CHAPTER II

LITERATER REVIEW

2.1 Hot ductility of steel

The term of "hot ductility" refers to the amount of hot deformation a material can accommodate without fracture or severe cracking [1]. Steels have a region of extremely low ductility during or immediately after solidification. When a stress due to solidification shrinkage or other external stress is applied to steel in this region, a crack is generated as it becomes unable to withstand such force. In continuous casting of steels the temperature range of low ductility and hot crack susceptibility can be simulated with the aid of hot tensile test after in-situ solidified from melting.

Suzuki et al. [2-4] have studied the hot ductility of carbon steels with hot tensile tested on cooling after melting to lower temperature. They have presented the embrittlement that occurs in the temperature range between the melting point and 600°C could be divided into three region of occurrence according to the temperature range where embrittlement occurs. They proposed a simple curve of reduction of area and the temperature range between melting temperature and 600°C as shown in Fig.2-1.

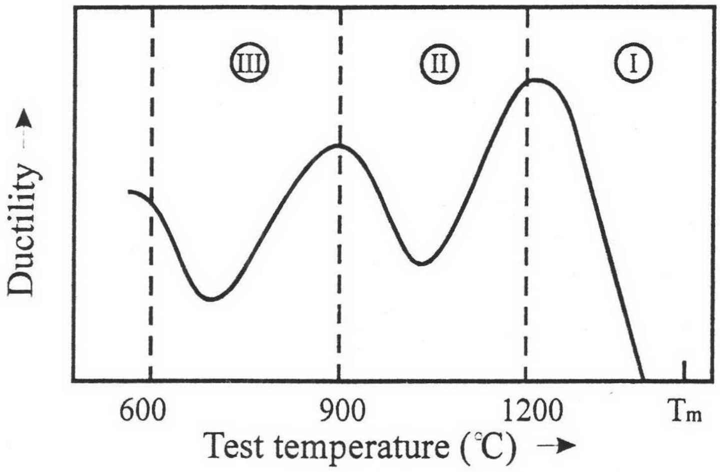

Fig.2-1 Schematic representation of ductility troughs appearing in the hot tensile test in steels [2].

In region I which is close to the melting point, the liquid phase causes the embrittlement, and ductility does not depend on the strain rate. In region II which corresponds to a stable austenite region and appear in the temperature range of 1200~900°C, the embrittlement occurs along grain boundaries as a result of intergranular precipitation of sulfides and oxides in the form of (Fe,Mn)S and (Fe,Mn)O. In region III which covers temperatures of 900°C to 600°C, the degree of the embrittlement increases as the strain rate decrease. This embrittlement is caused by such factors as intergranular precipitation, formation of proeutectiod films along austenite grain boundaries, matrix strengthening due to the precipitation and grain boundary sliding.

Thomas et al. [5] have comprehensively reviewed of hot ductility of plain carbon steel and proposed the mechanism of reduces hot ductility as shown in Fig.2-2. They divided the temperature zone of reducibility and their corresponding embrittlement mechanism into three zones. The first zone is high temperature zone at the temperature just below the solidus. In Fig.2-2 the ductility of zone A is reduced by the microsegregation of sulfur and phosphorus residual at solidifying dendrite interface which lowers the solidus temperature locally in the interdendritic regions. The ductility remains effectively zero until the interdendritic liquid films begin to freeze. Severe embrittlement is experienced at all temperature above the zero ductility temperature, ZDT, which occur within 30-70°C of the solidus. Any strain that is applied to the steel in this temperature region will propagate cracks outward from the solidification front between dendrite. The resulting fracture surface exhibits a smooth, rounded appearance, characteristic of the presence of a liquid film at the time of failure. Increased contents of sulfur, phosphorus and tramp element all worsen the ductility. Manganese is beneficial since it preferentially combines with sulfur to form less harmful MnS precipitates, thereby preventing liquid film formation. This zone of reduced ductility is responsible for the problem of hot crack susceptibility at elevated temperature during continuous casting. The second zone of low ductility (zone B and D) in steel appears in the intermediate temperature range or in the range from Ar_3 temperature to as high as 1200°C. The ductility reflected in the appearance of the fracture surface. In the case of low

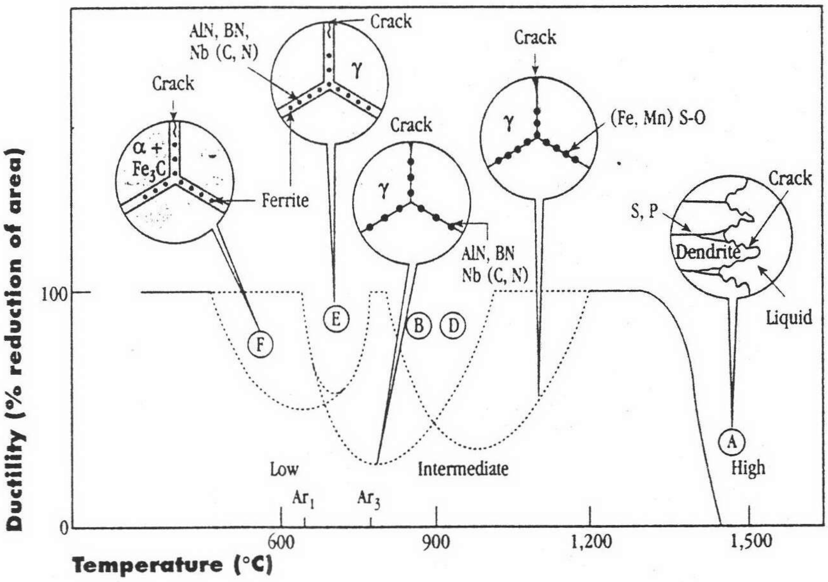

Fig.2-2 Schematic representation of temperature zones of reduced hot ductility of steel related to embrittlement mechanism [5].

ductility fracture always exhibit an intergranular fracture along austenite grain boundaries. The surface of specimens fracture zone of reduced ductility exhibits numerous precipitates of varying types including sulfides, oxides and nitrides (AlN or Nb(C, N) and BN). The third zone of low ductility (zone E and F) in steel occurs in the two-phase austenite-ferrite region below the Ar_3 temperature, or zone E in Fig.2-2. At a lower temperature this range has a major influence on the formation of cracks on and near surface. The embrittlement in this temperature range is correlated to strand straightening operation temperature.

Mintz et al. [6] have comprehensively reviewed the hot ductility of steel in the high and low temperature zone. They divided the temperature range of hot ductility of steel between 1100-700°C into three zones. The first is a high ductility low temperature range, which results from the presence of a large volume fraction of the more ductile ferrite phase. The second is a high temperature ductile region covering the range within which grain boundaries particles are dissolved and boundaries are able to migrate so that any initiated cracks are prevented from linking up and enlarging. The third region is a trough between these two ranges in which low ductility intergranular failure often. These intergranular failures arise as a result of stress and strain concentration at the austenite boundaries caused either by the presence of thin films of the softer deformation induced ferrite enveloping the austenite grains or by grain boundaries sliding in the austenite. Both failure mechanisms are encouraged by the presence of grain boundary precipitates and inclusions, coarser grain size and lower strain rate.

2.2 Implication of hot ductility for hot cracking

The evaluated curves of the reduction in area at fracture and the maximum load related to the test temperature shown in Fig.2-3. The figure shows a characteristic hot ductility trend for a large range of different steel composition [7]. At a temperature during steel solidify, with increasing crystallization at a remaining melt amount of 20 to 30% the linking of the crystals has gone so far that the specimen is able to transmit small forces [8]. This temperature is called the zero strength temperature (ZST). Nevertheless, in this state the specimen fails without any macroscopic deformation, because the remaining melt located between the primary grains is not capable of transmitting the occurring tensile stress and strains to the neighboring grains [2-4].

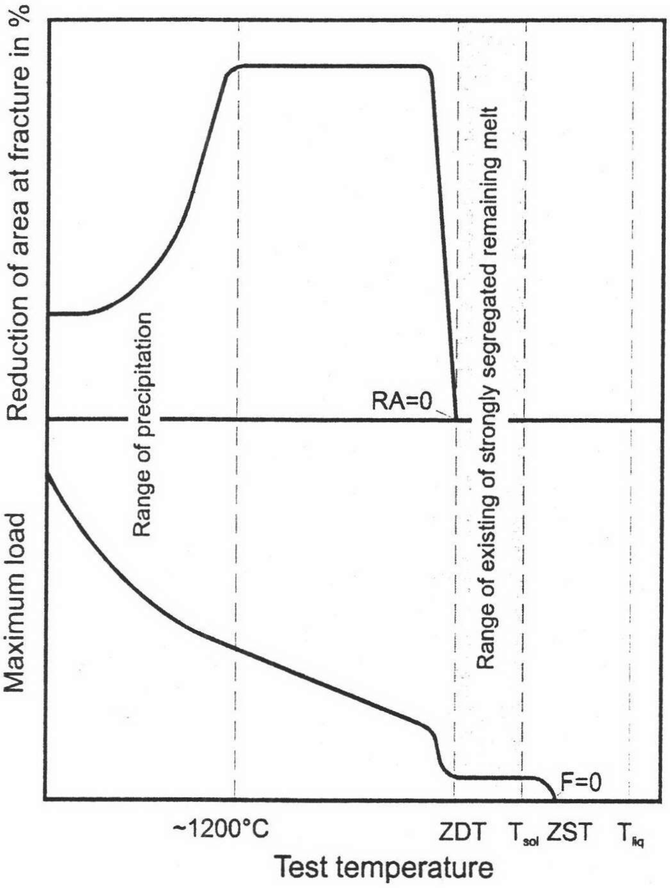

Fig.2-3 Schematic trend of reduction of area after fracture and maximum load versus test temperature curve [7].

If these locally segregated areas solidify with decreasing test temperatures, measurable reductions of area occur for the first time at the so-called Zero Ductility Temperature ZDT [9]. Whilst the strength steadily increase with decreasing temperature, the reduction of area at fracture drops more or less sharply after reaching a maximum value, which can be as much 100% depending on the grade of steel. This so-called ductility drop is caused by the decreasing solubility of the austenite for alloying and tramp elements at decreasing temperatures and the connected precipitation of particles, on the austenite grain boundaries [6]. The minimal reduction of area at fracture can therefore decrease to 0%. Related to the conditions during continuous casting, the critical temperature range ΔT between the Zero Strength Temperature characteristics the mechanical properties at the solid-liquid phase boundary. The extension of this range is seen as a measurement for the internal crack susceptibility and the hot cracking tendency of steel during continuous casting [10,11].

Brimacombe and Samarasekera [12] have presented the schematic presentation of mechanical properties of steel at high temperature as shown in Fig.2-4. The strength and ductility of steel have small value below the solidus temperature because of the existence of interdendritic liquid film. All cracks observed in continuously cast steel originate and propagate along the interdendritic in mushy zone. The ductility loss of the mushy zone is associated, as depicted in Fig.2-2, with the microsegregation of solute elements at solidifying dendrite interfaces. This solute enrichment locally lowers

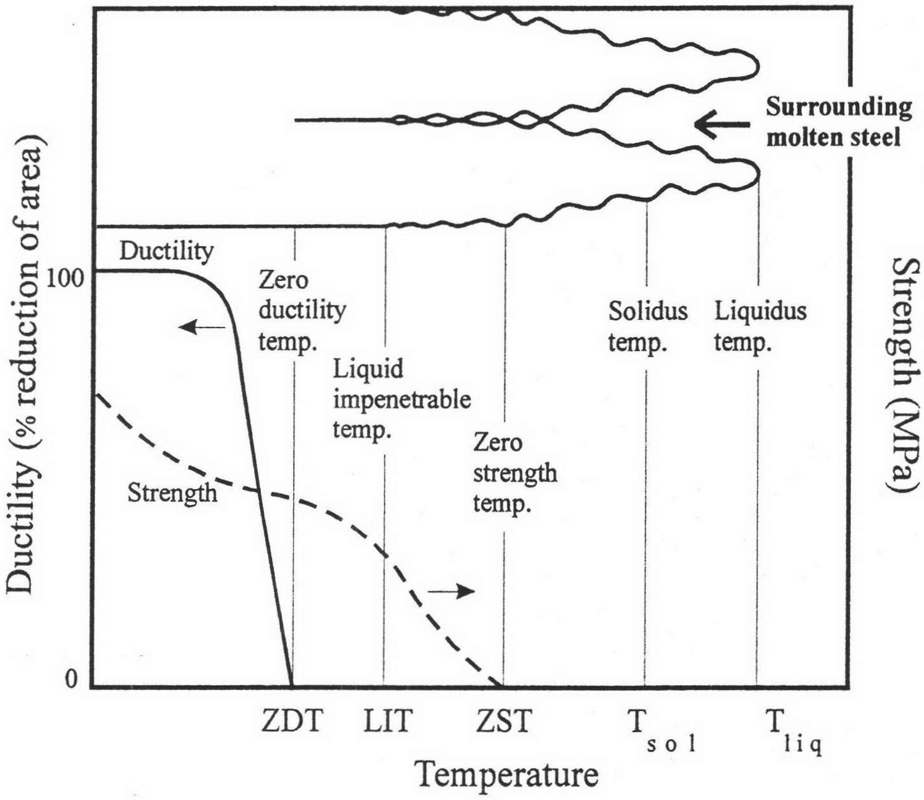

Fig.2-4 Mechanical properties in the temperature zone of reduced ductility and corresponding presentation of solid-liquid interface [12].

the solidus temperature of interdendritic liquid and consequently reduces the zero ductility temperature of steel. A tensile strain applied to the mushy zone or in the range between the solidus and zero strength temperatures causes the separation of dendrites and resulting fracture surface exhibits a smooth, round appearance characteristic liquid film failure. Hot tear can take place under a small strain when the interdendritic liquid film is thin enough to resist feeding of the surrounding liquid through the dendrite arms. Clyne et al. [13] have developed the crack susceptibility coefficient to estimate the cracking tendency in continuously cast steel. They divided the mushy zone into the mass and liquid feeding zone and the cracking zone. Cracks formed in the mass and liquid feeding zone are refilled with the surrounding liquid, whereas cracks formed in the cracking zone can not be refilled with the liquid because the dendrite arms are compacted enough to resist feeding of the liquid.

2.3 Influence of composition on hot ductility

According to Thomas et al. [5] and Brimacombe and Samarasekera [12] the high temperature range of low ductility is affected by microsegregation of solute elements of solidifying dendrite interface. The intermediate temperature of reduce ductility is strong influence by precipitates grain boundaries. This two ranges of reduce ductility is taken consideration because it is corresponding to hot crack initiation during and after solidify from melting inside the strand.

Suzuki et al. [3,4] have investigated the ZDT of steel with various carbon content from 0.003-1.6% and found that the ZDT drops down to lower temperature with increasing of carbon content, Fig.2-5. It can be noticed that the ZDT appear around 1500°C for steel contains 0.11% carbon whereas raising the carbon content up to 1.6% the ZDT appear at around 1200°C. They also proposed that ZDT has a linear relationship with the equilibrium solidus temperature of Fe-C binary alloy ranging from 0.003-1.6%; $ZDT=1.14T_{sol}-231$, and there was no singularity between 0.1 to 0.2% carbon content. The reason for this phenomenon is due to the solidus temperature decrease with increasing carbon content.

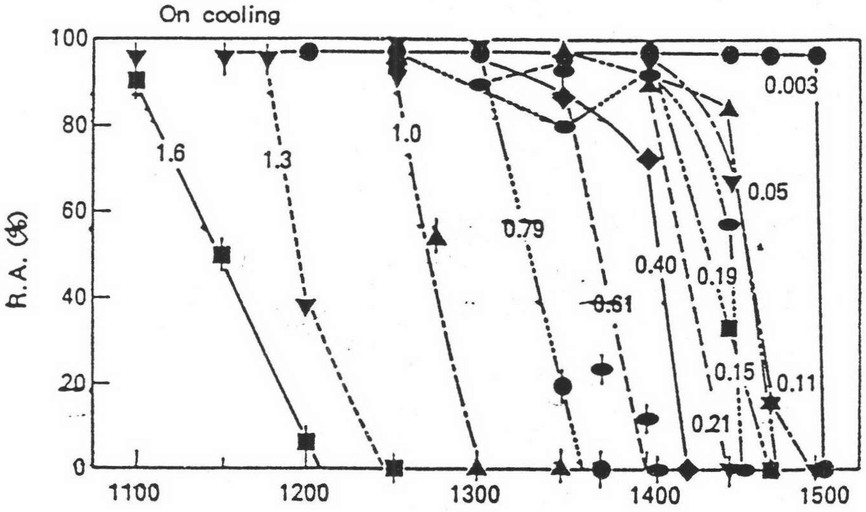

Fig.2-5 Hot ductility in Fe-C binary alloys with melted specimen (strain rate: 5/s). Numerical values in each curve show C content [3,4].

Sulfur in one of solute elements that have an adverse effect on the mechanical properties of steel. Sulfides rich in iron have a lower melting point. They form as films on the primary grain boundaries and weaken their cohesion. In the steel cooled from a high temperature the following sulfides are found: sulfides already suspended in the molten steel; sulfides segregated and precipitated during solidification of the steel; and solid sulfides precipitated in austenite grains and along grain boundaries by decrease in solid solubility of sulfur in steel with lowering the temperature of the solidified steel [14]. Kim et al. [15] have studied the effect of sulfur content on ZDT, ZST as shown in Fig.2-6. They demonstrated that the effect of sulfur content on ZST and LIT is not significant, whereas the effect of sulfur content on ZDT is significant because sulfur is segregated at the final stage of solidification. They concluded that the brittle temperature range extends to the lower temperature, and the possibility of cracking is expected to increase with increasing sulfur content.

Manganese increases the strength of steel. At the same time, it has a bearing on precipitation behavior, morphology, and the composition of sulfides. Many researchers have studied the interaction of manganese and

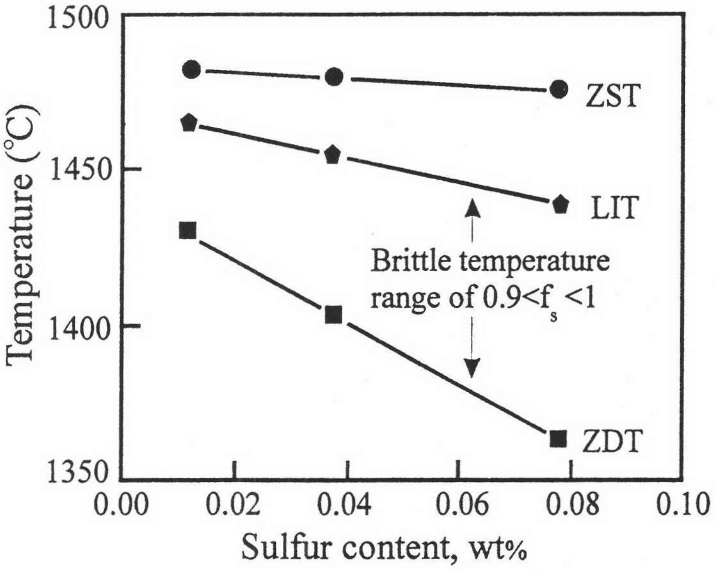

Fig.2-6 The ZST, LIT and ZDT of 0.3%C steel as a function of sulfur content [15].

sulfur and its effect on internal cracking. Higher manganese levels cause sulfur precipitating from the matrix during cooling to be removed completely by combination to manganese sulfide and thus create better condition for the cohesion of the grain bond than the significantly lower melting ferrous sulfide [14]. Steels, if adjusted to higher Mn/S ratios for improving their resistance to hot cracking, generally also feature higher sulfur levels [14]. Lankford [16] has proposed the opinion from his studying that the low ductility results from the precipitation of liquid FeS-droplets in between the austenite grain boundaries that are area for premature crack formation. He observed that low carbon steel with the ratio of Mn/S above 60 is not susceptible for embrittlement, because the sulfur is bonded in a stable phase. MnS for example precipitates in the matrix and predominantly at the grain boundaries. Mintz [17] reported that when steel are cast, lower manganese levels increase the solubility of sulfur in the austenite at solidification as well as producing a finer more closely spaced intergranular separation of MnS inclusions and this may lead to a deterioration in hot ductility. Suzuki et al. [4] have studied the effect of Mn/S ratios on hot ductility as shown in Fig.2-7. They demonstrated that the embrittlement is very sensitive to the Mn/S ratio in steels and if Mn/S ratio is smaller than 40, severe embrittlement occurs as typical point out by Lankford [16]. They also found that not only the Mn/S ratio, but also the absolute value of manganese and sulfur are important and if sulfur is less than 0.0065% or manganese is higher than 0.75% even through Mn/S ratio is small, no embrittlement occur. As shown in Fig.2-7 Poor ductility means RA is less than 40% (×), good ductility mean RA is higher than 60% (o), and (Δ) is between 40 and 60% test at strain rate of 5/s, cooling rate of 20°C/S in the melted specimen.

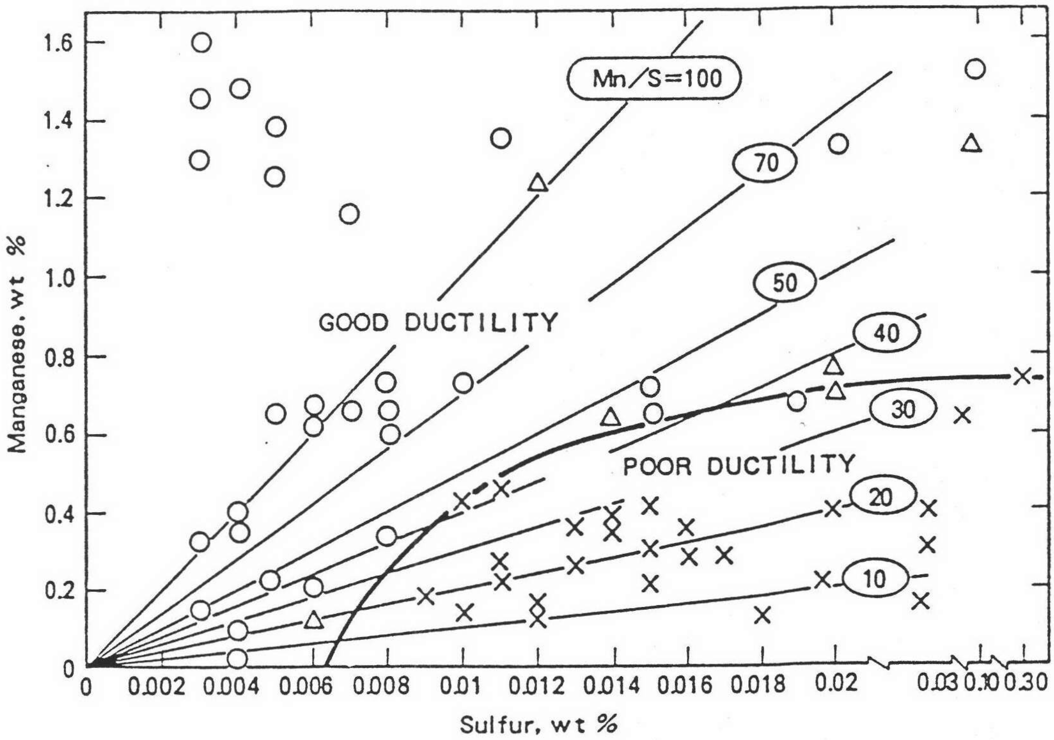

Fig.2-7 Effect of Mn and S on the embrittlement in the temperature between 1200 and 900°C in low carbon steels [4].

Another elements which influenced on reduce hot ductility are nitride. Knowing that nitride precipitates (Al, Nb and B) are largely responsible for lowering ductility, it is found that increasing nitrogen contents are associated with decreasing ductility and extension of the low ductility trough to higher temperature [5,18]. Vanadium, another common microalloy and nitride former, is not nearly as detrimental to ductility as aluminum and niobium and may even be beneficial [5]. Oxygen has been seen to have only a slight deleterious effect on hot ductility presumably due to its contribution to (Fe, Mn, and Al) inclusions and reduction in internal cleanliness. Oxide precipitates are far less damaging than either nitrides or sulfides [5].

2.4 Effect of test variables on hot ductility

Many researchers have investigated the effect of test variables such as strain rate and cooling rate on hot ductility. Suzuki et al. [4] have studied the effect of strain rate on hot ductility near the melting point of low carbon aluminum killed steel. They indicated that the ductility near the melting point does not depend on the strain rate. Decreasing the strain rate from 1/s to as low as 10^{-3}/s in tensile test of steels which has high sulfur content or low Mn/S ratio at temperature of 1100°C, the ductility improves. In this case, coarsening of the precipitates and reduction of intergranular cracking susceptibility during deformation probably cause improvement. At higher strain rates, less time is allowed for the coarsening of sulfide precipitates, that resulting in effective grain boundary pinning and thereby reduced ductility. Yasumoto et al. [19] studied the effect of strain rate on hot ductility of low carbon steel. They found that tensile test between 1100-700°C after solidified from melting with decreasing in strain rate from 10^{-1}/s to 10^{-2}/s have been shown to improve the hot ductility when unstable fine precipitates such as FeMnS are present. In this case, the inclusions probably coarsen, so that they are no longer able to pin the austenite grain boundaries. Even Nb-containing steel at the 1.4%Mn level can display improved hot ductility at very low strain rates (10^{-4}-10^{-6}/s) because of coarsening of the Nb(C, N) precipitation [1,20]. However another researcher found that a low strain rate allows time for diffusion controlled processes of (Al, Nb, B) nitride precipitation and grain void coalescence to take effect. As strain rate decrease, the embrittlement mechanisms are enhanced. Higher Al, Nb, B or N levels increase nitride precipitate solubility products that result in increased precipitation rate [5]. Various tests for range 10^{-1}-10^{-4}/s and temperature range 1100-700°C, increasing strain rate invariably improves the hot ductility [6,17]. The reason for this improvement are; (1) there is insufficient time for strain induced precipitation, (2) there is insufficient time for the formation and diffusion controlled growth of voids next to the precipitates and inclusions present at grain boundaries [6,17,21,22]. Cooling rate is also influenced on hot ductility. Slow cooling rate cause of coarse columnar grain size and the coarse grain size lead to decrease in the specific grain boundary area which raises the precipitate density on the grain boundaries. The hot tensile test from the melted produced a solidification structure with columnar grains perpendicular to the main direction of stressing in the tensile test. Coarse columnar grains and lower strain rates encourage grain boundary crack propagation due to carbonitride, for steel contain Nb(C, N), strain induced precipitation and thus increase the tendency to form cracks. Increasing cooling rate leads to a finer austenite grain size, it encourages microalloying, such as niobium and vanadium, finer precipitation result in lower ductility. Wilber et al. [1] demonstrated that slow cooling rate allows time for the slow diffusing manganese to combine with sulfur and form less harmful MnS precipitation which reduces FeS formation at the grain boundaries. In addition, high Mn/S ratios encourage harmless MnS precipitation inside the grains. This also explains the beneficial effects of high Mn/S ratio or lower sulfur level.

However the effect of test variables on hot ductility is very complicate because the different of steel composition, different test conditions etc.

2.5 Investigation of hot crack susceptibility of tool steel

The products called tool steels are intended to be used for the shaping of other metal by cutting, shearing, battering, drawing, extruding, die casting, or rolling, or for the shaping and cutting of wood, paper, rock, or concrete. Tool steels are carbon or alloy steels that are capable high wear hardened and tempered. Some desirable properties of tool steels are high wear resistance and hardness, good heat resistance, and sufficient strength to work the materials. Although tool steels are a relatively small percentage of total steel production, they have a strategic position in that they are used in the production of other steel products and engineering materials. The most commonly used classification system of tool steels is that established by the American Iron and Steel Institute. The AISI system of classifying tool steel is based on quenching method, application method, special characteristics, and composition. In it, tool steels are classified into 7 groups as shown in Table 2-1.

The former rout to produce tool steel is ingot casting. But today continuous casting can be carried out to produce this steel grade. One difficulty during

Table 2-1 Classification of tool steels [23].

Group	Letter symbol
1 Water hardening tool steels	W
2 Shock-resistance tool steels	S
3 Cold-work tool steels	
Oil-hardening	O
Medium alloy, air-hardening	A
High carbon, high chromium	D1
4 Hot work tool steels	H
Chromium type	H1 to H19
Tungsten type	H20 to H39
Molybdenum type	H40 to H59
5 High-speed tool steels	
Tungsten type	T
Molybdenum type	M
6 Special-purpose tool steels	
Low alloy	L
7 Mold tool steels	P

continuous casting of steel, which has high carbon content like tool steel, is the crack susceptibility of the strand. Due to heavy segregation of the element carbon and chromium into the core of the strand during solidification, the steels have a tendency of centerline segregation and blowholes in the area of the last solidifying melt. In industry a soft-reduction unit can be applied to reduce the strand thickness during processing and to minimize the negative effects caused by centerline segregation and blowholes. The effect of soft-reduction on the strand shell depends on the amount of reduction of the strand and on the casting speed. The knowledge of the highest possible reduction rate without serious crack formation in the solidification area or at the surface in dependency of steel grade is of major importance. However, a large amount of soft-reduction (less centerline segregation and blowholes) leads to high stress and strain at the local point of soft-reduction roller. Tensile stress and strain occur at the surface of the strand at the contact with the roller and at the solidification front or solid-liquid interface. When the strand pass the roller, the casting speed influence the strain rate at the solidification front and on the surface of the strand shell. If the strain exceed a critical value, the distance between the solidifying dendrites will be larger and the liquid phase will be sucked into this enlarged gap. This area influences the product homogeneity negatively. The variation of cooling rate and strain rate may lead to different condition of crack initiation in the strand shell.

The steel grade AISI L3 and AISI O1 were chosen for this investigation. Steel grade AISI L3 is one type of special purpose tool steels and embraces a series of steels of different carbon and chromium contents. The principal chemical composition, as propose by Roberts et al. [24], compose of 0.65-1.1%C, 0.1-0.6%Mn, 0.252%Si, 0.75-1.5%Cr and 0.2%V. Steel grade AISI O1 is oil hardening cold work die steels. The principal chemical composition are 0.95-1.1%C, 1.2%Mn, 0.25%Si, 0.5%Cr, 0.2%V and 0.5%W.

To measure the hot ductility and hot crack susceptibility of the steel under the condition similar to those of soft-reduction during continuous casting, the hot tensile test can be carried out for this purpose. However, there is a little works concerning to hot ductility and hot crack susceptibility of tool steel. Thome and Dahl [11] studied the hot crack susceptibility of high alloyed tool steels during continuous casting and in the temperature region of hot working. They have studied some grade of cold work tool steel and shown the result in Fig.2-8. They pointed out that the critical temperature ranges is increases with slow solidification. The ductility of the steels is reduced by the formation of coarser of embrittlement are voided. Faster solidification due to or harder cooling would be able to

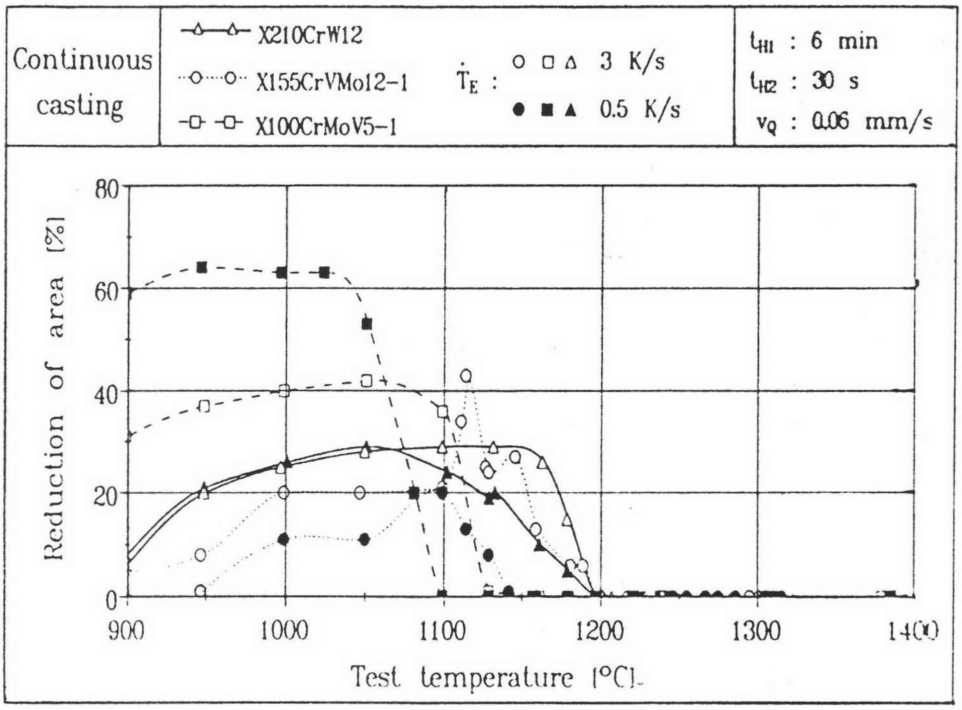

Fig.2-8 Influence of solidification rate on the ductility of cold work steels under continuous casting condition [11].

suppress crack tendency, via the formation of a finer grained and more homogeneous microstructure.