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HIGH TEMPERATURE BRITTLENESS OF CAST ALLOYS

Over-all mechanical properties of alloys are extremely low at the last stage of solidification where alloy exists at brittle temperature range (BTR). When the solidification process is completed a sudden and marked change in strength and ductility of metal is observed. It means that as long as liquid phase is present, metal will fail in a brittle manner. There are known different theories of brittleness of alloys in existence of liquid phase. The idea involved by authors of the paper is as follows: three major factors caused by presence of liquid may be taken into account:

- *decreasing the energy needed for crack nucleation;*
- *increasing atomic diffusional flux out of the crack tip;*
- *creating a path for abnormally quick diffusion of atoms from the crack tip.*

***Key words:** high temperature brittleness, hot tearing, shrinkage brittleness, mushy state.*

Introduction – mechanism of tear formation in solidifying alloy

The latest variation of the mechanism of extremely low of mechanical properties of solidifying alloys is proposed by Campbell [1] (Fig. 1).

The development of isolated regions of segregates is seen as tensile strain is applied. When this finally exceeds the ability of the liquid film to accommodate it, the action of the continued extension drains the liquid film, forming a tear [1].

During the first stages of solidification the quantity of solid phase is small and the dendrites are freely dispersed in liquid, i. e. they are not in contact with each other (Fig. 1a). The metal possesses very little coherence and the contraction (because of cooling process) can be accommodated without difficulty. As the temperature falls quantity of liquid phase decreases. The development of coherent network of the dendrites with liquid films between their arms is observed as tensile strain is applied. (Fig. 1b). For the condition of less liquid, less strain can be accommodated by slip along the lubricated boundaries. The metal approaches «iquid film» stage [2] at the temperature

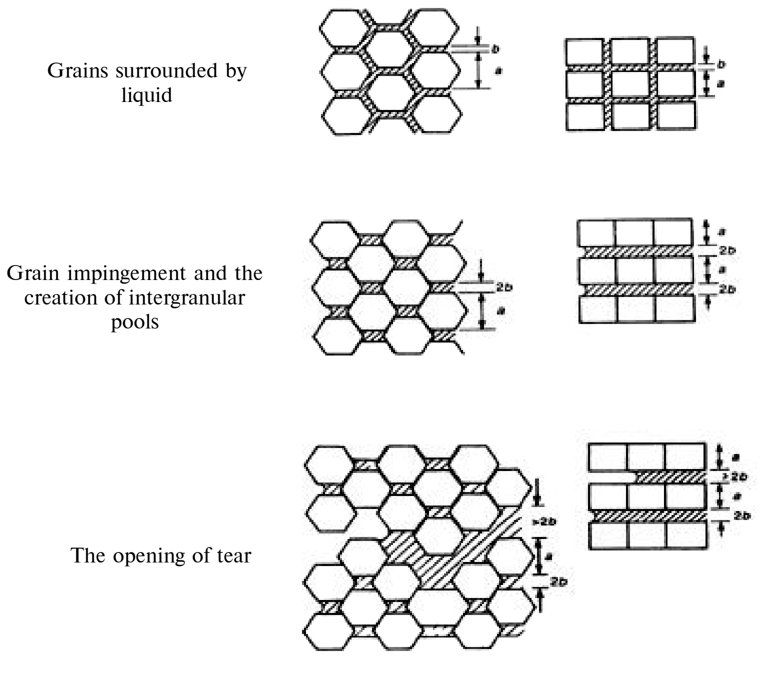


Fig. 1. Hexagonal and square models of grains, size *a*, surrounded by a liquid film of thickness *b*

that is near to solidus. According to widely accepted W.S, Pellini «liquid-film» theory [2], at the «liquid film» stage of solidification over-all mechanical properties of alloys are extremely low because the very narrow liquid films that separates solid grains have no appreciable strength compared to the adjoining solid dendrites.

If stresses arise, extension is highly concentrated in liquid film regions resulting in high unit strains. The liquid film is widened under the external stress until the critical width has been exceeded, at which point the liquid film recedes (Fig. 1c). Crack starts to develop. The tear propagates as the meniscus recedes further. Separation takes place between crystals. Fracture forms by disturbing of continuity of the liquid layer between crystals.

At the grain boundary, when the direct contact crystal-crystal is reached, the hundreds micrometers thick frontier zone of metal has a freezing point considerably below that of the bulk crystalline material. The effect of liquid film at the grain boundaries, but perhaps only a few atoms thick, is still present. This explains by the presence of impurities which have segregated to the grain boundaries. Even in the case of solidification of pure metals the outer surfaces of the metal and the internal grain boundaries are know to have a freezing point several hundred degrees below that of the bulk crystalline material [1–5].The fracture process involves the rupture of solid/solid contact areas or «bridging points» (Fig. 2). If contact zones have progressed to such an extend that the strength of the metal will be greater than required to prevent interdendritic separation the general flow of the bulk material can occur and the hot metal may fail in a ductile manner [1–5]. Extension occurs by uniform creep flow of solid metal. The strains are distributed in a relatively uniform fashion trough the coherent metal. No concentration of strains is possible. The effect is that the velocity of crack growth is reduced quite drastically.

Taking into consideration liquid film model of hot tearing, some workers have analysed the possibility to increase the tensile strength of an alloy at the liquid film stage. This results the following conclusions: tensile stress required to cause a separation of crystals covered by liquid (strength of metal at liquid film state):

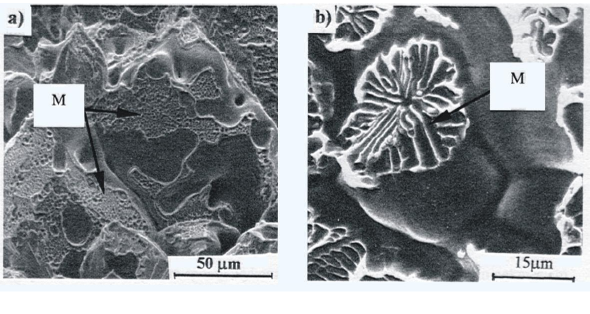


Fig. 2. Fracture surface of an weld of steel, showing the ruptured solid bridges M [3]

- is proportional to surface tension of liquid and inversely proportional to the thickness of liquid film; the effect of elements on the tensile strength of an alloy at the liquid film stage can be attributed to their influence on the surface tension [6, 7];

- depends on distribution of liquid phase; low dihedral angle (ie low interfacial energy between liquid and crystals) results in «spreading» of liquid over grain boundary and increases grain boundary area covered by liquid [8,9];

- depends on grain size; for a fixed dihedral angle and volume fraction of liquid a small grain size gives an increased area of solid-solid contact [10, 11].

The are known models [1, 2, 3, 10–17] that discuss an effect of various factors on the brittle temperature range (BTR) or on the time the alloy remains within this range. The broader is this range, the greater is the probability that the solidifying weld or casting will suffer a failure.

Model of hot tearing

The assumption of liquid film theory that the last-solidifying liquid is distributed in a film-like morphology is correct only for unrealistically low difference temperature between surface and core of solidifying ingot. This introduce some doubts on the generalization of the liquid film theory.

When real solidification process takes place one can distinguish at least two zones in the cross section of an ingot: a solid layer and an internal mushy zone.

Let us isolate the fragment of solidifying metal (Fig. 3) that compounds of two crystals and inclusion of liquid on their boundary-nuclei of crack.

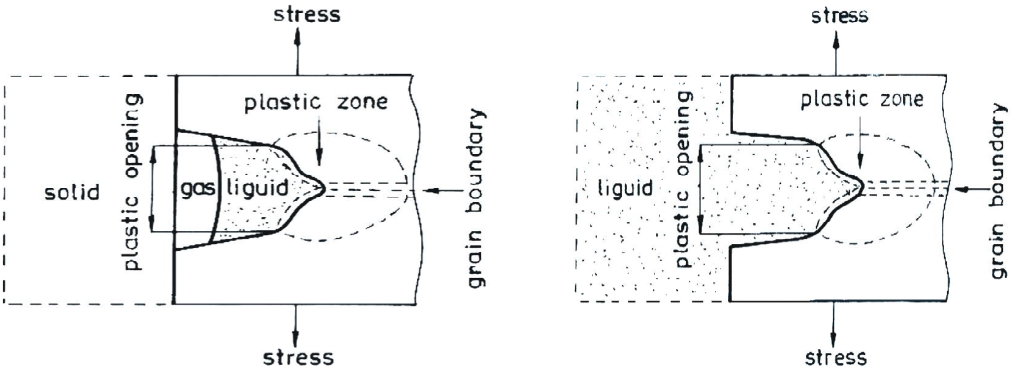
An analysis of the energy required per unit increase in area of crack [4, 5, 22] implies that:

1) the lowest energy requires developing of crack which goes along the crystal boundaries being in contact with the liquid phase;

2) the presence of liquid phase in an alloy causes a decrease of the amount of the energy needed for the formation of the crack.

Thus, the presence of the liquid phase makes the process of the crack formation easy to start.

As tensile stress is perpendicular to crystal boundary, vacancies create on crystal boundary. The tip of liquid phase inclusion is under compression stresses and lack of vacancies appear. Diffusional flux out from the tip creates the nuclei of crack. The velocity of crack propagation by diffusion mass transfer is proportional to the diffusional flux out from the tip. At a given driving force for diffusion (governed by the acting stress) diffusional flux increases with the concentration of the atomic defects at the surface. The equilibrium concentration of these defects is expected to grow exponentially with the surface energy reduction.



a b

Fig. 3. Scheme of building of an alloy (end of solidification of casting): a — not enough liquid to fill a nuclei of crack and b — enough liquid to fill nuclei of crack [18]

In general, the surface energy at the solid metal-wetting liquid interface $\gamma_{s\text{-}l}$ is typically from several to ten times smaller then $\gamma_{s\text{-}g}$ at the solid — inert atmosphere interface [18]. The surface energy at the liquid metal — crystal formed from this liquid should be much lower. The first, chemical composition of crystal and liquid is almost the same, the second — there is almost ideal the fineness of crystal surface been in contact with liquid. Thus, surface energy reduction makes a wetted surface more efficient source of defects [18—20]. This suggests that a solid-liquid interface, in particular crystal — liquid metal formed from this crystal which is the most surface-active, should have much larger the equilibrium concentration of atomic defects than a free surface, that is to say should be more atomically rough [18]. At the given driving force for diffusion of vacancies from the wetted surface to climbing dislocations or growing vacancial voids in the near surface layer (governed by the acting stress) the diffusional flux should hence increase with the concentration of the active sites («kinks») at the surface. Thus, surface energy reduction because of presence of liquid makes the driving force for the crack extension greater [18].

The number of atoms have to be removed from the tip to increase crack length. Robertson [21] probably as the first recognized that liquid can act as a very fast pathway. Glickman [18] submit as the possible transport mechanism the abnormally fast surface diffusion. The important is that the constituents which form with the base metal low melting point surface products make surface diffusivity D many orders of magnitude larger than its normal value in solid D_S and larger than in liquid D_L [18, 21].

At the late stages of solidification there is insufficient liquid metal available and the path of liquid from other areas is blocked by the network of dendrites to allow refilling and healing of the created tears. The volume of liquid phase decreases with time lapse. When the liquid is sucked into a crack, a void within the interdendritic space occurs on the back side of the crack as a consequence of crack developing. (Fig. 3a). The increasing liquid viscosity brings a simultaneous drop of diffusivity. Because of the small volume, liquid concentrates at the crack tip and within a narrow area around the tip and finally there is lack of liquid at the crack tip and there is no longer the path for an easy diffusion.

In general, type of cracking (brittle or ductile) is controlled by velocity of crack growth. The mechanism of failure depends on whether during the deformation process the crack is able to attain its length before the ultimate deformation occurs. The idea is presented in Fig. 4 [18]. It is assumed that because of presence of liquid the grain boundary crack increases its dimensions with the velocity according to curve 2 (Fig. 4b) and reach a characteristic dimension L_{ch} in a short time τ_2. At a given strain rate, the short time of crack growth determines a small deformation to failure — elongation A_2 — as well as small stress to failure — ultimate tensile stress R_{m2} (Fig. 4a). If velocity of crack growth is small (Fig. 4b, curve 1, no liquid) before the length of slow growing crack attains dimension L_{ch} the sample fails ductile after long time τ_1, and mechanical properties attain values: elongation A_1, tensile stress R_{m1} (Fig. 4a). The lower is the crack growth the longer the time-to-failure. At a given strain rate, long time to failure determines directly high elongation to failure. The increase in elongation causes a proportional increase in the tensile strength.

Verification of model

Presented model suggests, that alloys fail in the brittle manner because liquid accelerates crack extension while the fundamental properties of the solid are not affected. To verify this suggestion the tensile tests of steels at high temperatures were made. Samples of cast carbon steel (0,22 %C) after testing at different temperatures are shown in Fig. 5. Let us notice, that there is a narrow temperature range at which the very rapid change in reduction of area begins. Fig. 6 shows the deformation curves of samples showing in Fig. 5. At the initial stage, these curves

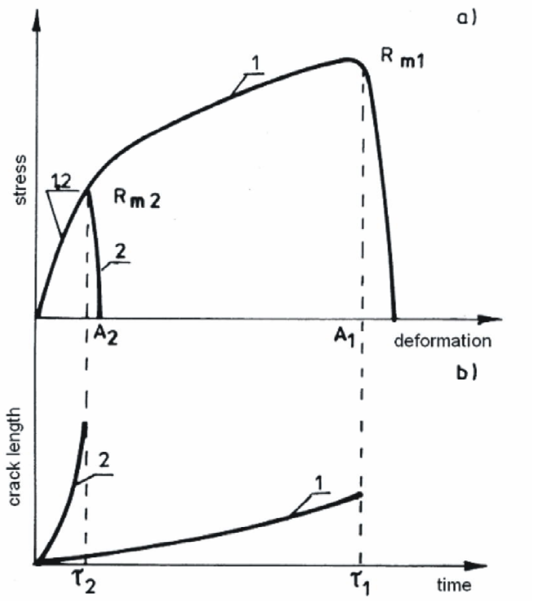


Fig. 4. Scheme of strain-stress diagram (a) and kinetics of development of crack nuclei (b)

are similar to each other. In the case of curve for steel tested at temperature 1496^{0}C the rapid drop of force after short time of test is observed. The crack size has been reached characteristic diameter (diameter of sample), finally resulting in brittle fracture. Remaining curves have a rounded maximum drop in a mild way due to the formation of a severe necking down, reaching 100 %. Therefore it is to be expected that in spite of a reduced force, the stress in the specimen will continue to increase until the plastic failure occurs. Similar results were obtained for the other grades of steel. Examples of diagram for cast steel 0.42%C is shown in Fig. 7.

It suggests, that presence of liquid does not affect the fundamental properties of the solid metal. The solid phase fails in a macroscopically brittle manner because liquid accelerates dramatically the crack kinetics

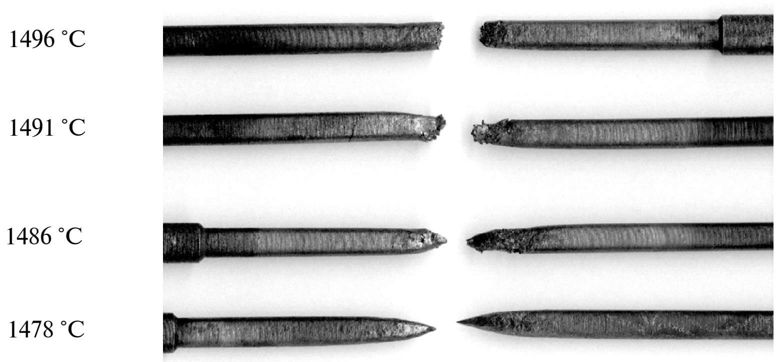


Fig. 5. Samples of cast carbon steel (0,22 %C) after testing at different temperatures

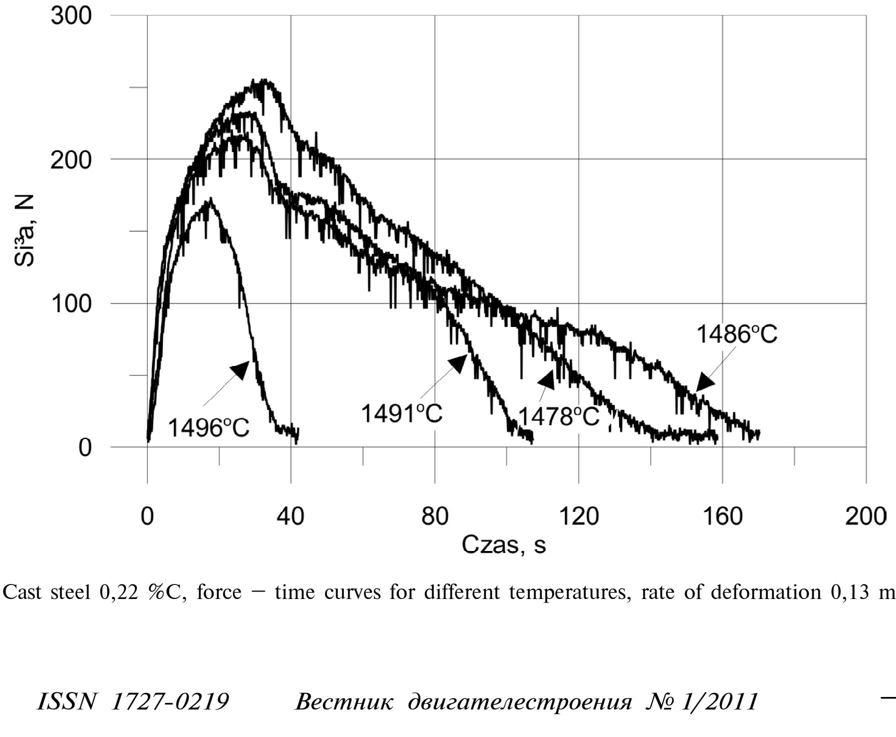


Fig. 6. Cast steel 0,22 %C, force – time curves for different temperatures, rate of deformation 0,13 mm/s

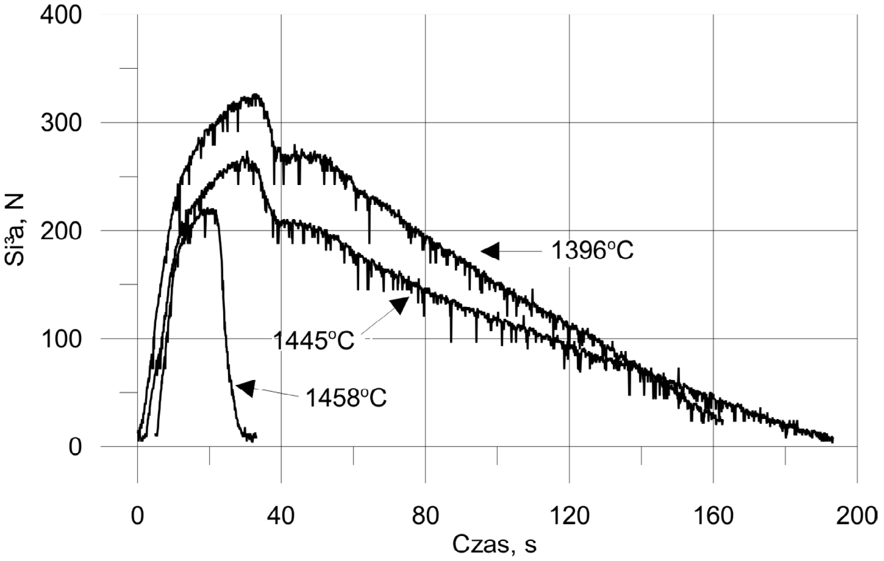


Fig. 7. Cast steel 0,42 % C, force – time curves for different temperatures, rate of deformation 0,13 mm/s

Summary

As long as liquid phase is present solidifying metal will fail in a brittle manner. Brittleness is not caused by presence of shrinkage voids, since voids are formed only as a result of the liquid penetrating into the opening crack which is a nucleus of fracture. At the moment when the liquid volume is insufficient, the development of brittle fracture will be hampered in spite of the shrinkage porosities already formed in the alloy. The presence of a liquid perfectly wetting the crystals considerably increases the rate of the crack. After transition to the ductile state, the initial increase of force is similar, but because the rate of the crack growth is low, failure occurs with a very severe plastic deformation.

The phenomenon of brittle failure of alloys within the range of solidification temperatures is a special case of LME.

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Иренеус Телейко, Генрик Адриан, Богдан Гузик Высокотемпературная хрупкость литейных сплавов

В целом, механические свойства сплавов являются крайне низкими на последней стадии кристаллизации, на которой сплав находится в диапазоне температурной хрупкости. Когда процесс кристаллизации завершается, наблюдается внезапное резкое изменение прочности и пластичности металла. Это означает, что до тех пор, пока присутствует жидкая фаза, металл будет хрупко разрушаться. Известны различные теории хрупкости сплавов при существовании жидкой фазы. Идея авторов статьи заключается в следующем: должны быть приняты во внимание три основных фактора, обусловленные наличием жидкости:

- *уменьшение энергии, необходимой для зарождения трещины;*
- *увеличение атомного диффузионного потока из вершины трещины;*
- *создание пути для аномально быстрой диффузии атомов из вершины трещины.*

Ключевые слова: *высокотемпературная хрупкость, высокотемпературное разрушение, усадочная хрупкость.*

Іренеус Телейко, Генрік Адріан, Богдан Гузик Високотемпературна крихкість ливарних сплавів

У цілому механічні властивості сплавів є вкрай низькими на останній стадії кристалізації, на якій сплав знаходиться в діапазоні температурної крихкості. Коли процес кристалізації завершується, спостерігається раптово різка зміна міцності та пластичності металу. Це означає, що до тих пір, поки присутня рідка фаза, метал буде крихко руйнуватися. Відомі різні теорії крихкості сплавів при існуванні рідкої фази. Ідея авторів статті полягає в наступному: повинні бути прийняті до уваги три основні чинники, обумовлені наявністю рідини:

- *зменшення енергії, необхідної для зародження тріщини;*
- *збільшення атомного дифузійного потоку з вершини тріщини;*
- *створення шляху для аномально швидкої дифузії атомів з вершини тріщини.*

Ключові слова: *високотемпературна крихкість, високотемпературне руйнування, усадочна крихкість.*