ULTRA-HIGH STRENGTH IN STEEL

by

V. R. Parameswaran
Defence Metallurgical Research Laboratory, Ishapore

ABSTRACT

Very high strength levels in steel, not obtainable by conventional methods of hardening by quenching and low temperature tempering, are obtained by new hardening techniques involving the thermal-mechanical treatment of metastable austenite.

The earlier attempts on such hardening techniques and the development of new processes such as 'Ausforming' investigated in the Ford Motor Company Research Laboratoires and "Maraging" developed and patented by the International Nickel Company (Mond) Limited, are briefly reviewed here.

Introduction

Steel has been the most common constructional material due to its superiority over other alloys. Though the strength to weight ratio of steel is much smaller than that of alloys like Duralumin and Aluminium-Magnesium alloys, it possesses excellent resistance to reactions in nuclear vessels, retains good strength at high and low temperatures, and withstands alternating loads better than the above alloys. The utility of steel can be considerably enhanced if its strength to weight ratio can be increased. The possibility of further increasing the strength is indicated by the fact that even the best of high strength steels manifest only a fraction of the potential theoretical fracture-strength of 2·5 million p.s.i. of iron, as calculated by FRENKEL's classical method. However, the limiting factor in effecting such improvements in mechanical strength using the conventional technique of quenching followed by tempering at lower temperatures, is the loss in ductility and toughness that follows the increased hardness and strength. Thus various investigators have been working on this problem of increasing the strength of steel by methods other than conventional. This aspect has come into prominence recently on account of the requirements imposed in the design of modern aircraft and special weapons. The following is a short review of the various such investigations carried out.

Most of the techniques generally employ mechanical working of metastable austenite at a temperature where it remains stable for sufficiently long time without undergoing transformation and they differ mainly in the manner and the modus operandi of giving the deformation at high temperature.

Early Attempts

As early as 1950, Richard F. Harvey[1] used the principle on oil hardening high carbon tool steels. He used two lean alloys—(A) Chrome-Vanadium (C .. 0·95%) and another, (B) Chrome-Molybdenum (C .. 1·04%) steel. The steels in the form of strips 3″ × 3/4″ and 0·051″ thick were quenched from austenitising temperature of 1500°F in a salt bath kept at about 500—515°F and after homogenising, were shot peened while hot on one side and then quenched in oil at room temperature. The intensity of peening was measured by the curvature. On measuring the hardness values in both cases, the shot peened side showed an increase in hardness of 2·3 numbers on the Rc scale over that obtained on the other side. The retained austenite also was found less on the peened side than the other by about 7%, although the method of determining was not mentioned. In this new technique of step quenching (See Fig 1) as he called it, high intensity of peening was allowable without danger of cracking. Other properties investigaged, like, fatigue, impact and tensile were incomplete.

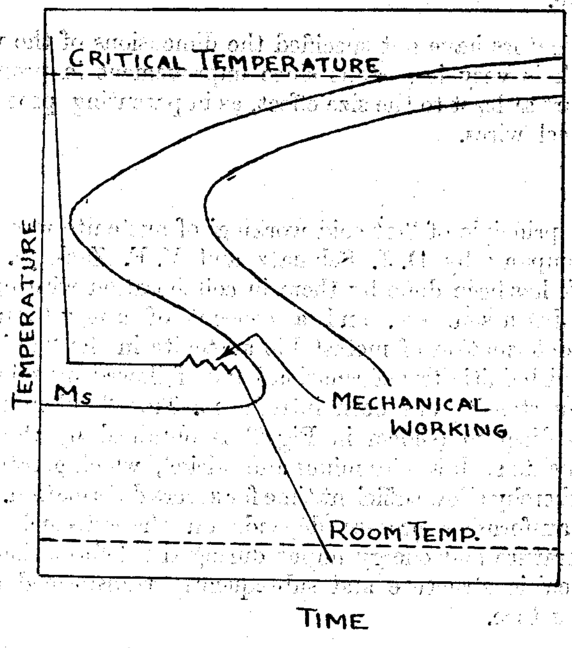

FIG-1

Lips and Van Zuilen[2] in Holland reported in 1954 the remarkable increase in strength achieved in strips by working the metastable austenite. The steel used contained 0·35% carbon, 1·50% chromium and 4·50% nickel.

NOTE—The figures appearing in parenthesis pertain to the references appended to this paper.

The improvement in properties was reported as shown below:—

	Conventional hardening	*New Method*
Yield point (p.s.i.)	295,000	400,000
Hardness .. Rc	56·5	58
Elongation %	2	12
Reduction in area%	5	42

The strip showed outstanding spring qualities and ductility quite unusual for the high hardness attained.

Wires of very high mechanical properties and creep strength were obtained by the same workers by drawing plain carbon music wire (0·92% C) after austenitising, through dies kept immersed in suitable hot liquids at proper temperature. The new method yielded a wire that had a creep strength of 310,000 p.s.i. in contrast to the old method that gave a creep strength of 220,000 p.s.i. to the wire.

The investigators have not specified the dimensions of the wire and strip employed which is very important since improvement in properties can be attributed in part at least to the size effect, as in patenting process of drawing high carbon steel wires.

Ausforming

The above principle of 'hot cold working' of austenite was studied in the Ford Motor Company by D. J. Schmatz and V. F. Zackay[3]. Considerable amount of work has been done by them in collaboration with others like J.C. Shyne, W.M. Justusson, etc. and a concept of a new term 'Ausforming' as the plastic deformation of metastable austenite in the 'bay' area between the pearlitic and bainitic transformation bands followed by subsequent transformation to martensite has been introduced. This 'bay' in the isothermal transformation diagram (shown in Fig 2) is obtained by the addition and balance of elements such as chromium and nickel, which greatly stabilise the austenite and thereby allow sufficient time for severe deformation. The successful application of ausforming process depends on the extremely close control of time, temperature and energy imput during the deformation for retaining the fully austenitic structure and subsequently transformed completely to martensitic structure.

In their first series of experiments, 5 steels melted in vacuum with chromium content varying from 1·42—1·46%, Nickel content ranging from 3·96—4·75% and Carbon from 0·28—0·97% were rolled at different temperatures giving different amounts of deformation and then quenched. The specimens were then tempered at various temperatures and the variation of mechanical properties with tempering temperatures for different amounts of deformation at 1000°C were plotted for different alloys. The tensile strength, yield strength and elongation were found to increase with increasing percentage of deformation at any temperature. A 0·49% Carbon alloy when deformed 75% at 1000°F.

quenched and tempered at 200°F showed tensile strength exceeding 400,000 p.s.i. For the ausformed material, the yield to tensile ratio was higher than the conventionally hardened material and ductility was good with no evidence of brittle fracture. However, the effect of retained austenite on the strength of these steels after ausforming was not studied.

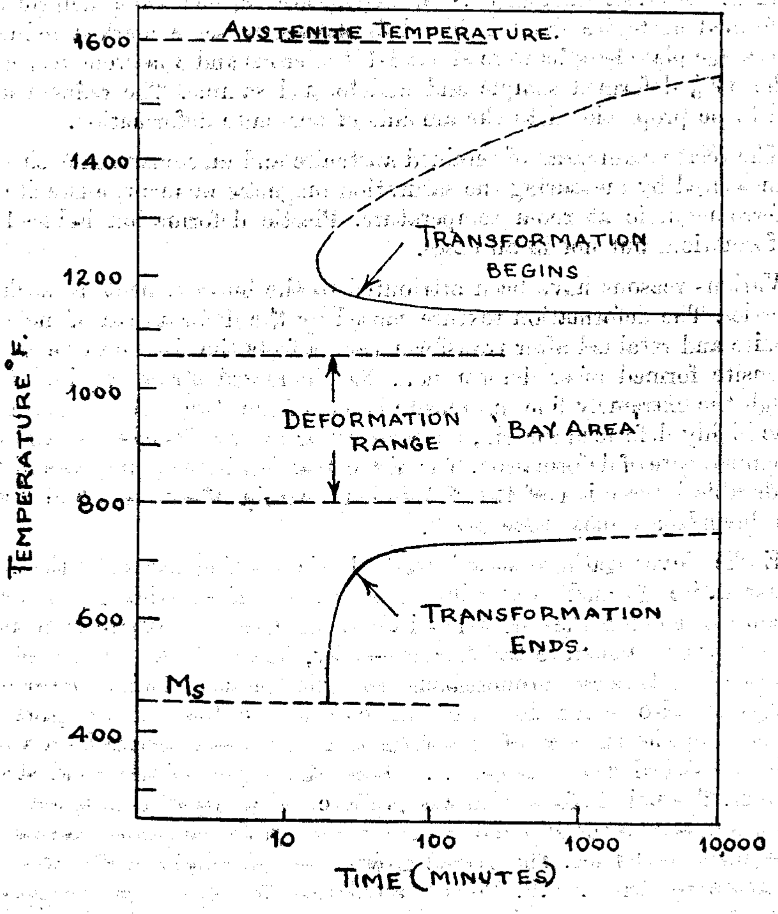

FIG-2.

More systematic work was undertaken by Schmatz, Zackay and Shyne[4] in which three air melted and two vacuum melted steels were tried with Carbon ranging from 0·31 to 0·63%, Chromium between 2·21 and 2·94%, and Nickel between 1·03 and 1·65%. All steels contained 1·50 to 1·60% Silicon, as this retarded the tempering and improved the impact resistance in the 500°F embrittlement range. The TTT curve of one steel was determined as a representative of all others and the 'bay' temperature was 800—1050°F. The specimens were austenitised, cooled in air up to deformation temperature, deformed by multipass rolling and then quenched in oil and tempered at different temperatures. Tensile tests on 1/8″ dia samples ground from bar stock showed that as in ordinary martensite, in the ausformed steels also, the higher carbon steels exhibited greater strengths over the complete tempering range. Highest tensile strengths were observed for the vacuum melted steels—464,000 p.s.i. for the steel V-63 (0·63% C) and 440,000 p.s.i. for the steel V-48 (0·48% C) both after deforming 93% at 1000°F, quenching in oil and then tempering at 212°F. Electron micrographs of martensite formed from deformed and undeformed austenite showed that deformation causes a marked refinement. The average plate lengths were about 1-1/2 microns and 3 microns respectively for the 93% deformed sample and undeformed sample. The refinement was found to be proportional to the amount of austenite deformation.

The relative amounts of retained austenite and martensite in each sample was measured by measuring the saturation magnetic moment, austenite being non-ferromagnetic at room temperature. Plastic deformation induced more transformation, but not in all cases.

Various reasons have been attributed to the improvement in mechanical properties. The deformation texture caused by the deformation of metastable austenite and retained after transformation, affects the size and orientation of martensite formed after deformation. The increased stress required for slip through the extremely fine martensite is one of the strengthening mechanism. In the highly deformed matrix, no recovery or recrystallisation is expected at the temperature of deformation. The dislocation density may be quite high and considerable interaction of the dislocations within themselves and with the grain boundaries may take place.

Earlier investigations showed that plastic working increases the amount of martensite formed. Cottrell[5] in a series of experiments on retained austenite concluded that straining induces complete transformation at temperatures where austenite transforms readily, and that the amount of transformation is linearly proportional to the plastic strain. Jepson and Thompson[6] also concluded that in eutectoid carbon steels, pronounced increment in the amount of transformation to bainite occurred on stressing within the critical stress range, i.e., about the region of the yield stress of austenite. The bainite formation was preferred with respect to distribution and orientation, due to the slip and twinning along preferred planes and directiins in the austenite lattice. The overall growth rate of bainite needles were found to decrease by stress. L.F. Porter attributes the maximum strength of the deformed material tempered at 200°F to an increase in the rate of precipitation of Epsilon carbide. Increase in rates of transformation to bainite and precipitation of Fe$_3$C is assumed to have caused the higher value of yield to tensile ratio of the ausformed material at a lower tempering temperature than the undeformed material.

R.W. Lindsay and E.A. Monier also investigated on the lines of Lips and Van Zuilen[2] with Chromium-Molybdenum-Vanadium steel sheets coated with Magnesium oxide, and packed between cover sheets of low carbon steel. The whole pack was heated to austenitise, transferred to a furnace kept at the bay temperature and rolled to give different percentages of reduction. They observed an increase in strength due to prior deformation, but not so remarkable as predicted by the Dutch workers.

W.H. Chang of the Flight Propulsion Laboratory of the General Electric Company has reported from his tests that strain induced transformation and cold working of transformation products contribute to the strengthening effect. Specimens of different steels were given 75% reduction in thickness by multi-pass rolling, checking being done after each pass for any transformation to have occurred. It was seen that steels which developed strong magnetism (showing larger transformation) had larger strength increments, though in the undeformed condition they were not of higher strength.

The results recorded in experiments with a particular steel, AM-357 annealed from 2000°F, refrigerated for 8 hours at 300°F and tempered at 800°F for one hour, showed a proof strength of 145,000 p.s.i. at 0·2% elongation of gauge length. The same steel after rolling at 800°F with 85% reduction in area followed by refrigeration and tempering as above, gave an yield value of 194,00 p.s.i. Again, the same steel pre-refrigerated at 100°F for 10 minutes to cause partial transformation, followed by rolling at 800°F, refrigeration and tempering as above increased the yield value to 234,000 p.s.i. These remarkable results show the effect of mechanical working on transformed products in strengthening of steels.

The effects of various metallurgical variables such as grain size, carbon content, tempering temperature and the amount of retained austenite on the strength of ausformed steels, were studied by Zackay, Schmatz and W.M. Justusson of the Ford Motor Company[7]. An alloy H-11 tool steel (Vascojet 1000) containing 0·40% C, 5·00% Cr, 1·30% Mo and 0·50% V was austenitised at 1900°F, air cooled to deformation temperature (not given) in the bay region, deformed by rolling, oil quenched and double tempered at 950°F. After each pass through the mill, the temperature of the work piece was determined by an infra red testing device. Simultaneously, the amount of transformation was also determined magnetically using a Helmholtz coil coupled to a fluxmeter. When not deformed this alloy in strip form exhibited tensile and yield strengths of 309,000 p.s.i. and 240,000 p.s.i. respectively. The strength increased as the percentage deformation at a particular temperature increased. 50% deformation at 950°F gave tensile strength of 370,000 p.s.i. and 94% deformation gave tensile strengths of 408,000 p.s.i., whereas corresponding values for deformations at 1700°F were 357,000 p.s.i. and 397,000 p.s.i. respectively. At a particular deformation level, both the tensile and yield strengths were found to decrease as deformation temperature was raised from 700°F to 1200°F. The speeds of deformation which are important, have not been mentioned.

It was found that grain size (ASTM Nos 0—6) had little effect on strength, but the strength increased and ductility decreased with increasing carbon content; and for the alloys of higher carbon content, the amount of retained austenite was also found to increase with increase in percentage of deformation.

Applicability of Ausforming

Ausforming—the thermal mechanical treatment of metastable austenite—has not yet been established as a regular technique for obtaining consistently regular results. There can be different ways of deforming the austenite at different temperatures and speeds by rolling of bar, rod, strip and sheets, hammer and press forging, shot peening, extrusion and hot spinning, wire drawing and deep drawing of sheets, etc. It is expected that high velocity deformation by explosives will be very helpful.

Since the heat-treatment and fabrication can be done simultaneously, the application of the technique can be diversified and can be adopted for any process done at elevated temperatures and in which there is appreciable metal flow.

There are many limitations as well. The mechanical treatment needed at high temperature and later quenching, limit the size of article formed. The loss of strength in the vicinity of a weld would restrict the use of welded construction on materials strengthened by this process. Also, the material would have to be fabricated at its highest strength levels rather than being fabricated in the annealed condition and heat-treated later. These disadvantages limit the versatility of the technique.

Much remains to be done in evaluating properties such as notch-sensitivity, fatigue resistance, behaviour at low temperatures, etc. There are many promising applications in the defence and non-defence areas. Some development efforts have been done on prototype production of small-scale rocket casings and aircraft forgings. The known high elastic strength suggests that ausformed material may find use in high strength wire, springs and suspension applications. The process can be considered wherever high strengths accompanied by adequate ductilities are required.

Maraging

The International Nickel Company (Mond) Ltd[8,9] have announced a new hardening technique called 'Maraging' involving the precipitation hardening of martensite, in their new 18% Nickel alloy steel, which they claim as the only known material that can achieve an yield strength of over 250,000 p.s.i. and yet retain nil ductility temperature below—60°C. The notched tensile strength is above 400,000 p.s.i. measured under severe test conditions with a notch radius of 0·0005″. The nominal percentage composition of the alloy is:—

Carbon	0·03 max
Silicon	0·10 max
Manganese	0·10 max
Nickel	17·00 to 19·00
Cobalt	7·00 to 8·00
Molybdenum	4·60 to 5·10
Titanium	0·30 to 0·50

Small additions of Boron and Zirconium are also made.

10-ton commercial heat was produced in an arc furnace by air melting and ingots as large as 23″×42″ were rolled into plate. The hardening is accomplished by holding for about 3 hours at 450—500°C followed by air cooling. No quenching is required to develop optimum mechanical properties even in large section sizes. Machining characteristics were excellent both as rolled and fully hardened Sound crack-free welds can be produced in fully heat-treated plate without pre-heating. The following properties are claimed by the makers of the alloy in the air melted material in hardened condition:—

Ultimate tensile strength	112—124 tons per square inch
Elongation	10—12%
Reduction in area	48—57%
Notched tensile test	165—172 tons per square inch
(Theoretical notch concentration factor—10).	
Charpy V Notch impact strength at	20°C—18—26 ft lb
	—73°C—14-16 ft lb
	—196°C—12-15 ft lb
Nil ductility transition temperature	Below —60°C.
Endurance limit (10^8cycles)	About 45 tons per square inch

Vacuum melting and slight modification of base composition improve strength and toughness further. Preliminary tests have shown yield strength over 130 tons per square inch and notch tensile strengths above 190 tons per square inch with Charpy V notch impact energy of 22—25 ft lb at 20°C. The composition is modified as:—

Cobalt	8·00 to 9·00%
Titanium	0·40 to 0·70%

The modulus of elasticity of the alloy is (20·5 to 27·5)$\times 10^6$ p.s.i., and it has a density of 8·0 gms/cc.

Since the alloy can be worked easily and hardened to highest strength levels by simple process and can be welded at the highest strength levels, this alloy and the process of Maraging can be expected to have great importance in our future fabrication techniques of rockets and missiles.

Outlook

In view of various advantages and the numerous applications in defence for such high quality materials described above, development projects have been undertaken in the Defence Metallurgical Research Laboratory for establishing the techniques of manufacture of super strength wire.

Acknowledgement

The author wishes to express here his grateful thanks to Dr. N. Anjaneyulu, Director DMRL for the encouragement and permission to publish this article.

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