Thermomechanical ausforming technique for producing substitute ultra high strength steels

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THE most important high strength structural alloy used up to the present time is steel. Its easy availability and diverse properties have further added to its undisputable choice for such applications. Other materials (Al & Ti based alloys) which offer similar advantages have only limited applications. The demand for materials with higher strength to weight ratios, has increased considerably in past few years. This is evidenced by the increasing demands by the aircraft industry and space research programmes. Mobility, economy of weight and space and transportability provide further incentive for such highly improved mechanical properties. To effectively meet this situation considerable efforts are being made to fill the need for improved ultra high strength steels.

Some of the important methods by which strength of iron can be increased are by interstitial and substitutional solid solutioning, decreasing grain size, cold working and dispersion hardening. In low alloy or plain carbon steels, highest strength is obtained when the steel is transformed to martensitic structure. The tensile strength of heat treatable low alloy steels has gone up to 110 tons/in^2 by suitable alloying and heat treatment procedures. Increase in strength is generally accomplished by lowering the tempering temperature and has been obtained at the sacrifice of certain amount of ductility and toughness. A great deal of effort has also been directed on the high alloy high strength steels with excellent ductility and toughness. Maraging, precipitation and controlled transformation steels are some of the products of such efforts. The mechanism leading to high strength in these alloys is based on dispersion hardening by the process of precipitation during ageing treatments. The scope of utilisation of these alloys is also limited due to their higher cost of production.

The need for developing inexpensive high strength steels for structural purposes is still felt. Harvey[1] proposed a step quenching treatment, in which the steel is first quenched from the austenitizing temperature into a hot liquid bath maintained above Ms temperature and metastable austenite is then superficially formed by shot pinning and transformed to martensite. He reported some improvements in the properties by such a treatment.

A departure from the conventional heat treatment of steel which attracted attention was first suggested by Lips and Van Zuilen[2] in 1954, as a means for obtaining higher strength in hardenable steels. They reported that unusually high strength could be developed in 4·5% Ni, 1·5% Cr, 0·35–0·9% C plain carbon steels by hot-cold working of metastable austenite prior to quenching to room temperature. Some Russian investigators[3,4] have also reported about the improvements in the resistance to temper embrittlement of steels employing similar procedures. Schmatz and Zackay,[5] Kula and Dhosi,[6] Justasson and Schmatz,[7] Raymond et al[8] and others later confirmed on the basis of their work the feasibility of this thermal/mechanical treatment as a means to improve the properties of high strength steels. Based on the results reported by all these workers and also on the work carried out at BISRA, Duckworth presented a series of excellent papers[9] where he extensively discussed this new field and put forward various classifications and terminologies of thermo-mechanical treatments or TMT.

Definitions and terminologies

As mentioned earlier, the process TMT consists of mechanical working of steel in its austenitic condition with subsequent rapid quenching to prevent recrystallization of the deformed austenite. Broadly, there are two known ways of using TMT. In the first instance the steel is mechanically worked in the stable austenite range (above the AC$_3$ point and the recrystallization temperature) while in the second case the steel is deformed in the range of metastable austenite below the recrystallization temperature. Fig. 1 is the diagramatic representation of the TMT process taken from Harvey.[1]

Deformation of metastable austenites below the recrystallization temperature can again be divided into

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different processes included in TMT. These are (1) controlled rolling the low temperature rolling of ferrite/pearlite steels (2) isoforming-deformation during isothermal transformation to pearlite and bainite, (3) cryoforming deformation of controlled transformation steels and (4) ausforming-deformation of metastable austenite prior to the transformation to bainite and subsequently quenched to martensite.

This paper mainly deals with the ausforming process and the effects of composition and process variables on the mechanical properties of substitute high strength steels, in relation to their potential applications.

The ausforming process

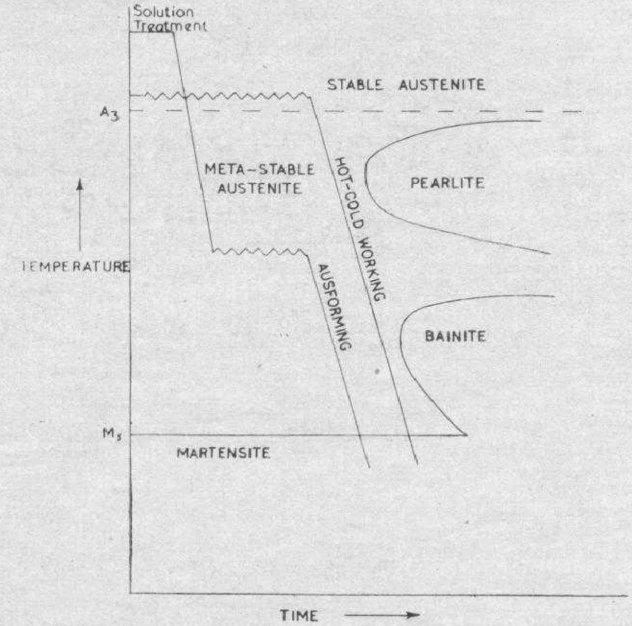
It is well known that the isothermal transformation diagram of any steel (Fig. 1) represents the time dependent reactions and their kinetics. It has also been known that such reactions or transformations do not take place instantaneously and the time required for various transformations to occur are characteristically represented in such diagrams. Ausforming process consists of interposition of plastic strain between the critical temperatures i.e. AC_1 and the Ms. It may also be described as the strain hardening of metastable austenite within the temperature region that exists in the 'bay' between the transformation regions of pearlite and bainite, quenching of the strain hardened austenite to martensite, followed by tempering of the martensite so formed.

Alloying elements in steel profoundly affect the transformation characteristics by altering the incubation period and reaction kinetics of isothermal decomposition. By suitable addition of carbide forming elements, such as, chromium ; molybdenum, vanadium, etc. a 'bay' may be developed in the metastable austenite which is sufficiently stable to resist decomposition during deformation.

It is therefore apparent that there are two essential factors to get an ausformed steel : deformation of metastable austenite and its subsequent quenching to form martensite ; these factors are to be controlled carefully by proper selection of alloying elements and the temperature range of sub-critical deformation.

Plastic deformation procedures

The deformation during ausforming operation may be introduced by a number of processes. In most of the earlier work on laboratory scale measured amount of deformation (extension or compression) was introduced with the help of a tensometer.[10] In later work connected with large scale production, rolling, forging and drawing operations have been mainly used. Shyne et al[11] and Cohen and Tarranto[12] used multipass rolling as the means of deformation, while considerable success has been achieved in BISRA by carrying out the ausforming operation by drawing.

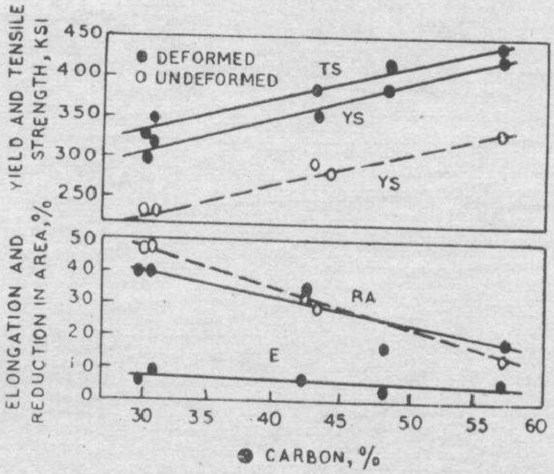


1 *Schematic representation of the principles of 'ausforming' and 'hot-cold working' (Harvey[1])*

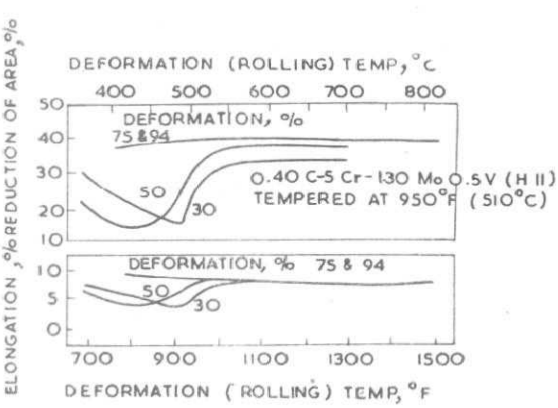
Role of carbon and other alloying elements

It has been established convincingly that carbon is an essential element in steel for achieving appreciable strengthening in the ausforming process and that it plays a vital part in determining the mechanical properties as it does in conventional heat treated steels. It has also been demonstrated[13] that the strength and ductility of ausformed steels are directly dependent upon the carbon content for a given amount of deformation and at a given tempering.

Previous attempts to correlate the properties of the austenite with the strength of the subsequently transformed martensite have been considered on the basis of the contributions from carbon.[12,14] In the absence



2 *The influence of carbon content on the tensile properties of deformed 3·0% Cr–1·5% Ni ; steels. (Zackay et. al [13])*



3 *The dependence of the ductility of a type H-11 steel on the deformation temp. and the amount of deformation (Zackay et al*[13])

of carbon, strengthening of steels by ausforming is small. However, above a certain amount the effect of carbon becomes comparatively less.

Justasson and Schmatz[7] have shown that the response to ausforming in 3% Cr steel is independent of carbon from 0·3–0·6% (Fig. 2). Raymond et al[8] have shown that for a given alloy composition, increase in strength is constant for a range of carbon contents. The level of carbon above which the strain hardening of austenite and the strengthening response to martensite become independent is relatively low and nearly of the order of 0·1% wt. These authors have therefore concluded that some minimum carbon level is necessary to maximize the rate of strain hardening of the austenite and thus fully attain the benefits of ausforming processing.

Other alloying elements play an important role in the ausforming response of steel. One of the important and initial requirements is a large 'austenite bay' in the isothermal transformation diagram of the steel. Alloying additions are therefore to be made to ensure that during the ausforming operation austenite remains stable and does not transform to pearlite or bainite. The carbide forming elements like molybdenum and chromium are quite useful as they separate the pearlite and bainite transformation ranges on the T-T-T diagram of most of the low alloy steels. These elements also cause precipitations of their respective carbides during ausforming in the austenite matrix which has been reported as one of the important factors in the strengthening mechanism.[9,15,16] The rate of strain hardening of austenite[8] and the strengthening response of martensite formed from strain hardened austenite are interrelated.[17,18,10]

It has been reported[9] that alloying elements which increase the rate of work-hardening of austenite during ausforming are beneficial for the increase in strength of the ausformed martensite. Austenite stabilizers which lower the stacking fault energy and hence raise the work hardening rate, such as manganese, have been found to have definite beneficial effect on ausforming response, particularly with moderate amounts of deformation.[19] Silicon also has a beneficial effect as it slows down the rate of diffusion of carbon and thereby resists over-tempering of ausformed steel.[13]

With regard to the ausforming response of high alloy steels Cohen and Tarranto[12] reported very encouraging results with a low carbon steel containing 31% nickel. These authors achieved an increase of 300 psi in yield strength for 1% reduction of the austenite with no appreciable change (40% elongation) in ductility value. Malagiri[20] reported some interesting results with 13% Cr and 9% Ni and 15% Cr, 4% Ni and 3% Mo stainless steels containing 0·4% and 0·13% C respectively by deforming at 800°F and 1000°F. Attempts to ausform other type of stainless[21] or maraging steels[22] have not been successful to the same extent.

It may however be stated that low alloy steels exhibit better response to ausforming and best results have been achieved with low alloy martensitic steels.

Metallurgical and operational variables

Even though the alloying elements play the major role in achieving success in the ausforming of steels, there are other factors which are equally important to develop the ausformed propeties fully. These are as discussed below.

Austenitizing temperatures

It has been established that ductility and toughness in martensitic steels increase with decreasing grain size of martensite. Since grain size of martensite is directly dependent on prior austenite grain size, it is obvious that austenite grains should be kept as small as possible by keeping the austenitizing temperature to the minimum i.e. just high enough to take into solution the required carbon and other alloying elements as these have an important role in the ausforming response of the steel. Zackay and Justasson[13] have however reported that strength and ductility of ausformed steel are independent of solution temperature but later work by Duckworth et al[23] has shown that the low soultion temperatures are preferable from the point of view of strength though this leads to some loss in ductility.

Temperature, time and amount of deformation

Considerable amount of work has been done to work out the role of these parameters and the results of recent work are quite consistent. Generally the strength of a strain hardened metal is dependent upon the amount of deformation, the temperature and time of deformation. It has similarly been established by some workers[14] that lowering of deformation temperature in ausforming process leads to greater strength increases.

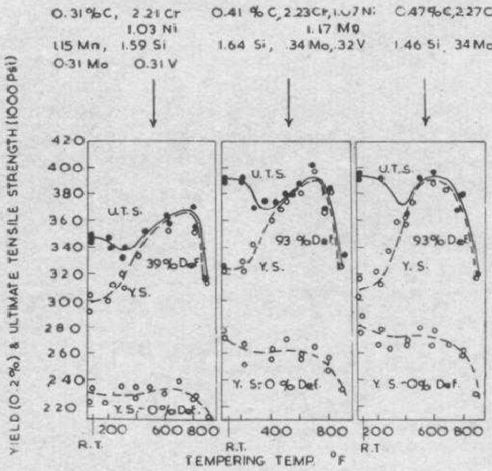
Duckworth et al[22] and others reported that lower deformation temperatures give improved strength without any significant drop in ductility. Kula and Dhosi[6] have however reported about the reduced impact properties due to lowering of the temperature of deformation. Grange and Mitchell[24] have also shown that a change in the austenite grain shape, produced by a given deformation, is more important than the deformation temperature, provided there is no transformation or recrystallization.

It is however obvious that the deformation should be carried out at the highest possible temperature to decrease the working load.[25] It may be mentioned that successful ausforming operation has been carried out at temperatures as high as 800°C.

Zackay et al[13] have shown that the period over which deformation is carried out at any particular temperature is not a critical factor provided adequate hardenability exists. Other workers[25] have also reported that of deformation at a given temperature has little effect provided recrystallization or phase transformation does not take place.

The amount and rate of deformation are important variables in ausforming process and have considerable influences both on the increase in tensile strength and ductility. Zackay et al[13] showed that tensile and yield strength of a 0·4% C–5% Cr–1·3% Mo–0·5% V increases at the same rate with the amount of deformation. The rate of increase however falls rapidly at higher temperature of deformation and with higher degree of deformation.

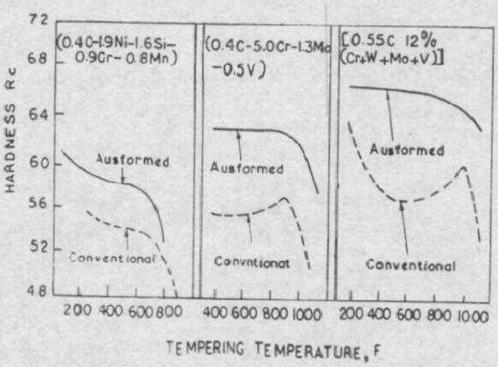
The rate of deformation is also quite important in the ausforming process as increase in the working rate has been found to improve both tensile strength and ductility. As regards the effect of amount of deformation on the ductility of the ausformed steels, the information given by various authors are not consistent. Kula and Dhosi[6] reported that ductility values are practically independent of the deformation temperature and amount of deformation in a 0·4% C, 1% Ni, 1% Cr steel, while Shyne et al[11] showed that ductility in two 3% Cr, 1·5% Ni, 1% Mn, 1·5% Si, 0·4% Mo steels containing 0·48% and 0·63% C deformed to 90% were however much better than conventionally treated steel. The ductility of the ausformed steels containing higher carbon showed rapid decrease during tempering while those of conventionally treated steels showed a general improvement. Conventionally treated steel with lower carbon content shows better improvement in ductility values with increasing tempering temperature. Zackay et al[13] reported that ductility of an ausformed steel containing 0·3 C, 3% Cr–1·5% Si is somewhat complicatedly related to the deformation temperature and the amount of deformation as will be evident from Fig. 3. It will be apparent from Fig. 3 that above a cartain critical deformation temperature (in this case about 1000°F) any amount of deformation between 30% and 94% results in ductility change, equal to or greater than observed in the conventionally heat-treated condition. At lower deformation temperatures, however, these authors reported that about 75% deformation was required to obtain good ductility.



4 *The response to tempering of steels A-31, A 41 and A 47 fully hardened after 93% austenite deformation (Shyne et. al[11])*

Effect of tempering of ausformed steels

Tempering is nowadays regarded as one of the important procedures subsequent to deformation and quenching in achieving higher strength along with better ductilities in ausformed steels. The response of ausformed steels to tempering is however very much unusual in many respects and it is difficult to find out any direct correlation with the alloying elements and other ausformed conditions though these factors have great influences on tempering behaviour. Figs. 4 and 5 (taken from Ref.[11, 13]) show the effect of tempering on ausformed steels properties. It will be noticed that though no secondary hardening exists in the results shown in Fig. 4, tensile values of some steels show a definite decrease at lower tempering temperatures followed by an increase at still higher temperatures. It has been reported that hardness responses to tempering in the low alloy ausformed steels are similar to that of conventionally treated steels (except that the overall values are much higher for ausformed steel) while hardness vs tempering curves of the ausformed medium and high alloy steels do not show any significant variations in their values, such as, secondary hardening effect etc.



5 *Effect of tempering temperature on the hardness of some ausformed steels (Zackay et al[13])*

The alloying elements which retard the softening effect during tempering are very much beneficial. Tempering effects associated with high silicon content ausformed steels may be mentioned in this connection. It has been observed[13] that at tempering temperatures between 300°C and 450°C, an anomalous increase in yield and tensile strength of about 40 000 lb/in^2 is observed in the alloy containing 3% Si compared to that containing $\frac{1}{2}$–1% Si.

The strength levels of ausformed steels decrease considerably during tempering at higher temperatures though the strength levels maintained are much higher than those of conventionally treated steels of similar composition. A vast improvement in the impact properties is also noticed at this stage.

Mechanism of ausforming

The mechanism of strengthening due to ausforming has been the object of much study. It has been more or less established that the enhancement of mechanical properties of the ausformed martensite is undoubtedly due to a number of complex interrelated factors. The earlier theory on the inherited strain hardening of martensite from the austenite during ausforming is still regarded as one of the important factors.[9, 12] It has however been shown that strain hardening of the austenite is ineffective in the absence of carbon[12] and that increased strain hardening of austenite gives increased strength of ausformed martensite up to a certain degree of ausdeformation. Some authors[26] have therefore expressed their doubts in this explanation while others[27] are of opinion that the transmission of the strain hardening of austenite, caused by the precipitation, to the martensite may be regarded as one of the more possible mechanisms. Electron microscopic studies of thin foils ausformed steels have shown that nucleation or very fine precipitation of alloy carbides during deformation of metastable austenite and their improved diffusion during subsequent tempering are also to be regarded as important factors responsible for strengthening mechanism.[16] Kelly et

TABLE I Mechanical properties of different types of high strength steels

Steel type and compositions etc.	Treatments given	T. S. tons/sq. in	Y. S. tons/sq. in	Elongation %	Reduction Area %	Charpy test values at 20°C ft-lbs
Maraging (18Ni–8Co–5Mo)		55–60	42–52	17–19	70–75	
do	Aged at 450°C	95–110	85–94	14–16	65–70	30–60
do		111–122	104–118	10–12	45–60	15–30
do		115–120	108–112		60	26
Ausformed maraged		116–135	114–137	6·3–7·5	56–61	25–35
Controlled transformation						
Armes 17/7. P. H–Mo		94	90	9	55–60	40–45
Armes 15/7. P. H		100	95	7	55–60	40–45
Armes 14/8. P. H–Mo		105	95	5	55–60	40–45
A. M. 350		80	60	10	55–60	40–45
A. M. 355		90	75	15	55–60	40–45
Firth Vickers 520 sl		80	72	15	55–60	40–45
		Rolled at R. T. (40%)				
301 AISI	Strain	125	85·3	9	40	56–115
(0·12C, 17·4Cr, 7·20Ni)	Hardened	101	72			
302 AISI						
(0·09C, 18·6Cr, 8·8Ni)	(rolled at −75°)	93	81·5	13	40	56–115
308 AISI		80	68			
(0·05C, 19·8Cr, 11·4Ni)			71·5	32	40	56–115
			59			
Ni–Mo Ausformed (air melt)	Tempered at					
3·0Ni, 3·0Mo, 0·2C	315°C	92·86	—	—	—	41
do	do	120·54	—	—	—	17
do	365°C	102·68	—	—	—	11
do	do	112·05	—	—	55	9
do (Vac. melt)	do	117·86	—	—	84	27
do	315°C	108·93	—	—	84	22
5% Cr–Ausformed Steel	515°C					
(5Cr–1·3 Mo, 0·5V and 0·4C)		175·00	161	7·6	37	—
En 56 C	500°C 1 hr.	130·00	—	12	—	30

al[28] showed that the strength increase due to ausforming is due to the deformation twinning of ausformed martensite to a very high degree similar to that produced with very high carbon martensite. It has also been reported by many workers that increased dislocations density in the ausformed steel is also a factor in strengthening mechanism.

The relative importance of each of these factors however varies with the composition of steels and on the deformation details. It can be inferred therefore that the ausforming process is an effective combination of hardening due to mechanical deformation and precipitation.

General considerations

It may be concluded from the above discussions, that ausforming is a highly effective means of achieving high strength, improved fatigue strength, superior fracture toughness and greater wear resistance to low alloy steels. Tensile ductility is not affected in most cases and under favourable conditions there may even be an improvement.

While comparing the properties of the ausformed steels with those of high alloy high strength steels, it is found at the first instance that both maraged and ausformed steels represent the strongest and toughest engineering materials currently available. The controlled transformation steels or precipitation hardening steels do not exhibit such excellent toughness.

The high alloy high strength steels are difficult and expensive to produce from the steel-making point of view, but very easy to manipulate, while the ausformed steels are cheap and easy to cast but difficult to manipulate afterwards. As regards weldability, maraging steels are easy to weld if successfully cast. The weldability of other high alloy high strength steels such as controlled transformation or precipitation hardened steel is quite delicate due to balance of composition, like carburizing and nitriding etc. The ausformed steels however stand the risk of completely lowered strength at the welding zone due to coagulation of the precipitates and stress relaxation. The ausformed steels are much more fine grained and have higher carbon content than other high alloy high strength steels. Ausformed steels are hardened by carbides instead of inter-metallics unlike high alloy high strength steels.

Table I gives some of the mechanical properties of the high alloy high strength steels along with the values of the ausformed steels. While comparing these values with the corresponding values of ausformed steels (Table I) it will be apparent that the ausformed steels have undoubtedly higher strength with comparable or better toughness.

Practical field of application of ausformed steels

The unusual high fatigue and torsional strengths of ausformed steels suggest that they can be used in vehicle suspension systems, such as, torsion bars, coil springs, etc. Their high hardness, toughness and elevated temperature strength recommend them for use in tools, such as punches, dies, cutting tools and shears. Other possible applications are in high strength bolts, aircraft parts, such as, landing gears, structural panels, high strength forgings, and also in agricultural and earth moving equipments.

In defence equipments the possible applications are in missile cases, mortar and rifle barrels, armour body and vehicle, very high strength forgings, extruded parts and sheets in aerospace hardware. It may be mentioned at last that the biggest drawback for the industrial adoption of the ausforming process is that it combines fabrication and heat treatment in one manufacturing process. This obviously imposes limitation on size, shape and subsequent machining and joining operations of the part produced. However, suitable practices can definitely be evolved in future to overcome these difficulties.

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