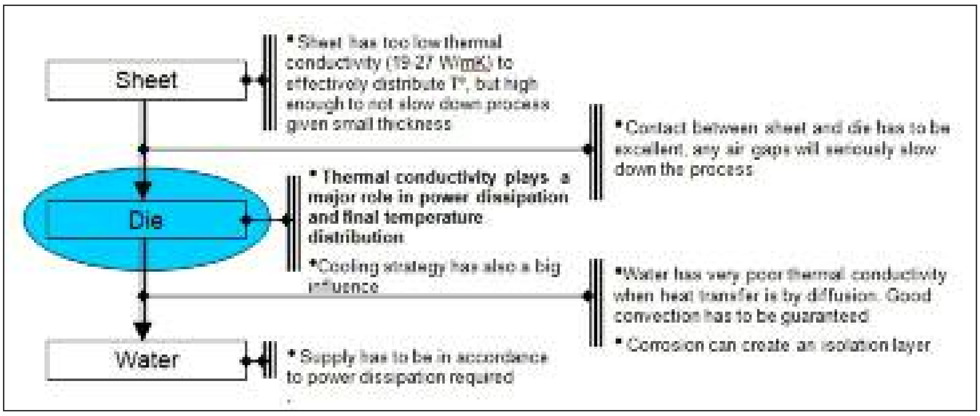

Fig. 2: xxx

serial transference process, the slowest link determines the speed. So when the contact between sheet and die is good enough and the water flow sufficient and turbulent enough, then the heat extraction rate is determined by the thermal conductivity of the die in the stationary regime (in the transitory regime the heat capacity plays a very important role also). From the heat conductivity values of the most commonly employed sheet [1], and given that sheet thickness is normally small, no significant heat transport through sheet cross-section can be expected, so the heat of every sheet unitary volume element has to be extracted through its surface (the interface with the die). From the heat transfer coefficient between sheet and die in the whole process temperature range [2] it can be concluded that heat transport at the interface does not necessarily need to be the slowest step on the heat extraction chain, as is the case in other hot forming processes like aluminium die casting [3]. From the heat transfer coefficient dependence on contact pressure [2,4] it becomes clear that a lack of proper contact between die and piece will lead to a much poorer heat extraction rate on that zone, which combined with the poor heat transport in the sheet cross-section already commented, will imply the formation of a "Hot Spot" where the mechanical properties of the component might not be the ones desired. The excellent contact between piece and die will even become more important if holding times are reduced. To improve heat transfer through the tooling two things can be done: improve thermal conductivity of the tooling solution (increase thermal conductivity of tool material and avoid the formation of thermal barriers: improper coatings, formation of corrosion layers ....) and optimize the cooling strategy. A greater thermal conductivity of the die material has some side effects that indirectly allow further increase in productivity. The most representative of these side effects is the directly proportional decrease of the thermal loading on the cooling channels, which allows them to approach the working surface without increasing the risk of thermal shock cracks (see Fig. 3). This, together with the fact that a higher thermal conductivity implies also a higher cooling down of the die during the open die time, and thus a lower die temperature when

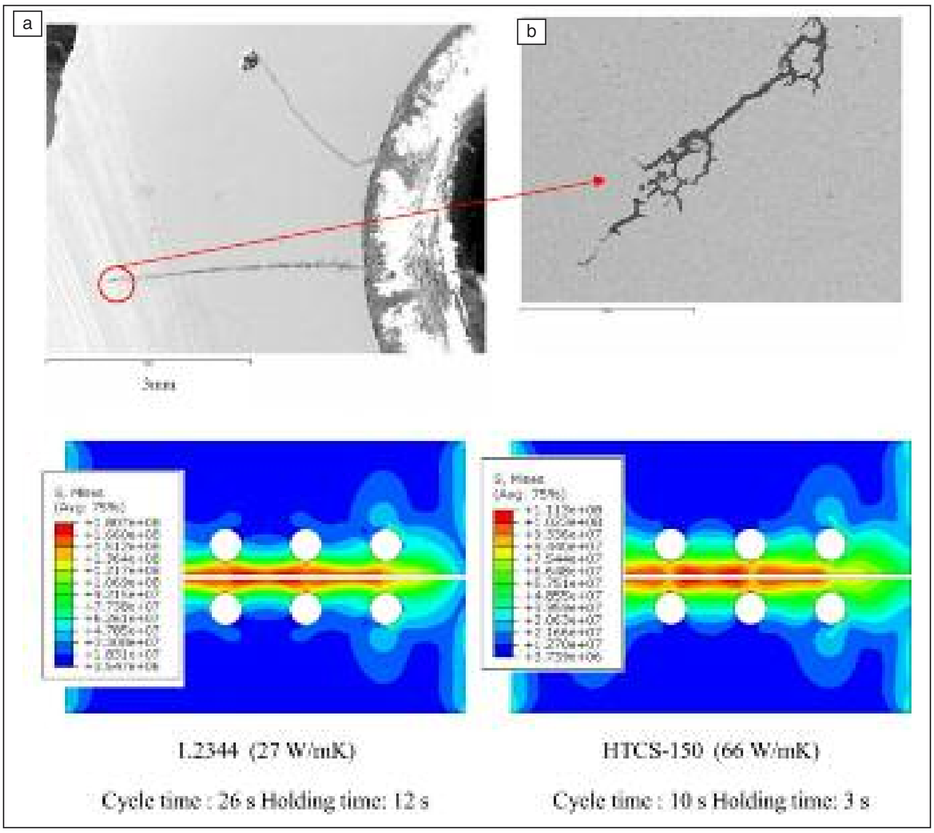

FIG. 3
a) Water corrosion building an oxide isolation layer on the cooling channels and promoting stress corrosion cracking. b) Effect of the tool material thermal conductivity on the thermal loading of the die (12mm holes placed 5mm from the surface).

a) Corrosione in acqua che provoca uno strato di isolamento da ossido nei canali di raffreddamento e promuove processi di stress corrosion. b) Effetto della conducibilità termica del materiale da utensile sul carico termico dello stampo (fori da 12mm a 5mm dalla superficie).

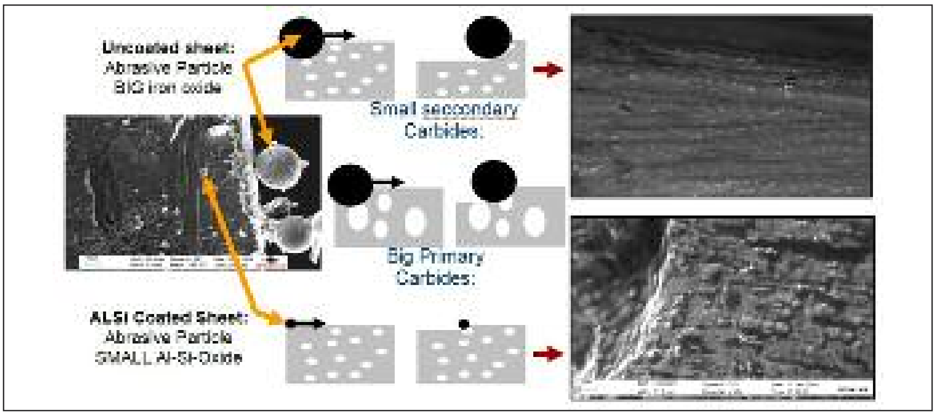

FIG. 4
Effect of the relative size between abrasive particles and abrasion resistance particles in the tooling material.

Effetto della dimensione relative fra le particelle abrasive e le particelle resistenti all'abrasione nel materiale da utensile.

the new sheet comes in, are mainly responsible for the fact that doubling thermal conductivity allows for more than a threefold productivity increase.
Besides cracking running from cooling channels to die surface due to thermo-mechanical loading, often accompanied by an improper corrosion protection on the cooling fluid leading to stress corrosion cracking, the main failure mechanism for Press Hardening dies is wear. The wear nature is strongly dependant on the type of sheet being used, with special mention to its coating. This is also the case for one of the main causes of die maintenance, namely sheet or sheet coating sticking on the die surface. Four kinds of sheet coatings were considered when developing the new tool materials: no coating (uncoated sheets), Al-Si inorganic coatings, Zn-Fe inorganic coatings and sol-gel process inorganic-organic coatings.
When hot forming uncoated sheet, and unless major precautions are taken in the furnace atmosphere and transportation from furnace to press, scale will form on the surface of the sheet. This scale is mainly composed by iron oxide particles which are not extremely hard but are often large in size. As can be seen in Figure 4, when the oxides on the sheet are large, the tool material has to have large ceramic particles embedded to withstand the abrasive action of those oxides. In the case of tool steels the ceramic particles of large size most commonly used are primary carbides. Also hardness of the tool material at the surface will have a big influence. The presence of big iron oxides will lead to a fast deterioration of the surface condition in the corner areas of the die where normal pressure is high and there is significant relative movement between sheet and die, unless pertinent measures are taken when designing the tooling solution.
The usage of coated sheet normally decreases the abrasive wear load but sheet coating adhesion on the die might strongly affect the maintenance costs. It is not uncommon to have to remove the coating adhesion on the die every couple thousand strokes, and the adhered material is not easy to detach from the die surface. The adhesion propensity depends on various factors including pro-

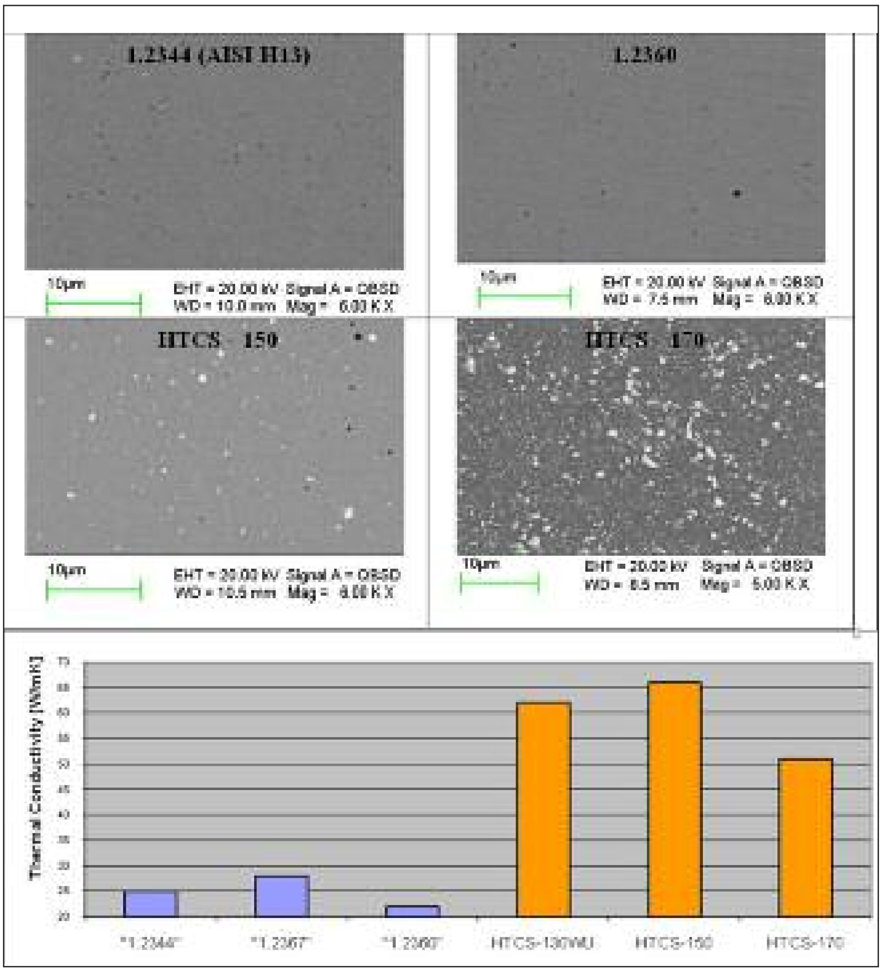

FIG. 5
Microstructure and thermal conductivity of some tool steels used for hot stamping dies.
Microstruttura e conducibilità termica di alcuni acciai da utensile utilizzati negli stampi per stampaggio a caldo.

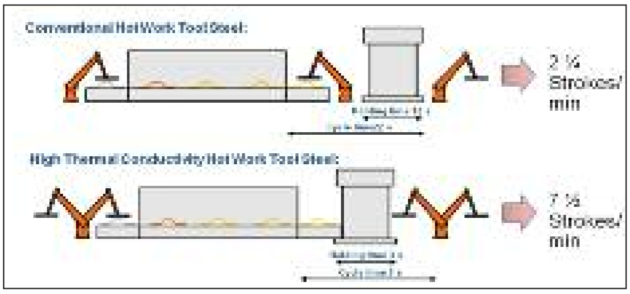

FIG. 6 ***Comparison of the productivity attainable with a conventional and a high thermal conductivity tool material in Hot Stamping.***
Confronto in termini di produttività ottenibile tra un materiale da utensile convenzionale e uno ad alta conducibilità termica nello stampaggio a caldo.

cess parameters (sheet coating temperature/time exposure, sheet-tool relative displacement,...) and tooling condition (surface finish, coating, surface temperature,...). The inorganic coatings usually alloy during the heating of the sheet to be formed. This diffusion process to attain the desired coating composition in the sheet surface is time and temperature dependent, and the process windows are usually small. Intentional or accidental under-exposure (incomplete diffusion) leads to an especially adhesive sheet coating. On the other hand over-exposure to process temperature or excessive temperature can easily lead to formation of iron oxides on the surface and thus causing the failure mechanism described in the last paragraph (big iron oxide abrasion). It should not be forgotten that most coatings are applied through a hot dip process, thus very homogeneous thickness distributions are difficult to attain, and thus over and under exposure zones are often found in areas with respectively smaller and larger sheet coating thickness. In the case of Al-Si coating the formation of corundum, like oxides leads to a very aggressive abrasive loading, but those oxides are usually small as can be seen in Fig. 4 and thus can be dealt with using smaller abrasion resistant particles in the tool material side.
The so called inorganic-organic coatings, are the most forgiving for the tool steel. In figure 5 it can be seen why several different types of high thermal conductivity tool steels had to be developed for hot stamping, depending on the tribological loading on the tool material mainly determined by the sheet's coating nature.
The main advantage of having improved thermal conductivity in the tool material as has been extensively seen is the increase in attainable productivity. Time can be reduced also in the open die period, since the temperature decay is also faster in this phase. In fig. 6 it can be seen that with more than double thermal conductivity productivity can be almost tripled.
Altering the cooling rate can also have an influence on the component properties. In several applications a faster cooling leads to finer microstructures and increased mechanical properties. In Hot Forming of 22MnB5, when high mechanical properties are desired, a critical speed has to be attained leading to a fully martensitic microstructure. In figure 7 it can be seen that for undeformed areas this critical speed is around 27 ºC/s which can be attained with a conventional tool steel for thin enough sheets. It is also well known that excessive cooling, leads to decreased ductility [4], and poorer

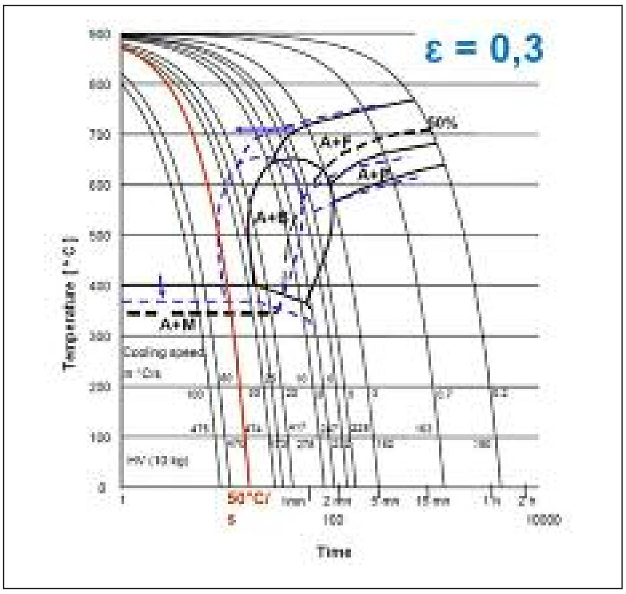

FIG. 7 ***TTT Diagram for 22MnB5 for different strain levels (graph provided by ARCELOR).***

Diagramma TTT per un acciaio 22MnB5 per diversi livelli di deformazione (grafico ARCELOR).

crash performance. This lack of ductility, together with dimensional accuracy, is the main reason for direct water cooling not being applicable for automobile applications. In figure 7 it can be seen that in strained areas, the deformation energy tends to accelerate the transformation kinetics, and thus a higher critical cooling rate is required to attain a fully martensitic microstructure (50ºC/s for a 0,3 strain). To precisely determine the effect of the high thermal conductivity on the properties of the component, an experimental tool was constructed and fully instrumented, thermal cameras where also employed, and then the mechanical properties of the components in different zones were measured. In Figure 8 the experimental set-up and some results obtained can be observed.
Tailored components are very helpful to further increase the crash performance, while maintaining weight. Having different properties in different parts of some structural components is also interesting for facilitating subsequent operations like trimming. Hot Forming provides one further way to attain such a goal by producing microstructurally tailored components from one originally homogeneous blank. One way to do so is through differential cooling as can be seen in the TTT-Diagram in Fig.7. The most energetically efficient way to attain this differential cooling is through the construction of a die with different thermal conductivities in different areas (see Fig. 9). The innovation presented here allows the thermal conductivity range of the hot work tool steels to be broadened from roughly 20-30 W/mK to 5-66 W/mK –Fig. 9-. With the NA-

$T_{extraction}$ °C	$R_{p0.2}$ MPa	R_m MPa	A_{80} %
Tool Steel: 1.2344; Cycle time: 26 s; Holding time: 12 s.			
75	1130	1477	5,1
127	1086	1496	5,4
170	1121	1475	6,0
178	1097	1485	5,6
Tool steel: HTCS-150; Cycle time: 10 s; Holding time: 3 s.			
77	1145	1529	4,8
128	1090	1450	5,2
152	1071	1455	6,6
153	1130	1477	6,1

FIG. 8 ***Experimental set-up, components obtained and properties in a flat area of the component for a conventional and a high thermal conductivity hot work tool steels.***

Impianto sperimentale, componenti ottenuti e proprietà relative ad un'area piana del componente per un acciaio da utensile convenzionale e un acciaio ad alta conducibilità termica.

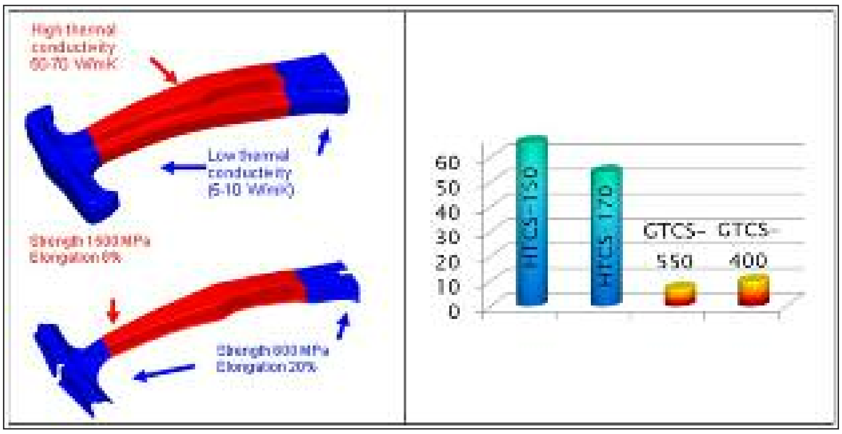

FIG. 9
Tailored components obtained with a tailored thermal conductivity die are possible with the thermal conductivities of the tool materials shown.
È possibile ottenere componenti ottimizzati con la conducibilità termica opportuna dei materiali dello stampo riportata in figura.

NOCASTING® technology any discrete or continuous thermal conductivity variation within this range can be attained within a continuous solid pre-form. Given the low thermal conductivity of the sheet itself, the same procedure can be applied for a very localized property tailoring, this can be used for example to reduce the hardness of the areas to be trimmed after hot forming.
Despite the great improvement achieved with the High Thermal conductivity tool steels in "Press Hardening", mainly due to the remarkable productivity increase attainable, and wear resistance optimization, there are other applications where the production costs can be further reduced with this new hot work tool steel family. This is so, because a high thermal conductivity brings about a greatly improved resistance against thermal fatigue (doubling thermal conductivity can bring an order of magnitude increase in thermal fatigue resistance for many applications). "Hot Forming" dies do not usually present thermal fatigue despite the high sheet temperature when contacting the tools (over 800 ºC) due to the low sheet thicknesses involved (and therefore the limited heat source). Some closed die forging, some extrusion, hot rolling and specially casting applications do benefit from a greatly improved resistance against thermal fatigue.

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Vantaggi dell'utilizzo di acciai da utensile ad elevata conducibilità termica nella formatura a caldo degli acciai

Parole chiave: acciaio – formatura a caldo

Lo stampaggio a caldo è una tecnologia relativamente nuova in cui gli acciai per utensili svolgono un ruolo di essenziale, in quanto influiscono fortemente sulle proprietà del componente ottenuto, lo stampo ha un forte impatto sui costi di investimento e di manutenzione e, soprattutto, l'incidenza sul costo del componente prodotto è insolitamente elevata. Questo perché in questa tecnologia la produttività rappresenta un fattore di costo essenziale, e il materiale usato per l'attrezzatura, insieme alla strategia di raffreddamento, ha un notevole effetto sul tempo del ciclo ottenibile. In regime stazionario, il calore deve essere trasferito dal pezzo prodotto al liquido di raffreddamento il più velocemente possibile. Così la strategia di raffreddamento e ancora di più la conducibilità termica del materiale costituente l' utensile sono i fattori determinanti, dando per scontato che il contatto lamiera-utensile e la turbolenza del liquido di raffreddamento siano sufficienti. Inoltre, la conducibilità termica del materiale dell' utensile influenza l' efficacia della strategia di raffreddamento che può essere utilizzata, poiché rappresenta uno dei fattori principali che determinano la resistenza a shock termico. Il comportamento tribologico degli utensili è fortemente dipendente dal rivestimento applicato sulla lamiera . In questo lavoro sono stati determinati con precisione i requisiti per gli stampi del processo "Press Hardening" attraverso simulazione e sperimentazione. In seguito sono stati sviluppati alcuni acciai da utensile per lavorazioni a caldo con conducibilità termica elevata e resistenza all'usura adattata ad ogni specifico strato di rivestimento. Nella valutazione di questi acciai da utensile si è visto che i requisiti previsti per questo tipo di materiale erano effettivamente quelli necessari.