

WELCOME

CAST AUSTENITIC MANGANESE STEELS

SOME PRACTICAL NOTES

PRESENTED BY

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INTRODUCTION

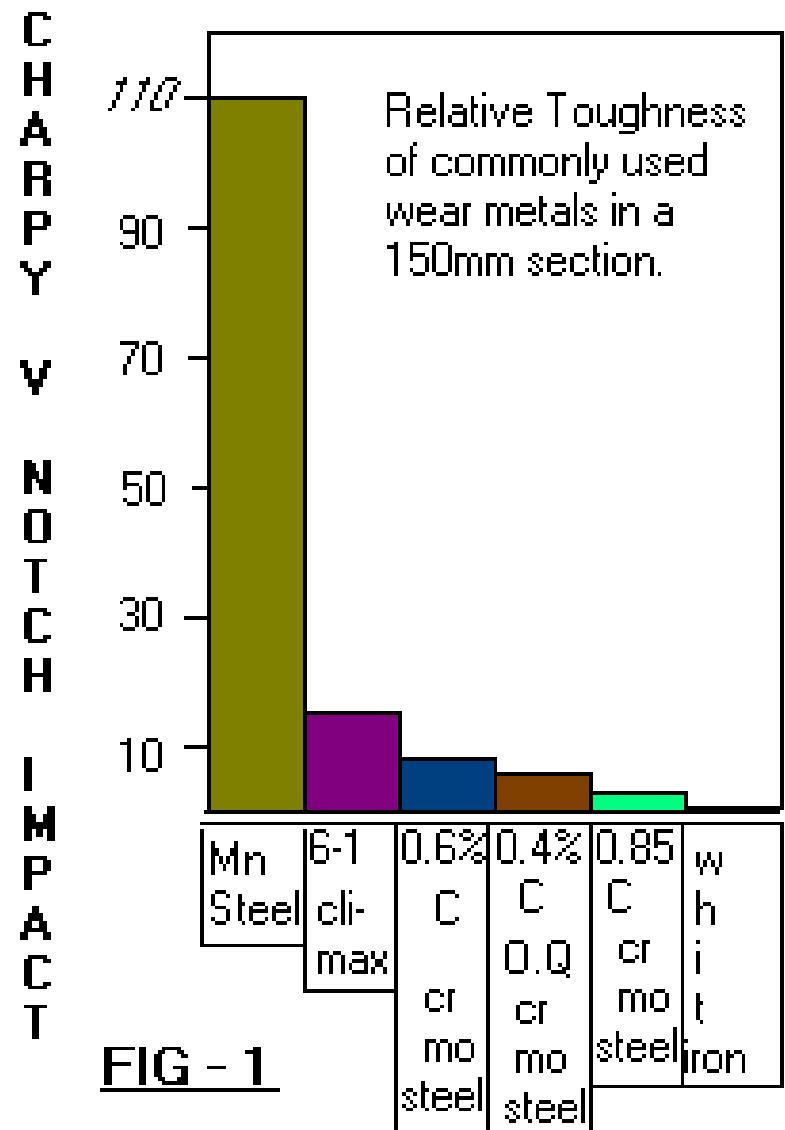
- AUSTENITIC MANGANESE STEEL WAS DISCOVERED BY R. A. HADFIELD IN 1882 AND SINCE THEN IT HAS BECOME ONE OF THE MOST IMPORTANT STEELS WHERE EROSION OF COMPONENTS TAKES PLACE BY CONTINUED ABRASION AND IMPACT.
- IT IS A 1.2% CARBON – 12% MANGANESE ALLOY STEEL HEATTREATED TO AN AUSTENITIC CONDITION, WHICH IS STABLE AT ROOM TEMPERATURE.
- OUTSTANDING TOUGHNESS, HIGH STRAIN HARDENING CAPACITY AND PARAMAGNETISM ARE THE PRINCIPLE VIRTUES OF MANGANESE STEEL.

APPLICATIONS

- ALTHOUGH AUSTENITIC MANGANESE STEELS ARE UNIVERSALLY KNOWN AS THE MOST USEFUL **ABRASION RESISTANT** MATERIAL, THERE IS A GENERAL MISCONCEPTION AMONGST BOTH THE MANUFACTURER AND THE USER ABOUT THE BASIC CHARACTERISTIC OF MANGANESE STEEL FOR ITS CHOICE FOR USUAL APPLICATIONS.
- THE PRIMARY REASON FOR SELECTING MANGANESE STEEL FOR ANY PARTICULAR APPLICATION IS NOT ABRASION RESISTANCE. IT DOES HAVE A GOOD ABRASION RESISTANCE, BUT IF, ABRASION RESISTANCE IS THE ONLY CRITERION, THERE ARE A NUMBER OF MATERIALS AVAILABLE WHICH ARE MUCH SUPERIOR e.g. MARTENSITIC WHITE CAST IRONS.
- THE OVERRIDING REASON FOR ITS CHOICE IS THE TREMENDOUS **TOUGHNESS** OF MANGANESE STEEL.

WHAT IS TOUGHNESS ?

- TO MOST PEOPLE, TOUGHNESS MEANS THE ABILITY TO WITHSTAND SEVERE IMPACT CONDITIONS WITHOUT FRACTURING.
- MANGANESE STEEL HAS THIS ABILITY AND ITS HUGE RESERVE OF IMPACT TOUGHNESS AS COMPARED TO OTHER WEAR MATERIALS IS ILLUSTRATED IN Fig-1.
- EVEN IN APPLICATIONS WHERE OTHER MATERIALS POSSESS SUFFICIENT TOUGHNESS FOR NORMAL CONDITIONS, MN STEEL MAY BE CHOSEN BECAUSE OF THE DANGER OF OCCASIONAL HIGH IMPACT.
- IF IMPACT & SHOCK IS ABSENT, AS IN PIPE CARRYING SAND-LADEN WATER, WHITE CAST IRON IS A BETTER CHOICE. FOR LIGHT OR MODERATE IMPACT, A HARDENED STEEL IS JUSTIFIED. FOR HEAVY IMPACT OR FOR LARGE SAFETY FACTOR, MN STEEL IS THE LOGICAL CHOICE.



WHY IS IT THEN USED IN WEAR APPLICATIONS ?

- The wear resistance of Hadfield manganese steel, having a fully austenitic structure obtained by water quenching from 1050°C , depends entirely upon the amount of **work hardening** which it subsequently experiences. An intriguing feature of austenitic manganese steel is its ability to **work harden** rapidly in the locality of sudden deformation. The physical mechanism which causes such hardening have been carefully studied and will be discussed latter, but understanding of this mechanism is not important for practical purpose of either manufacturing or application.
- Superficial work hardening of crusher liners maintains surface hardness of $\text{Rc } 45$ to 55 over a base of high toughness. This combination cannot be duplicated by heat treatment. The workhardened profile depends on the nature of deforming force. Typical effected depths are 0.5mm from shot preening, 2.5mm from crushing hard rock and 38mm from explosive hardening.

WHERE & HOW IT PERFORMS

- It is understood that performance of manganese steel will depend on the type of wear i.e. the wear is associated with heavy or moderate impact or no impact at all because deformation is a necessary pre-requisite for workhardening of manganese steel. Three different types of wear can occur in service i.e. **Gouging abrasion**, **Grinding or high stress abrasion**, and **Scratching or low stress abrasion**.
- In the first case, impact is always involved, such as in case of digger teeth cutting into rock, in gyratory crusher or impact crusher. In such cases manganese steel would be able to absorb huge amount of energy and undergo extensive plastic deformation without cracking. Even if crack is eventually developed, manganese steel has such a unique resistance to crack propagation that early detection is possible before equipment damage occurs.

- In the second type of wear, high stresses results from a crushing action such as in a ball mill. In such applications, logical choice, so far, has been Mn steels, mainly to avoid premature failures due to, either mishandling at user's end, or, negligence at manufacturer's end. But, by making judicious compromise on toughness for hardness, hard martensitic white cast irons, such as high chromium irons, are replacing Mn steels in this type of applications.
- The third type of wear is no way connected to impact, and the scratching results from loose particles lightly abrading the steels. During this type of low stress abrasion austenitic manganese steel, as there is no chance of deformation, will not harden sufficiently to prevent surface erosion.

A WORD OF CAUTION.

- In recent years, numerous attempts have been made to improve performance of manganese steels for different applications by modifying conventional composition and applying different heat-treatment techniques.
- It would be worth mentioning here that most of the field failures or poor performance of manganese steels of standard composition are not due to inherent short-comings of the choice of composition or heat-treatment, but due to ignorance about the metallurgy of the steel and carelessness / casualness during manufacturing stage.
- By and large, the experiences of reputed manganese steel foundries, indicate that, except in some special applications, standard manganese steel, if manufactured with necessary controls, gives better performance in most of the wear conditions, compared to costly variations.

CONTROLS? WHAT TO CONTROL?

- The properties of austenitic manganese steel are influenced by **HEATTREATMENT, POURING TEMPERATURE, CHEMICAL COMPOSITION** with respect to **CASTING THICKNESS**.
- These are the main controlling factors for optimum performance of austenitic manganese steels.

POURING TEMPERATURE

- Pouring temperature is a prime variable at the disposal of the foundry men. It is well known from both practical experience and published literatures that high pouring temperatures, resulting in **large grain size** and **alloy segregation**, are detrimental to the strength and ductility of manganese steel.
- The freezing range of manganese steel is about **1371°C** to **1260°C**. In plant cracking problems and inferior mechanical properties can be anticipated if pouring superheat exceeds **120°C**. And it will be much more pronounced as the **casting thickness** and **carbon content** increases.
- Thus in the production of heavy section castings, pouring temperature control becomes extremely important if adequate toughness is to be preserved in finished casting.

- In extreme cases of poor temperature control, toughness of the finished casting is not a concern since the casting would already have been lost due to hot tearing. Pouring temperature is one of the key factors affecting the hot tear resistance of manganese steel particularly at **high phosphorus content**.
- In spite of the fact that the adverse effects of high pouring temperature is known for years, poor temperature control has restricted the development of improved manganese steels and many field failures can still be attributed to high pouring temperatures. This situation evolved primarily due to non-availability of immersion pyrometers even a decade ago and reluctance to use it by some foundry men as an expression of lack of confidence on their capability of judging metal temperatures earned by their long experiences.

- **Pouring ladle** is another constraint to achieve low pouring temperatures consistently. With large arc furnace or induction furnace heats in a foundry, the time required to pour a heat can become excessive, resulting in a large temperature spread from the first till the last casting poured. Over the years steel foundries have been very reluctant to convert from antiquated lip-pour ladles. They believed that they could get better temperature control from lip-pour ladles, whereas in actuality the reverse is true. Because the slag has to be removed from a lip-pour ladle prior to pouring, the rate of heat loss is relatively rapid. Thus high furnace tap temperature had to be employed to ensure adequate temperature and fluidity during pouring period. Because of the high tap temperatures a basic magnesite refractory was used to prevent chemical reaction with ladle lining. However, masngesite has a relatively high thermal conductivity, which further increase the heat loss, necessitating even higher tap temperatures.

- With the advent of bottom-pour ladles, the potential for tighter pouring temperature control became possible since the steel is now covered with a thick layer of insulating slag (synthetic slag in case of induction furnace heats) and heat losses are much lower. However, because of the fear of chemical attack or perhaps tradition, the use of magnesite ladle lining continued. High thermal conductivity of magnesite makes it very prone to skulling and it was, only natural to raise tap temperature in order to maintain a clean ladle. This pouring system improved temperature control but the potential for very low and reproducible pouring temperature was not realized until magnesite ladle lining was eliminated.

With the availability of today's high quality alumina refractories, the desire for consistent low pouring temperatures is now a realistic possibility. When coupled with an efficient ladle pre-heat system, heat losses from a well designed alumina lined ladle are extremely low. Since the tapping temperature can now be drastically reduced, there is no chemical reaction with the lining of the ladle and the lining life is high. It is possible to maintain the desired low temperature without the fear of frozen ladle.

HEAT-TREATMENT

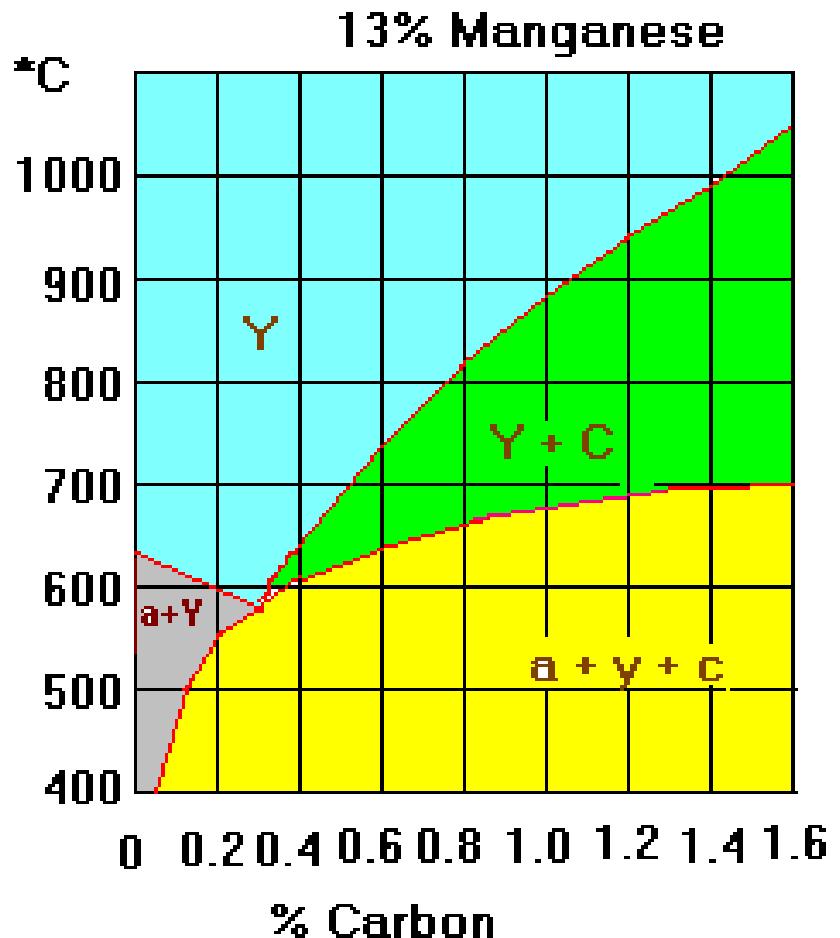
WHAT DO WE WANT TO ACHIEVE BY HEATTREATMENT

- The performance of Manganese steel in wear applications depends mainly on its capability to strain harden under impact and this is due to the presence of carbon saturated austenite in the metal structure.
- When casting cools inside the mould, it cools very slowly. This allows the austenite to decompose to carbide and ferrite. The quantity of decomposed products is dependent on cooling rate which in turn depend on section thickness and mould material.
- The purpose of heat-treatment as such is to retain **100% austenite** at room temperature with all the carbon dissolved in it.

HEAT-TREATMENT CYCLE

- The heat-treatment of Manganese Steel is simple in principle consisting of heating to a fully austenitic condition and rapidly quenching in water. Soaking should be performed above the carbon solubility line A_{CM} as shown in Fig – 2. The A_{CM} should be exceeded by 10° to $37^{\circ}C$ to compensate for carbon micro-segregation.

FIG - 2



Great emphasis is given on the importance of quenching speed. Thus foundries have invested heavily in the equipment necessary to provide for a rapid transfer of hot castings to a large water tank equipped with propellers for vigorous agitation and cooling tower to maintain cool water temperature. Even furnaces have been constructed with drop- bottom facility over the quenching tank itself. In spite of these precautions, a poor micro- structure is still one of the primary causes of premature field failures.

- It is true that slower cooling rates will aggravate toughness due to grain boundary carbide precipitation, especially in heavier sections. But all the undesirable constituents which form below the A_{cm} involve nucleation and growth, hence diffusion and time. It has been shown that retarded cooling down to $871^{\circ}C$ before quenching has no deleterious effect on ductility. This undoubtedly due to the slow rate of carbide formation in the range between A_{cm} to $871^{\circ}C$. Excited physical activity in transferring castings from furnace to quenching tank serve no useful purpose.

- Rather it is the cooling rate over the range of 871°C to 315°C which is important. However, the speed of quenching becomes immaterial if measures are not taken first to ensure that the carbon is in solution in the austenite. The majority of heat treatment related field failures is caused by poor temperature control rather than poor quench.

- Regarding temperature of water in the quenching tank after quenching, it is sufficient to see that water does not continue steaming after quenching. It can be taken care by ensuring that the volume of water in the tank is sufficient enough so that temperature does not rise beyond **50°C**.

- It is also to be noted that some amount of vapor will, in any case, form and, if they remained attached to the body of the casting as they are non-conductor of heat, will prevent the casting from transferring heat to water. As such it is recommended that the water is agitated just after quenching to drive away the steam bubbles from the tank.

- Manganese steel foundries typically use large bogie-hearth oil fired heat-treatment furnaces. This type of furnaces rely on radiation as the mode of heat transfer and, and since batch loading is used, extensive temperature gradients can develop. It is not uncommon to find a very large temperature spread (as much as 200°C) through a load of castings when the furnace is operating at the high soak temperatures needed for manganese steel.

- Modern batch furnaces incorporate a blower system to provide convection as a secondary means of heat transfer. This provides improved temperature control but, in practice, a narrow temperature spread is possible only when the furnace is empty and the situation changes when a load of castings is introduced. In addition, the load of castings have to be carefully arranged with sufficient clearance between castings to allow for the passage of the re-circulating furnace gasses. Since each load of castings is usually different from the previous one, good supervision becomes an important factor.

- Under actual production conditions, the ideal temperature spread should be $+/-15^{\circ}\text{C}$. However, unless a continuous furnace maintenance programme is followed to ensure a constant positive pressure within the furnace, the degree of temperature control will rapidly decline and large temperature gradient will again develop. It is also advisable to install additional furnace thermocouples over those originally supplied by the manufacturer.

- In an oil fired furnace, as described above, the rate of rise of temperature is another concern and from the commercial point of view the temperature is raised as quickly as practicable to shorten the total heat-treatment time, thereby saving cost. But, actually in practice, it is found that the rate of temperature rise from the starting point to about 700 to 800°C is very high and thereafter becomes very slow due to inherent deficiencies of the furnace. And this has resulted rejection of many castings due to cracks.

- It is advisable to load the furnace at room temperature as far as possible and even if it is to be loaded while the furnace is hot from the previous cycle, the burners should not be started for some time to allow heat to be absorbed uniformly through the load. Thereafter, temperature should be raised at a rate not exceeding 50°C per hour up to 650°C . A 1 hr soak at this temperature is necessary to allow the temperature to be uniform throughout the load. From here temperature can be raised at a rate of 100°C per hr up to the soaking temperature.

- It may be asked why it is necessary to be overly concerned with the temperature spread. If adequate carbide solution is all that is desired, the furnace controls can be adjusted to ensure that the coldest part of the load is above specified austenising temperature. However, if such adjustment is made to a furnace with a large temperature gradient, other zones of the furnace will attain excessively high temperature and manganese steels become severely embrittled by over heating.

- The embrittling effect of high heat-treatment temperature upon manganese steel is not well known. At high temperatures incipient fusion occurs at the grain boundaries producing, in severe cases, a continuous network of a ledeburitic type structure. The severity of this defect and the degree of embitterment is strongly influenced by increasing **section thickness, carbon and phosphorous content**. The molybdenum grades of manganese steels are particularly sensitive to incipient fusion, especially at higher carbon level.

- It is a common belief that the large columnar crystals and associated large grain size, which results from high pouring temperatures, are eliminated during heat-treatment. But this is not at all true. Those cannot be eliminated even after double water quenching. It can only be removed and replaced by a finer structure by soaking the castings at 630°C for 12 hours and furnace cooling to 400°C , followed by a conventional water quenching treatment.

This transformation characteristics of plain austenitic manganese steel have been employed to pre-harden the steel before putting it in service and consequently increase the ware life. By this method the steel can be put in service in a wear resistant condition and does not rely on service work hardening alone to produce the required degree of wear resistance. The initial hardness is developed by reheating the fully austenitic steel to within the temperature range of 600°C to 700°C for 6 hours. This treatment produces an acicular structure with carbide needles within the grains, the grain boundaries remaining comparatively free and it is followed by a slow cooling treatment to ambient temperature in time ranging from 10 to 48 hours. The steel is then reheated to within the temperature range of 730°C to 810°C for no less than 2 hours, when the carbide needles get rounded off, thus forming a globular precipitate. When the steel has reached this condition it is quenched rapidly. Steel 2 and 8 in Table 1 show the mechanical properties of such spherodised steel. These steels show increased wear resistance in applications where low stress abrasion is predominant.

Table-1. Mechanical Properties of Cast Austenitic Manganese Steel.

Sl. No.	C O M P O S I T I O N						Heat Treatment	BHN	U.T.S. Kg/mm ²	Y.S. Kg/mm ²	%E	Impact data
	%C	%Mn	%Si	%S	%P	%Others						
1	1.0-1.25	11.0-14.0					1050°C. W.Q.	185- 200	60-100	34-42	15- 40	Izod: 20°C 16ft-lb
2	1.0-1.4	10.0-14.0	0.10-0.30	0.01-0.03	0.1		1040°C.w.q 540-700°C a.c.48hr, 730-820°C, 2hr, w.q.	300- 400	94- 116	84- 98	10- 16	
3	1.34	12.0				Mo-0.5	1090°C.w.q	207	74	42	26	
4	1.22	11.9	0.51		0.019	Mo-2.0	1040°C.w.q pearlitized 590°C.a.c. austenized 980°C.w.q.	217	82	45	29	
5	Regular Manganese Steel(Keel Block)						1040°C.w.q.	175	80	38	40	
6	1.34	12.0				Mo-0.5 Cr-3.0	1090°C.w.q.	228	75	47	18	
7	1.07	10.6	0.5	0.014	0.028	Ni-2.78	As forged condition.		122		33	
8	1.23	13.6	0.57				1050°C.1hr, w.q. 600°C, 8hr, a.c. 980°C, 1hr, w.c.	207	92	42	68	Izod:- at+20°C 115 ft-lb

HOW TO ENSURE SUCCESS OF HEAT-TREATMENT

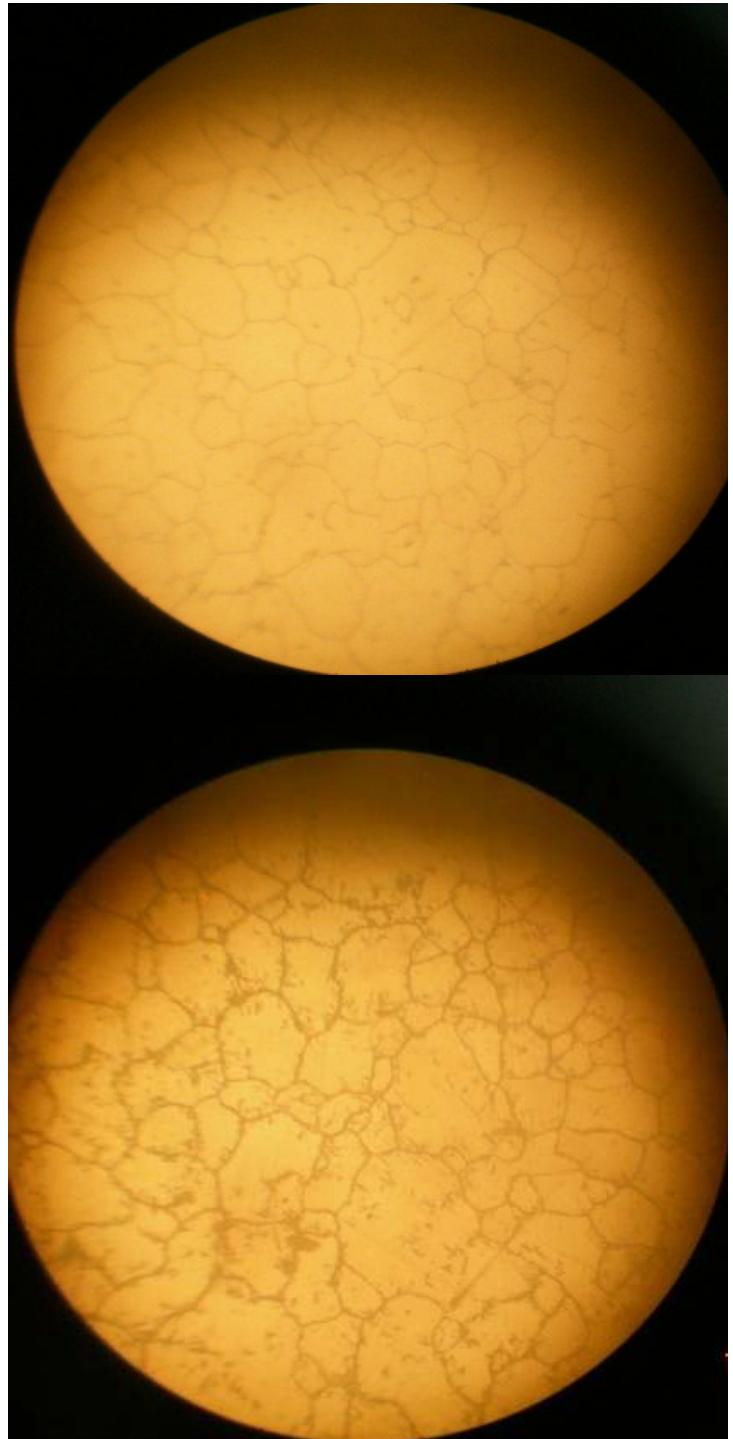
- To ensure that the heat-treatment has been successfully carried out, it has to be checked whether the purpose of heat-treatment i.e. to have **100% austentic** structure with all the carbon dissolved in it, has been achieved.
- There are a number of methods to check this, such as Bend test or Magnetic response test, but the most reliable check is the metallographic test.
- Microstructure of the casting or a representative test coupon which has been cast and heat-treated along with the casting is observed under microscope to ensure success of heat-treatment.
- How a successfully heat-treated manganese steel should look under a microscope is illustrated in **Fig:-3**

MICROSTRUCTURE

Fig-3A shows a microstructure of an austenitic manganese steel having 100% austenitic structure.

A good microstructure contain 100% austenite with very fine grain boundaries without any decomposed products and carbide precipitation.

Fig-3B shows a poor structure of manganese steel having undissolved decomposed products and carbide precipitates at grain boundaries.



CHEMICAL COMPOSITION

CARBON & MANGANESE

- Carbon and Manganese content in manganese steels are not only interrelated, they are related to casting thickness also.
- From Fig-4 it can be seen that %elongation of 13% Mn steel drastically drops with increasing carbon and section thickness.
- As such the choice of carbon content will depend on the ductility to be retained and the casting thickness. For all practical purpose it is safe to maintain carbon between 1.15 to 1.25%, higher the thickness lower the carbon, to take care of the inadequacies of industrial heat-treatment furnaces.

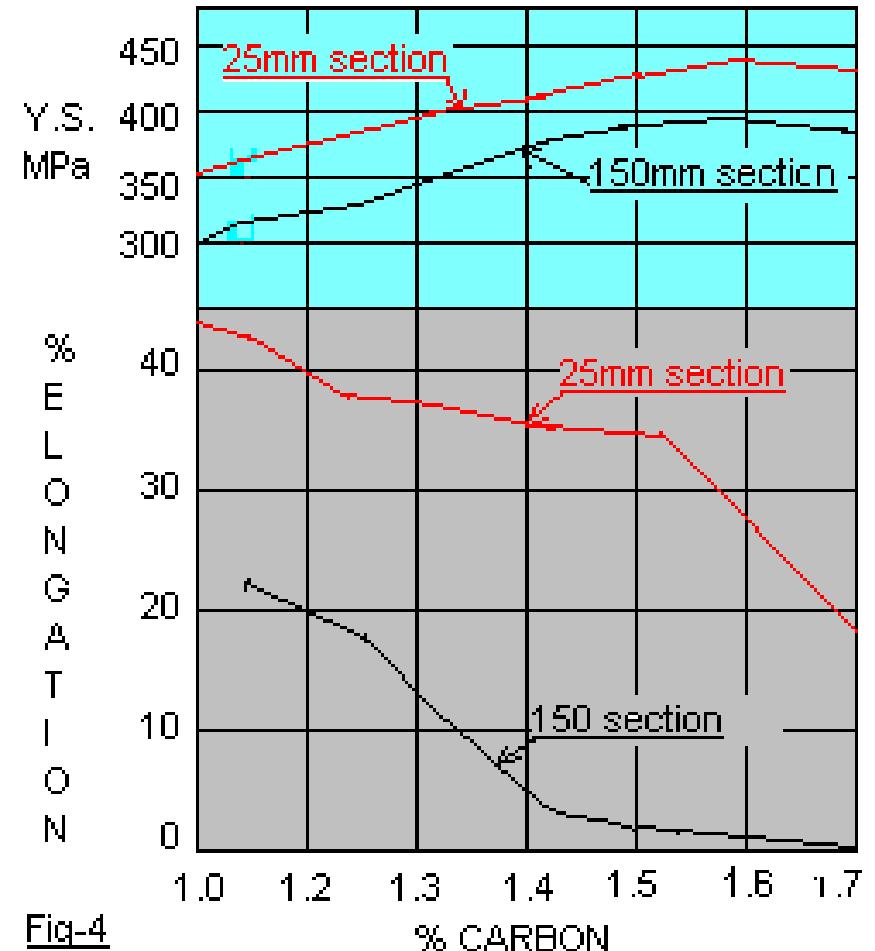


Fig-4

Comparision of 25mm and 150mm thick section

Base Composition-13% Mn, 0.6% Si, 0.035% P

Manganese contributes a vital austenite-stabilizing effect. It sharply depresses the austenite-ferrite transformation and thus helps to retain 100% austenite structure at room temperature after water quenching.

It is widely held that a Mn:C ratio of 10 was optimum without reference to exact levels. This was probably inherited from earlier steel making limitations as it is apparent that the fixed ratio has no basic significance.

Manganese within the range of 10 to 14%, has almost no effect on yield strength, but it does benefit tensile strength and ductility. Below 10% Mn the tensile properties decline rapidly to perhaps half the normal level at about 8% Mn.

For critical requirements 11% Mn is desirable as a minimum; though the improvement over 10% is slight. The maximum is rather arbitrary and probably depends more on the cost of the alloy than on metallurgical results, since acceptable properties may be produced up to at least 20% Mn.

- Austenitic steels with higher manganese contents ($>16\%$) are being manufactured for applications requiring low magnetic permeability, low temperature strength (cryogenic strength) and low temperature toughness. For low magnetic permeability, these alloys have lower carbon and the corresponding loss in yield strength is compensated by alloying with chromium, molybdenum, vanadium and titanium.

SILICON

- The misuse of Silicon has had a more damaging effect upon the reputation of manganese steel than has phosphorous. The harmful effects of P are widely understood, but the embrittling effects of silicon have gone relatively unnoticed.
- As per literature, silicon may be used up to 2% to moderately increase yield strength without significantly effecting toughness. This may be true for 25mm test bar data, but when we talk about heavy section castings, silicon can have a disastrous effect on toughness as shown in Fig-6. Even with 0.6 to 1.0% silicon, toughness is adversely effected with increasing carbon content.

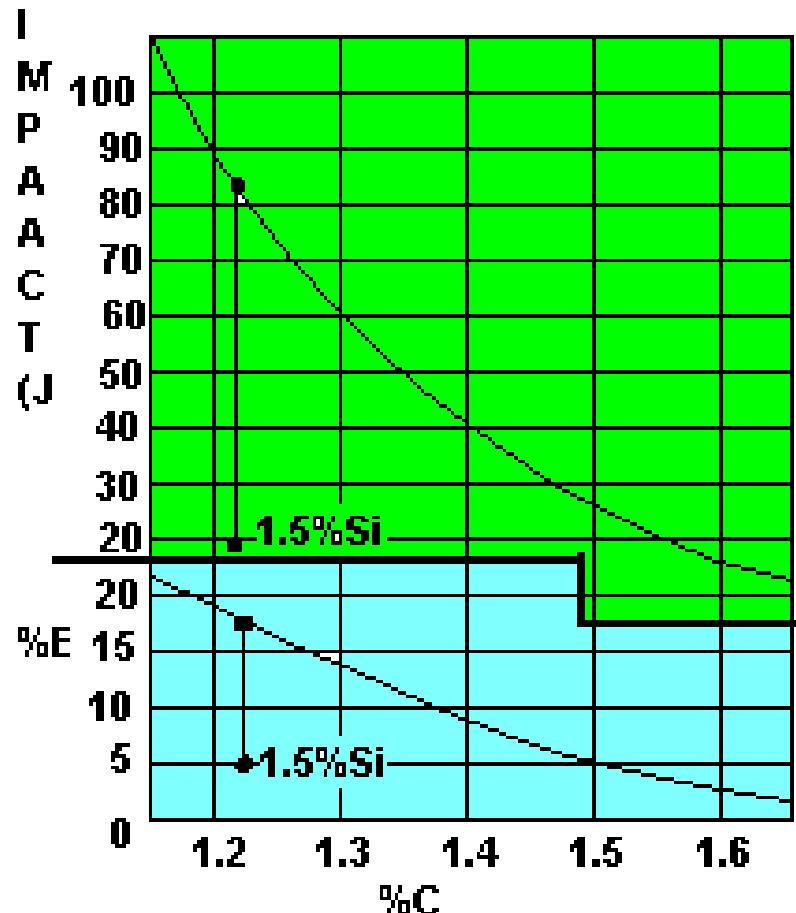


Fig-6.Effect of 1.5% Silicon upon Izod impact energy and tensile strength of 150mm section Mn steel.(13%Mn, 0.6%Si, 0.035%P)

PHOSPHORUS

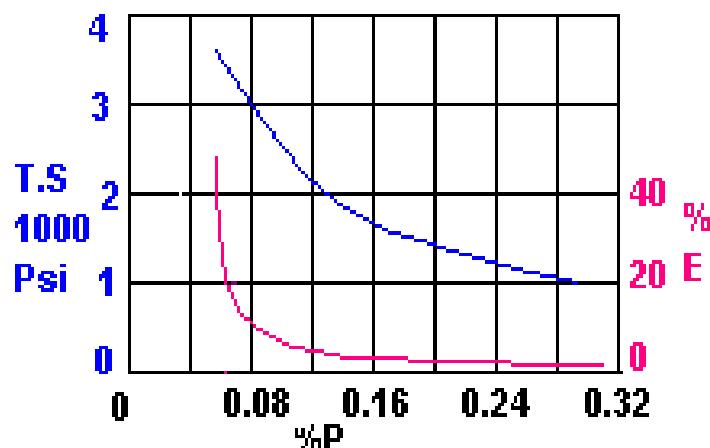


Fig-7. Effect of phosphorus on tensile strength and elongation at 1149°C

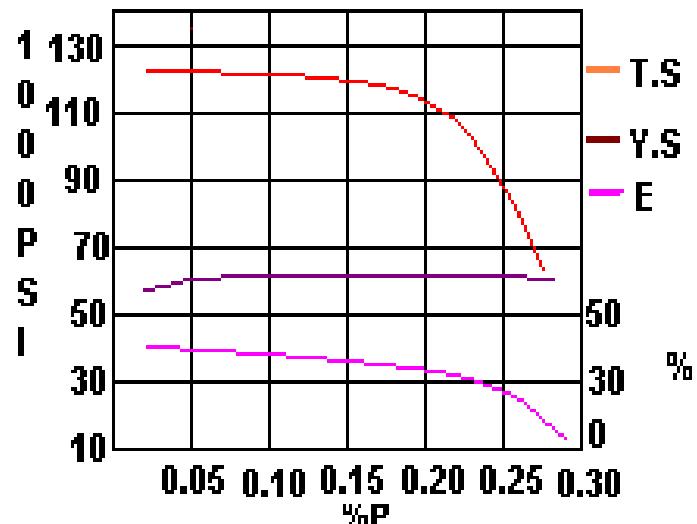


Fig-8. Effect of phosphorus on tensile properties at room temp.

- Although phosphorus content of 0.08% is permitted in specifications, experienced foundry men will hold phosphorus to much lower levels. The most serious problem faced with high phosphorus contents is the effect upon “in plant cracking” rather than the effect on the mechanical properties.

- With regard to the effect on the mechanical properties of the finished castings, tensile data on 25mm test bars show little change in properties up to 0.10%. However, statistical analysis of crusher performance data have indicated significant relationship between phosphorus content and toughness. The degree of embitterment was influenced by other factors such as thickness, carbon, silicon content and other alloy additions, but the clear message is that phosphorus should be held as low as practically and economically possible.

- Phosphorus above 0.02% progressively promotes intergranular cracking in manganese steels as in austenitic stainless steels. Above 0.06%, the high temperature plasticity of manganese steel is severely reduced and the steel becomes extremely susceptible to hot tearing. At such a high phosphorus level, microstructural evidence of grain boundary films of phosphide eutectic can be observed. Below 0.06% phosphorus, no microstructural evidence can be observed but phosphorus still effects the hot tearing propensity. The maximum tolerable phosphorus content is depended upon the severity of the stress system which is related to casting design, size and riser location. For massive, complex castings it is advisable to hold the phosphorus below 0.04%.
- Phosphorus also effects the cracking susceptibility during the removal of large risers and in welding operations. The same arguments apply here as for hot tearing. In case of welding, the phosphorus content of the weld metal (combination of base metal and weld rod) should not exceed 0.03% if cracking is to be prevented.

SULFUR

- Sulfur is seldom a factor in 13% manganese steel, since the scavenging effect of manganese, for which it is customarily added in simple steels, operates to eliminate it by slagging or fixing it in the form of innocuous rounded inclusions of manganese sulfide. Elongation of these inclusions in wrought steels may contribute to directional properties: in cast steels they are considered harmless.

ALUMINIUM

- The addition of Aluminium in plain austenitic manganese steel has a considerable influence on the shape and distribution of phosphides. In such cast steels deoxidized with 0.05% Al (residual content 0.02% Al) and containing 0.08% P, the phosphorus occur as large particles on the grain boundaries. When the residual aluminium content is increased to 0.08 to 0.15%, there is a major reduction in the amount of phosphide precipitated along the grain boundaries and the ductility and impact properties are slightly increased. The influence of aluminium after solution treating the steel was found to be equally favorable. If manganese steel is well deoxidized in this way, improvement in wear resistance properties will result.

CHROMIUM

- It may be more prudent to identify chromium as an impurity to manganese steel since misuse of this element has generated huge losses for both producers and users. Chromium increases yield strength and flow resistance, which can be useful in certain applications: however, on the other side of the ledger, chromium is very detrimental to toughness and is extremely sensitive to section size variation.
- Published data on effect of chromium is misleading since interaction with section size and carbon content are omitted. 25mm test bar data indicates no significant loss in toughness up to 2% Cr, whereas the actual sacrifice in a casting is considerable. Fig-9 shows effect of a 2% Cr addition on the impact strength of 150mm section manganese steel.

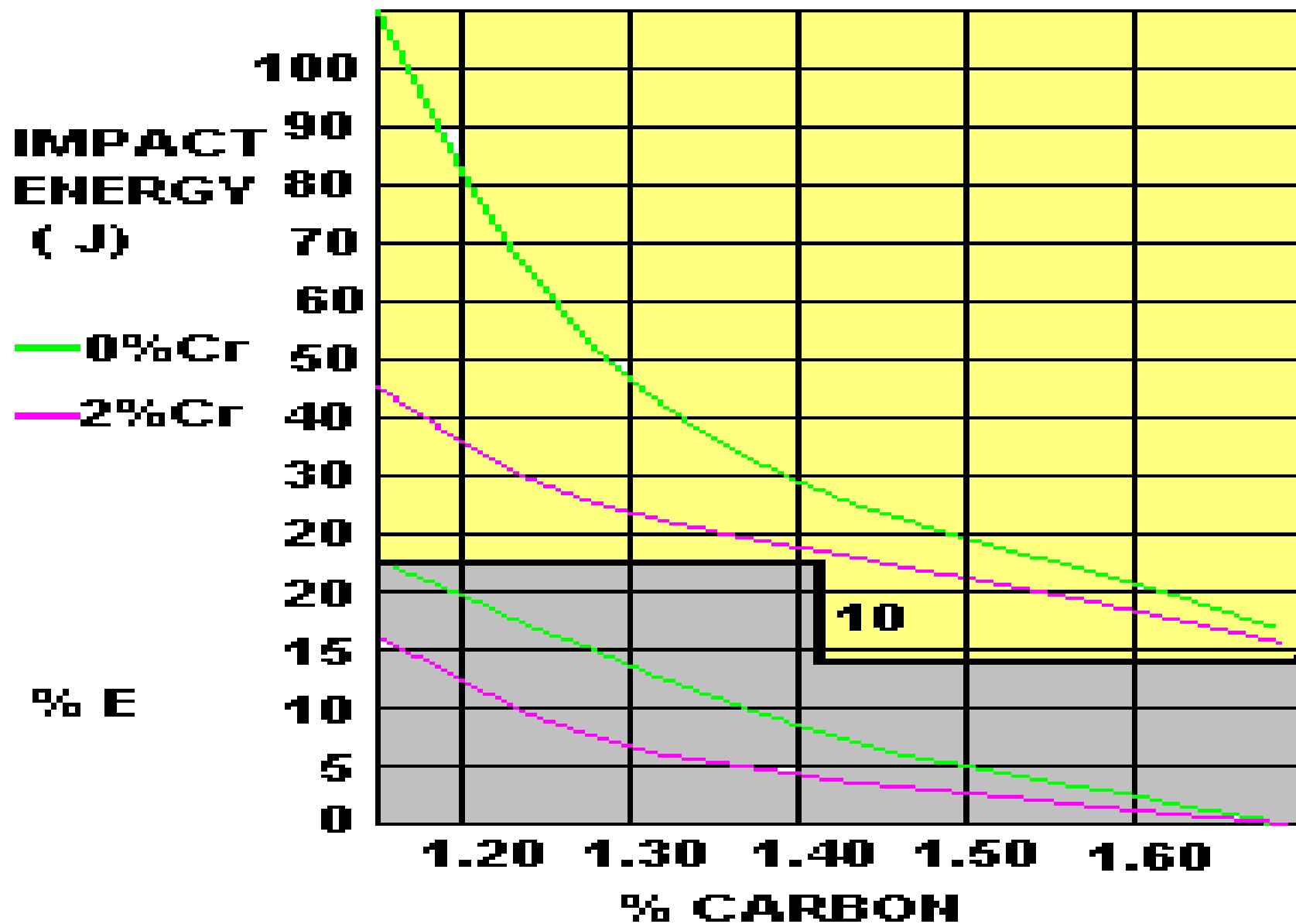


Fig-9. Effect of chromium on impact energy and elongation of 150mm Mn steel (13.0% Mn, .06% Si, 0.035% P)

- Even these data do not tell the whole story since chromium greatly inhibits the heat-treatment response, which further compounds the problems.
- For a 2% Cr-Mn steel at a typical carbon content of 1.20%, an austenising temperature in the region of 1125 to 1150°C is required to ensure complete carbon solution. Thus, when this requirement is coupled with the limitations of industrial heat-treatment equipment, it is easy to visualise the potential danger with the 2.0% Cr-Mn steel grade, especially at higher carbon contents. Only a slight deviation in any of the critical processing steps can destroy the remaining toughness and the result will be a cracked casting or one which will eventually fail prematurely.

NICKEL

- It has been shown that adding nickel to plain austenitic manganese steel decreases the tensile strength, slightly increases the ductility but has no effect on yield strength. However, nickel improves the toughness of such steel by inhibiting the precipitation of grain boundary carbides during re-heating and cooling. This produces a steel less susceptible to hot tearing and more amenable to welding.
- It has been reported that the addition of 3.5% Nickel to manganese steel with a carbon content of 0.7% prevents the precipitation of carbides during re-heating and maintains the tough austenitic condition without recourse to water quenching.
- Another beneficial effect of nickel is that it improves low temperature impact strength.

MOLYBDENUM

- An important contribution made by molybdenum additions is the significantly improved as cast mechanical properties and the enhanced resistance to carbide embitterment which occurs if manganese steel is re-heated. In foundry terms, this translate into easier shop handling with reduced propensity for cracking, especially during the removal of gates and risers, arc-air flushing and weld repair. For this reason, molybdenum (usually a 1% addition) is a valuable contributor to the production of massive crusher castings. However, it is very important to remember that carbon is the embrittling element and these beneficial effects for large casting production are only of practical significance at lower carbon contents.

- The ability of molybdenum to suppress carbide embitterment at elevated temperatures is also very useful for castings which encounter re-heating during service. Such application include castings subjected to repeated weld re-building and hard facing and wear castings used at elevated temperatures (up to 500°C). For complex thin section castings which are difficult to heat-treat without warping, “as-cast” molybdenum grades offer an alternative. A 1% Mo to a low carbon (up to 1%) manganese steel will have minimum elongation of 20% and charpy V-notch impact values in excess of 40 ft-lb for castings up to 37mm sections in the as cast condition.

- In the molybdenum grades of manganese steel, at a carbon level above 1.2%, incipient fusion will occur at a temperature below that desired for adequate solution of carbon in the austenite. Thus molybdenum grades are not suitable for high carbon content in the conventional heat-treatment form.
- The above is overcome by the dispersion hardened molybdenum grades with 2%Mo and 12%Mn, which offers a remedy to incipient fusion as high temperature solution treatment is avoided. The dispersion hardening treatment consist of transforming part of the austenite to pearlite by heating to 600°C, followed by re-austenising between 980 to 1010°C which dissolves the as cast carbides together with some of those present in pearlite. The undissolved carbide form a fine dispersion of spherodised particles and in this condition the steel has better yield, tensile strength and ductility than plain 12%Mn steel. Fig-10 shows how the cone crusher liners performs better due to the addition of 2%Mo followed by dispersion hardening treatment.

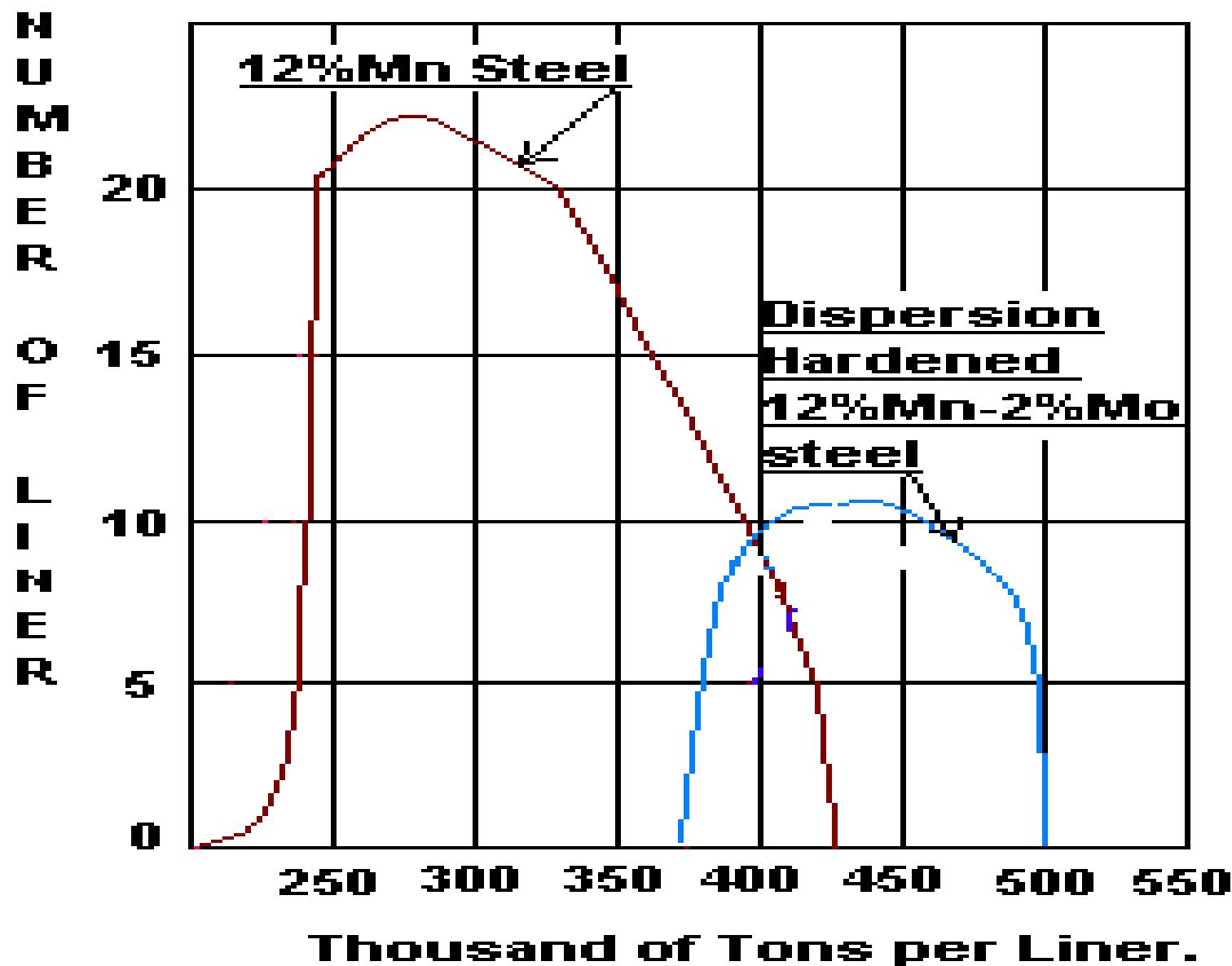


Fig-10. Frequency chart of service life of standard cone crusher liners used by the Climax Molybdenum Company.

TITANIUM, BORON, VANADIUM, COPPER, TUNGSTEN AND NITROGEN.

- **TITANIUM**:- Titanium has been added to conventional austenitic manganese steel in amounts ranging from 0.03% to 0.24% in order to refine grain size of jaw crusher castings and consequently increase their life by minimizing cracking. In heavy sections the grain refining effect is not prominent, but the titanium ties up carbon and in effect, makes the steel equivalent in ductility and yield strength to a lower carbon grade of manganese steel.
- **BORON**:- Boron has no effect in reducing the extent of the columnar zone in castings but can exert a grain refining action similar to titanium and nitrogen. The presence of boron will accelerate the formation of precipitates at low temperatures and will have a detrimental influence on this respect.

- VANADIUM:- Vanadium has been added to austenitic manganese steel in order to increase the initial hardness of the steel and thereby make it more wear resistance under conditions of low stress abrasion. Such a steel having the composition 1.8%C, 0.81%Si, 15.24% Mn and 5.5% V has been shown to be 50% harder in the water quenched condition than the normal manganese steel. The carbon content of this steel has been purposely increased in order to partly replace that which is used in carbide formation, without depleting the carbon content of the matrix. However, under conditions where the full work hardening of plain austenitic manganese steel is developed, this vanadium modified steel may have no advantage.
- COPPER:- Copper acts in a similar manner to nickel and molybdenum and markedly increases the stability of the austenite, though not to the extent as molybdenum. Thus it is possible to decrease the manganese content to about 6% in presence of 1.2%C and 3%Cu and produce a structure which is entirely austenitic and there was hardly any effect upon the yield and tensile strength, and the ductility. Unfortunately, the abrasion resistance of this steel containing copper are much inferior to those containing 1%Mo.

- TUNGSTEN:- Additions up to 3% tungsten to austenitic manganese steels have been studied. Such steels are given the dispersion hardening treatment to obtain a higher initial hardness value than would be obtained from applying the water quenching treatment to the conventional composition. Steels containing 2 and 3% tungsten work harden more rapidly than the conventional manganese steel, but not so rapidly as a dispersion treated 2%Mo steel.
- NITROGEN:- Nitrogen stabilizes austenite and it has been postulated that the solubility of nitrogen in austenitic manganese steels increases as the temperature decreases., 0.05 to 0.06% being soluble at normal atmospheric pressure and temperature. It has been shown that an austenitic manganese steel containing 0.035 to 0.06% nitrogen can be produced free of blow holes, but more work is required in this respect in order to obtain satisfactory results in commercial practice.

WORK-HARDENING

WHAT IS WORK-HARDENING?

- Theoretically, atoms in a metal crystal are supposed to be arranged in a regular, repeated three-dimensional pattern. But real crystals deviate from the perfect periodicity, they have defects or imperfections known as point defects, line defects and plane defects. The line defect, also known as dislocation, is the defect responsible for the phenomenon of slip, by which most metals deforms plastically.
- The usual method of plastic deformation in metals is by the sliding of blocks of the crystal over another along definite crystallographic planes, called slip planes. Slip occurs when the shear stress exceeds a critical value. The atoms move an integral number of atomic distances along the slip plane, and a step is produced which is known as slip line.
- One of the chief characteristics of the plastic deformation of metals is the fact that the shear stress required to produce slip continuously increases with increasing shear strain. The increase in the stress required to cause slip because of previous plastic deformation is known as **STRAIN HARDENING** or **WORK HARDENING**.

- It is known that the number of dislocations in a crystal increases with strain over the number present before and strain hardening results due to dislocation pile up on slip plains at barriers in the crystal. The pile up produce a back stress which oppose the applied stress on the slip plane.
- It is understood now that strain- hardening or work-hardening is caused by dislocations interacting with each other and with barriers which impede their motion through the crystal lattice. As such it can be concluded that the rate of work hardening can be increased if the barriers, which impede movement of dislocations, can be increased.
- Two important barriers for movement of dislocations are grain boundaries and solid solution alloying additions.

GRAIN BOUNDARY

- Grain boundaries exert a considerable influence on plastic-deformation behavior of metals. They may serve to either strengthen or weaken a metal, depending on temperature, rate of strain, and the purity of the metal. At temperatures below approximately one-half of the absolute melting point, and for relatively fast strain rate(so that recovery effects are not great), grain boundaries increase the rate of strain hardening. Associated with the increased strain hardening is usually an increase in yield stress and tensile strength.
- The fact that the slip lines stop at grain boundaries can be readily observed with the light microscope. However, by means of special etch-pit techniques and high-magnification electron microscopy of thin films it is possible to establish that dislocations pile up along the slip planes at the grain boundaries.

- Grain size has measurable effect on most mechanical properties. For example, at room temperature, hardness , yield strength, fatigue strength, and impact resistance all increases with decreasing grain size. The effect of grain size is largest on properties which are related to the early stages of deformation, for it is at this stage that grain boundary barriers are most effective. Thus yield stress is more depended on grain size than tensile strength.
- It does not need any more emphasis on the importance of grain size and thereby pouring temperature as it is the only variable in the process of manufacturing which contributes to grain size, because as-cast grain size cannot be refined by standard heat treatment.

SOLID SOLUTION

- The introduction of solute atoms into solid solution in the solvent-atom lattice invariably produces an alloy which is stronger than pure metal. There are two types of solid solutions. If the solute and solvent atoms are roughly similar, the solute atoms will occupy lattice points of solvent atoms. This is called **substitutional solid solution**. If the solute atoms are much smaller than the solvent atom, they occupy interstitial positions in the solvent lattice. This is called **interstitial solid solution**. Carbon, thus, forms interstitial solid solution with γ -iron in austenitic manganese steel.
- The distribution of solute atoms in a solvent lattice is not usually completely random. The solute atoms group preferentially at dislocations, stacking faults, low-angle boundaries, and grain boundaries.

- It is generally held that the hardening from solute atoms results from the interaction of solute atoms, in the form of “**atmospheres**”, with dislocations. Since the atoms in the region above a positive edge dislocation are compressed and below slip plane are stretched, the strain energy of distortion is reduced by large atoms collecting in the expanded region and small atoms collecting in the compressed region. **Interstitial atoms, such as carbon**, collect below the slip plane of a positive edge dislocation. Because the local energy is lower when a dislocation is surrounded by a solute atmosphere, a higher stress is required to make the dislocation move than that if there were no interaction between the dislocation and the solute atoms. Earlier it was believed that solute atoms would segregate only to edge dislocations, because a screw dislocation ordinarily has no tensile component. More recently it has been shown that there is a strong interaction between interstitial atoms and screw dislocations when the lattice is non-symmetrically deformed by the solute atoms.

POSTULATIONS

- It is now well established that the best, may be the only, way to improve performance of austenitic manganese steels substantially in wear applications involving erosion and impact is to augment its **strain hardening capacity**.
- From the previous discussions it is understood that two major factors are responsible for strain hardening of manganese steels and they are **grain size** and **interstitial solute atoms in γ -iron** which is stable at room temperature.

- Carbon forms interstitial solid solutions in γ -iron and is the largest contributor to the strain hardening capacity of austenitic manganese steel. It is to be realized eventually that, only by increasing carbon to the highest practically possible level where it can be kept in solution after quenching, significant performance improvement of austenitic manganese steels can be achieved, as it is evident in Fig-11.

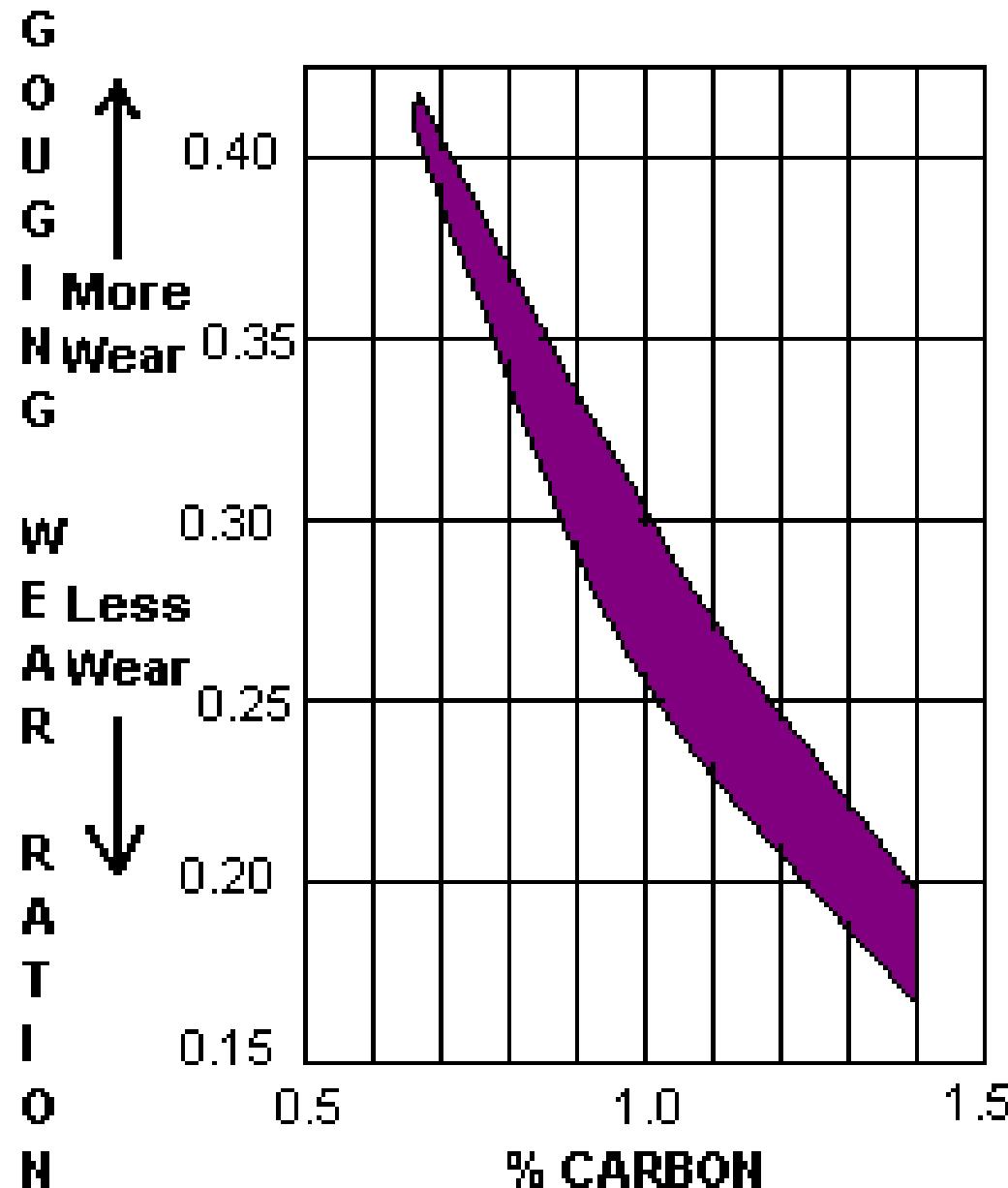


Fig-11. Gouging wear ratio of austenitic 12% manganese steel vs. carbon content

- There can be two ways to increase carbon content –
- a) To increase the cooling rate from 871°C to 315°C during quenching to such an extent so as to surpass the speed of precipitation of carbides from austenite. It may be possible in laboratory to simulate this situation, but does not appear feasible in shop floor, especially with heavy section castings.
- b) The alternative is to make the transformation of austenite more sluggish and slow so that the excess carbon is not allowed to precipitate even with standard quenching practice. It appears to be the best possible way to achieve this, is to increase the manganese content along with carbon, as manganese contributes the vital austenite stabilizing effect without effecting mechanical properties up to a level of 20% .

INCREASE CARBON? TO WHAT EXTENT?

- If we look at the Ternary diagrams of Carbon, Iron and Manganese, it will give us an idea about the solubility of carbon in austenite at different temperatures, but it is to be kept in mind, ternary diagrams represent pure metals in isothermal conditions. In the ternary diagrams shown, the “ α ” phase is a solid solution of carbon and manganese in “ α ” iron and the “ γ ” phase is a solid solution of carbon and manganese in “ γ ” iron. The phase designated as “C” is a carbide of the form $(Fe,Mn)_3C$. Manganese atoms dissolved in α or γ iron forms **substitutional solid solution** by replacing iron atoms from lattice points and carbon forms **interstitial solid solution** by occupying interstices in the lattice.

Fig-12

**Carbon-Iron-Manganese
Ternary Diagram at 900°C.**

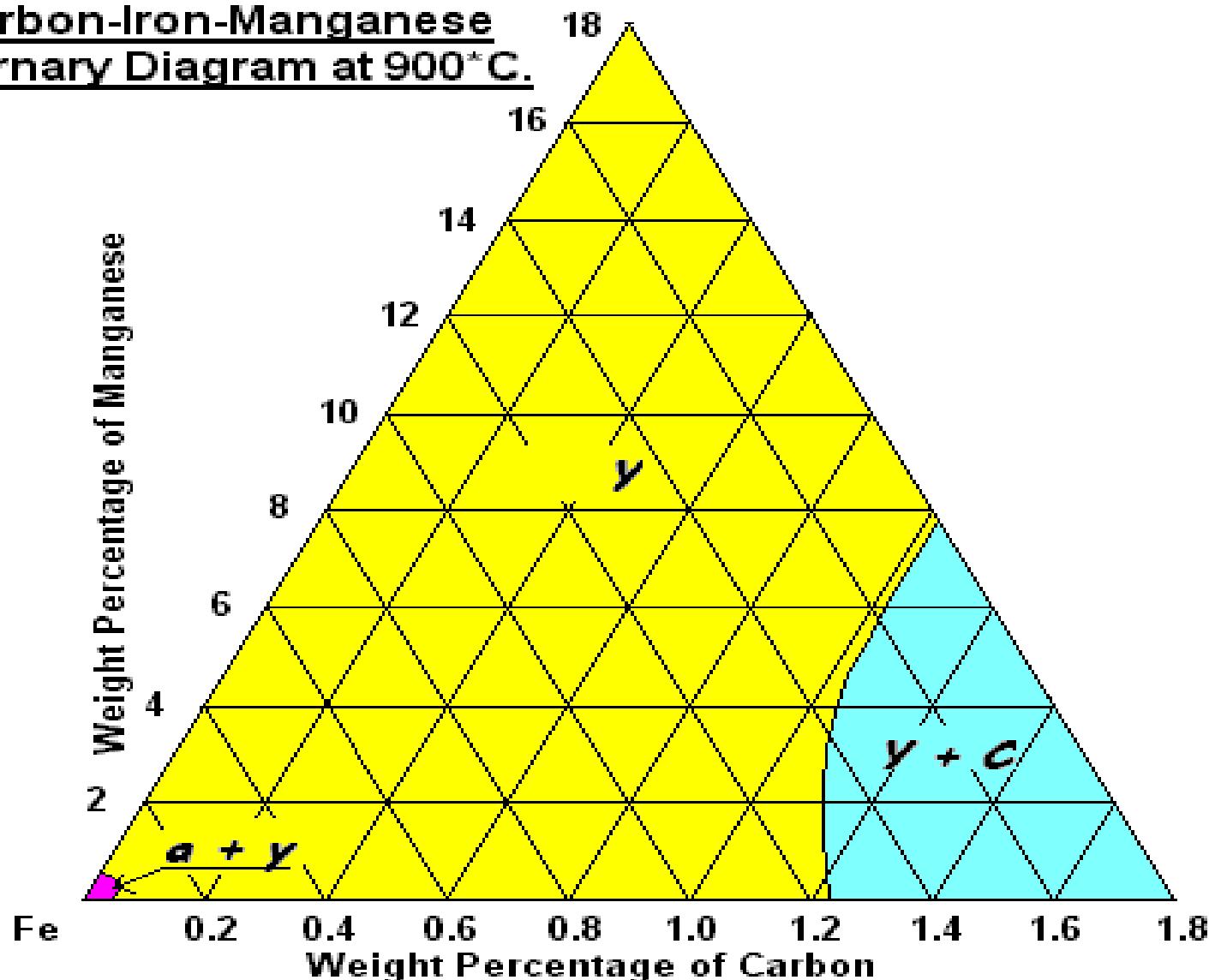


Fig-13
Carbon-Iron-Manganese
Ternary Diagram at 800°C

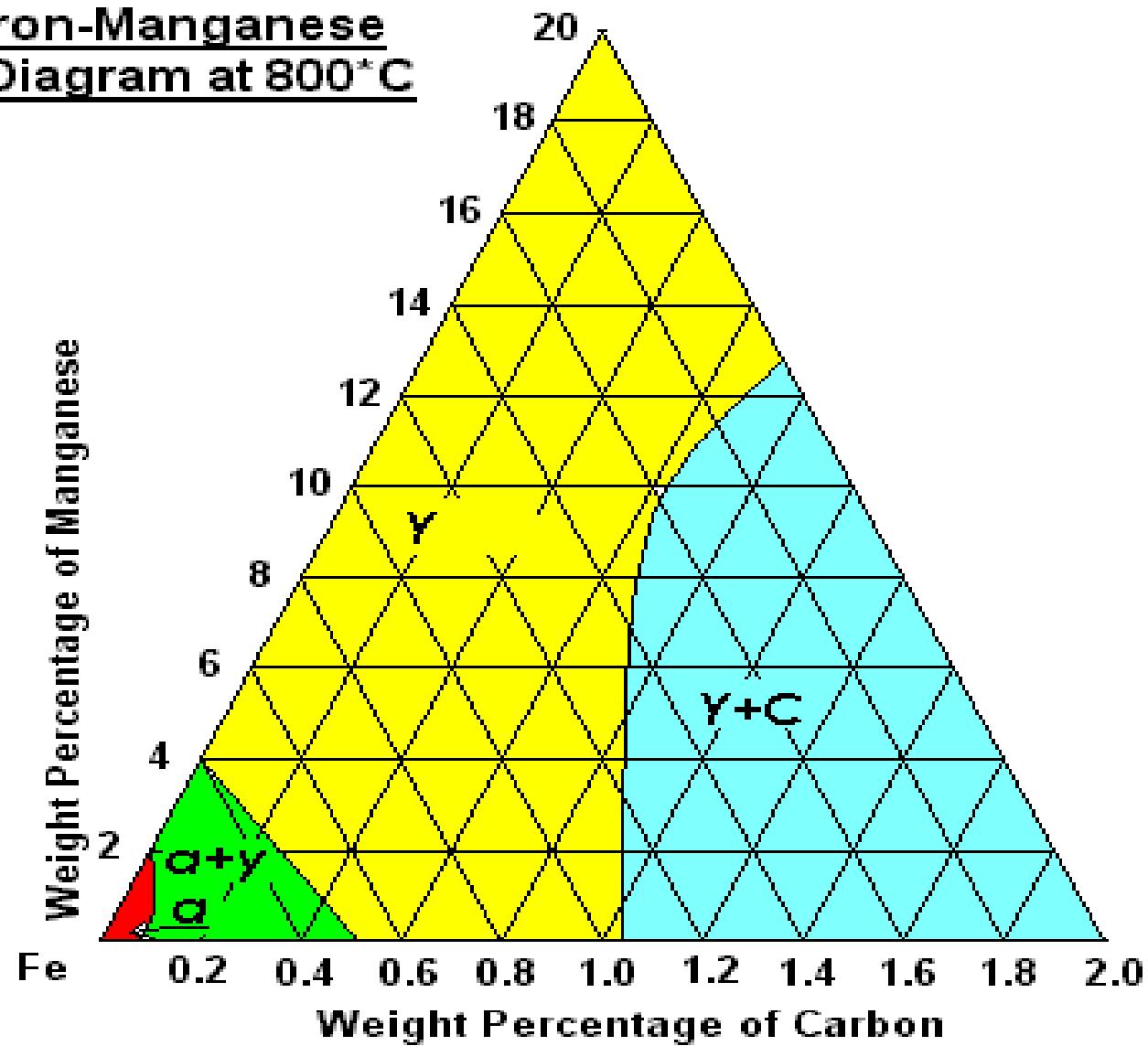


Fig -14

**Carbon-Iron-Manganese
Ternary Diagram at 700°C**

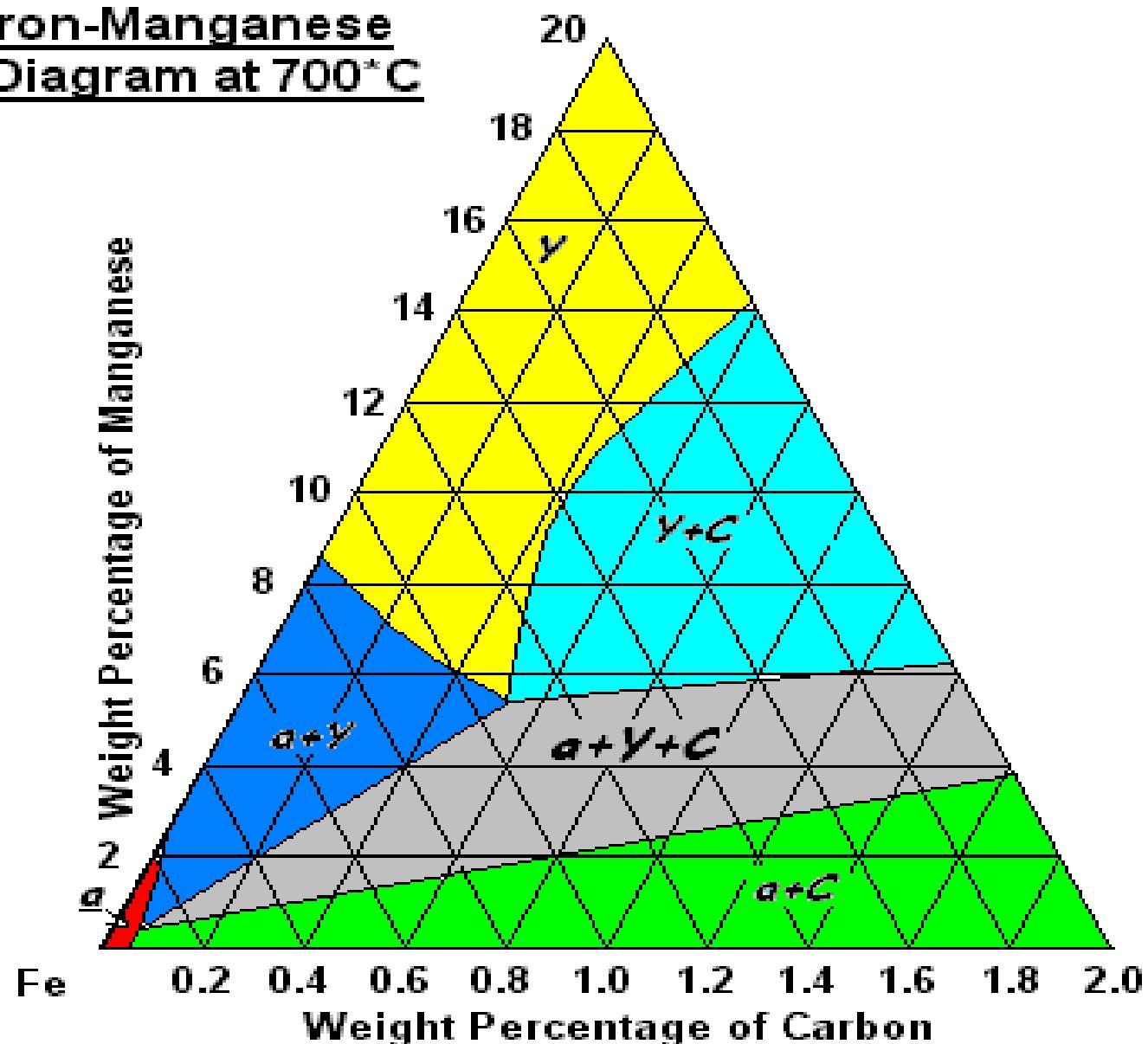
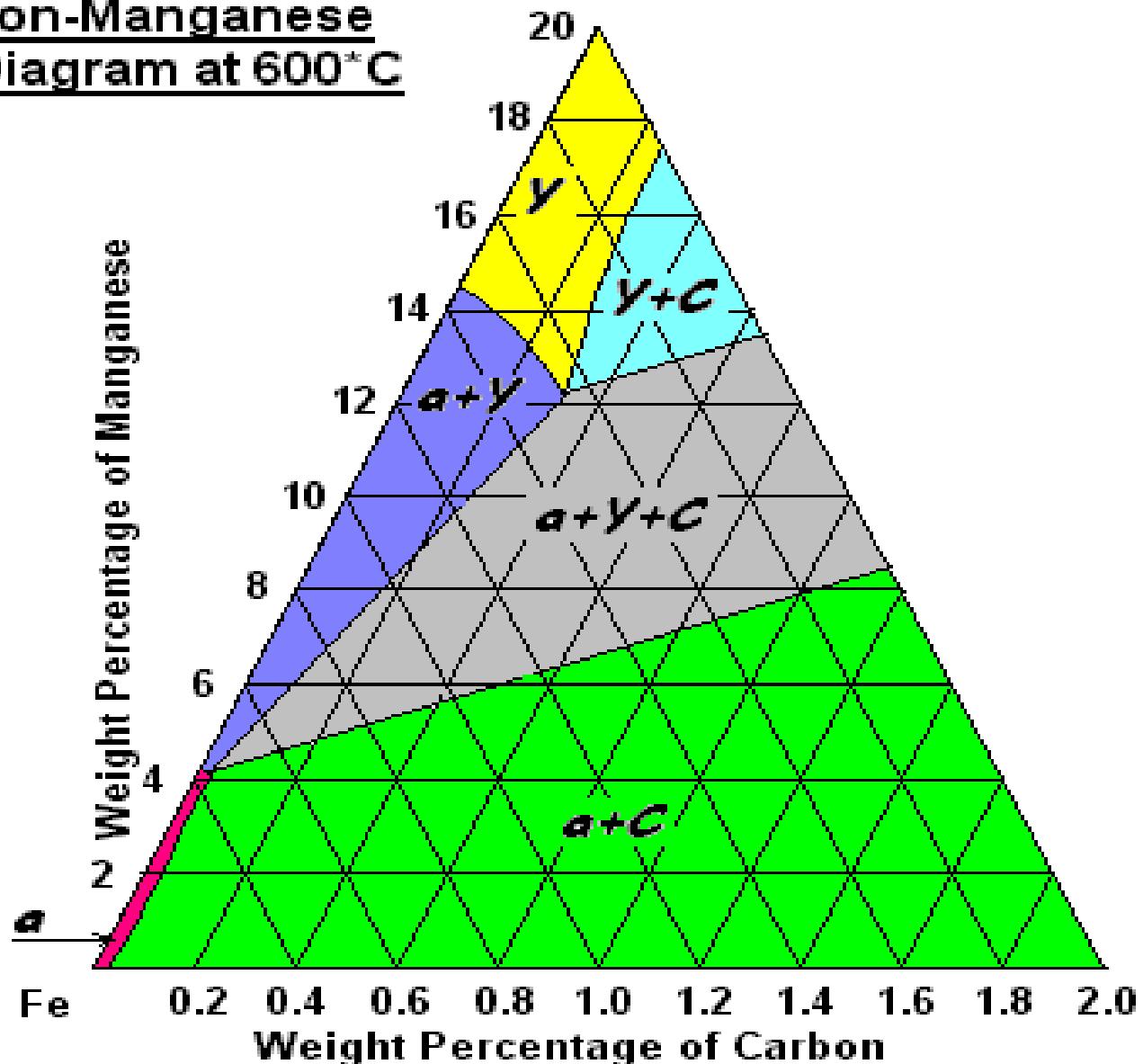
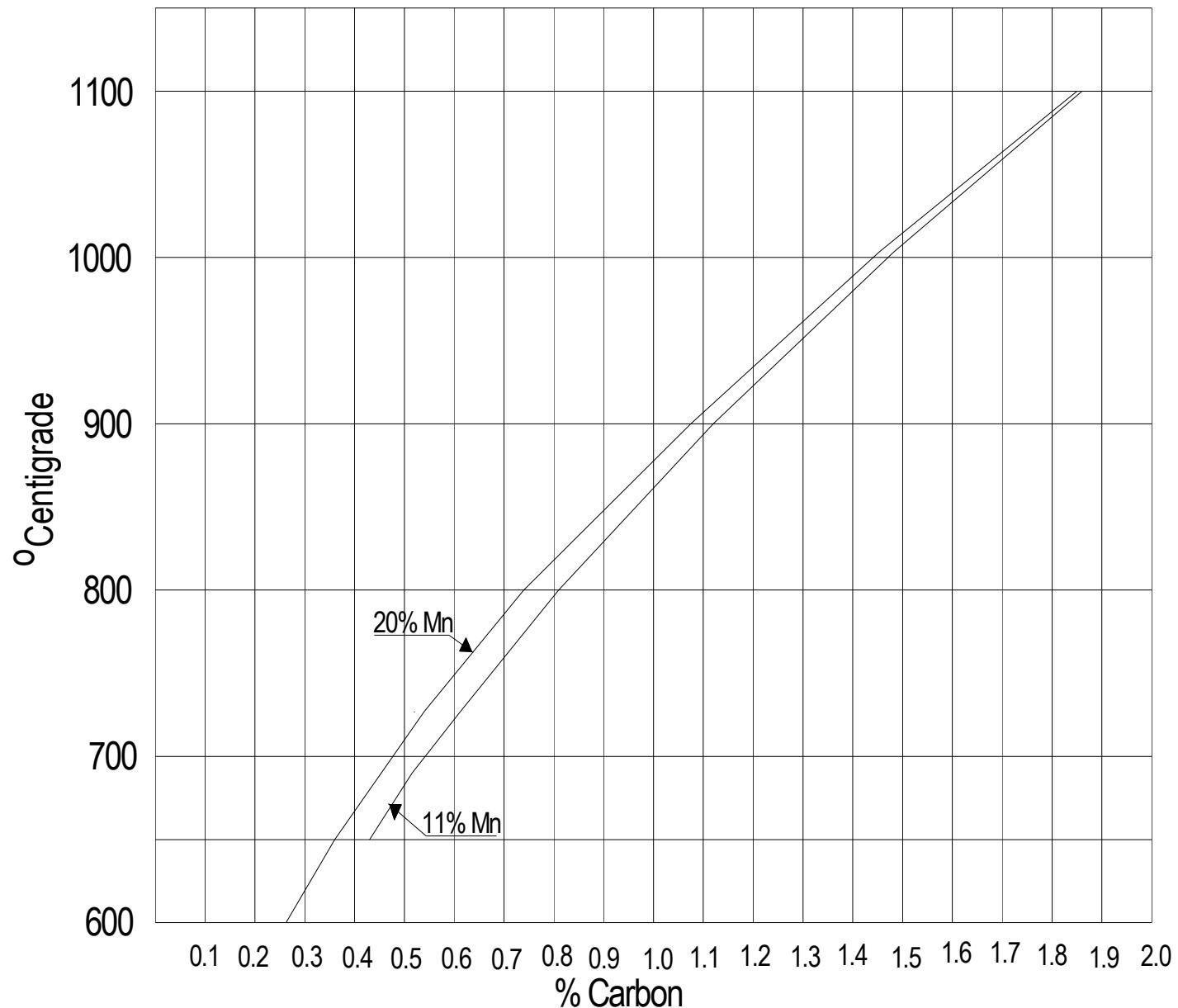


Fig-15
Carbon-Iron-Manganese
Ternary Diagram at 600°C



Keeping in mind that ternary diagrams shown before are true only at isothermal conditions, it can be seen that solubility of carbon in austenite at higher temperatures is much more than what is normally in solution after quenching. If the rate of transformation during quenching can be retarded further, a higher carbon content can be kept in solution after quenching. Figure- 11, constructed with the help of isothermal sections of Fe-Mn-C ternary system from 600 to 1100°C , indicates that carbon as high as 1.85% can be in solution at the austenizing temperature of manganese steel. If the rate of transformation during quenching can be retarded further, a higher carbon content can be kept in solution after quenching.

Figure - 11



Solubility of Carbon in Austenite in Isothermal condition in Fe-Mn-C System

CONCLUSIONS

- Since austenitic manganese steel castings have a big share of total demand of castings all over the world, innumerable foundries, right from the highly sophisticated and quality conscious foundries to even a foundry adopting thermit process for melting in a small crucible, produce manganese steel castings today. As a result there has been a wide scatter in the performance of standard austenitic manganese steel castings. This is because, except a few, most of the foundries do not have knowledge of metallurgy of manganese steel and not aware of the strict controls required to produce good quality manganese steel castings. And when complaints start coming from the users or the performance is compared with the products of the few good foundries, most foundries, almost blindly, start trying different modifications of manganese steels with different costly alloys, instead of trying to improve the manufacturing process.

- It can be safely said that scope still exists to improve the performance of not only the standard manganese steels, there is also scope for further improvement by increasing carbon content above the normally specified limit.
- The author has successfully produced austenitic manganese steel castings of 75mm section thickness with 1.5% carbon which has outperformed other grades of manganese steels at least by two times.
- But it will be wise to note that before venturing into variations from the standard manganese steel composition or heat-treatment processes, one should first standardize the process controls as discussed before, otherwise it may have disastrous effect on the reputation of the foundry.

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THANK YOU