Laser welding and subcritical annealing of a 2Cr-1Mo steel for pipes operating at high temperatures

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Abstract
Experiments were performed to perfect a process for the CO_2 laser welding of an ASTM A335 grade P22 steel for pipes operating at high temperatures. The corresponding conventional welding techniques require a rather complicated schedule that includes both pre- and post-heating to prevent cracks and martensite formations in melted and heat affected areas, and has a mean duration of several hours.
Qualification of the laser-welded joints was performed according to section IX of the ASME standards. The following results were obtained:
- *defect-free joints without any form of preheating;*
- *a post-weld subcritical annealing process able to reduce the hardness of the melted area to 280 HV in a few minutes (the hardness of the as-welded melted zone is around 400 HV); a similar process was applied at the end of the weld pass by modulating the power density delivered to the welded joint.*
- *Correct temperature distribution during annealing was ensured by means of a control system using a two-colour optical pyrometer focussed on the joint surface, and computerised checking of the incident laser power.*

Riassunto
È stata condotta una sperimentazione per la messa a punto di un processo di saldatura laser a CO_2 su un acciaio ASTM A335 grade P22 per tubi in servizio ad alta temperatura.
Le tecniche convenzionali di saldatura per simili manufatti richiedono un ciclo di saldatura piuttosto complesso comprendente un pre- ed un post-riscaldo al fine di evitare cricche e strutture martensitiche in zona fusa ed in zona termicamente alterata. La durata media di un simile processo è di alcune ore. I giunti saldati laser sono stati qualificati seguendo le specifiche riportate nelle norme ASME Sezione IX.
Sono stati ottenuti i seguenti risultati:
- il processo di saldatura laser non richiede alcun tipo di preriscaldo per ottenere giunti esenti da difetti.
- è stato messo a punto un trattamento di rinvenimento post-saldatura in grado di ridurre, in pochi minuti, la durezza in zona fusa a 280 HV (la durezza della zona fusa as-weld è intorno ai 400 HV); un simile processo è stato praticato a fine passata di saldatura modulando la densità di potenza incidente sul giunto saldato.
- per mantenere una corretta distribuzione di temperatura durante il rinvenimento è stato impiegato un sistema di controllo comprendente un pirometro ottico a due colori puntato sulla superficie del giunto e un controllo computerizzato della potenza laser incidente.

Introduction

Laser welding is ideal for extensively automated manufacturing schedules. At present, however, it is substantially confined to small thicknesses and cases where high strength is not an essential feature of the welded joint. Most laser welding applications in the automotive sector are of this kind.

Generally speaking, the applications described in the literature, as well as those undertaken in specialised laboratories, are characterised by methods that are often inconsistent with the international standards.

In this connection, it should also be pointed out that there are no standards dealing with laser welding, with the result that there is no clear definition of the machining parameter values to be recorded when qualifying a process, nor of the tests needed to certify a joint.

The research work lying behind this paper has revealed inadequacies in the standards commonly adopted for conventional procedures when they are to characterise laser-welded joints, owing to the particular shape of the seam.

The experimental part investigated the welding of a low-alloy ferritic steel for high-temperature applications. This is a sector in which laser welding can greatly reduce the technical problems involved, as well as being quicker and less expensive. The steel in question is primarily employed for products that have to work under pressure and at high temperatures, and must thus conform to special qualification standards establishing the fitness of the welding. The ASME standards (1) were chosen for this purpose.
Joints formed in materials of this type must be subjected to what is generally rather long post-process subcritical resistance or induction annealing.
A completely automatic laser welding and subcritical annealing process was therefore devised with a view to reducing the process time still further.

Experimental part

Material

The ASTM A 335 grade P22 steel employed in the experiments is a low-alloy Cr-Mo steel offering greater strength for the same carbon content than plain carbon steel at high temperatures: its creep strength at temperatures of the order of 500° C is 80 N/mm^2 compared with 40 N/mm^2 for mild steel.

The best mechanical properties are achieved by devising a heat treatment that provides a compromise between the fineness of the dispersed phases and their thermal stability. This must therefore be chosen in relation to the material's anticipated operating temperature and service life.
Steels of this kind are mainly used in the petrochemical, chemical and thermoelectrical industries for pressurised containers, boilers and pipework of every kind.

Weldments were made on pipes 42 mm in diameter and 3 mm thick. The chemical composition and mechanical properties of ASTM 335 grade P22 steel are set out in Table 1.

TABLE 1 - Chemical composition and mechanical properties of ASTM 335 grade P22 steel

C	Mn	Si	P	S	Mo	Cr	R	Rs	A
%	%	%	%	%	%	%	N/mm^2	N/mm^2	%
0.08	0.4	0.22	0.014	0.020	0.94	2.17	517	355	29

Conventional welding processes

Any basic arc-welding technique can be used on ASTM P22, though there are two factors that make it necessary to use greater care in choosing the right process and technology than when working with mild steel:

— high sensitivity to any hydrogen brought into the joint by the weld metal;

— structural changes caused by the welding heat.

Three precautions are thus required:

— preheating to about 350° C

— use of a basic electrode

— postweld heat treatment (T < Ac1).

Laser welding

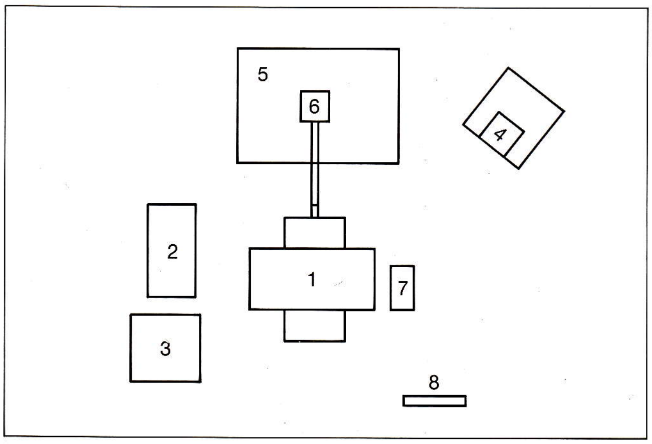
The welding and subcritical annealing tests were done with a continuous cross-flow CO_2 laser (max. power 2.5 kW) (2), a 3-axis (X, Y, Z) handling table, and an electronic spindle. Correct temperature during annealing was obtained with a control system comprising a two-colour pyrometer and computerised checking of the incident laser power.
A diagram and a photo of the layout are shown in fig. 1.

Operating schedule

The process parameters were optimised by means of preliminary penetration tests on solid metal prior to the welding of sample pipes.
Welds were subjected to the full series of examinations laid down in the standards.
When investigating the feasibility of laser welding this class of steels, the postweld heat treatment stage was studied in addition to optimisation of the process. Laser welded-and-annealed joints were therefore subjected to the qualification procedure already applied for the welded joints by the performance of mechanical tests (bending and traction).

The results given by this postweld heat treatment technique were then compared with those obtained first for laser-welded joints annealed by conventional methods, and then with joints TIG-welded according to the code directives (preheating, weld material, post-heating), so as to determine its limits.

Fig. 1 - Work station used for the tests
1) laser head 2) electrical and gas mixture supply unit 3) cooling water temperature checking unit 4) movable control console 5) operations booth 6) handling and focussing system 7) workpiece handling system power supply unit 8) gas pressure reduction and distribution unit



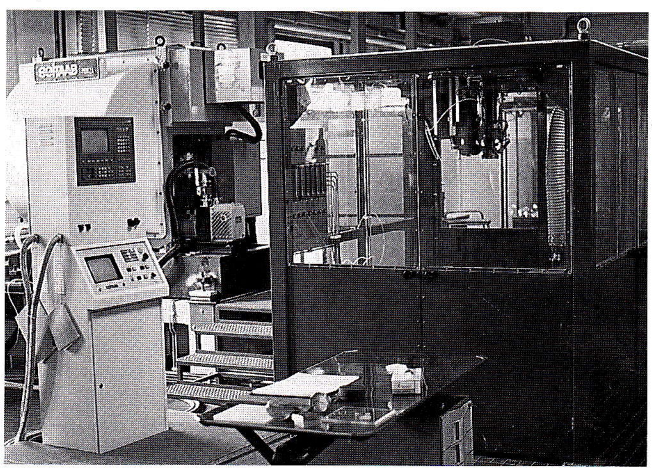


TABLE 2 - Welding parameter values employed in the experiments

	Laser power	Welding speed	Protective gas flow-rate coaxially	laterally
a	2100	0.85	25	40
b	1800	0.60	25	40
c	2500	1.50	25	40

Elaboration of the laser welding process

As already stated, preliminary penetration tests were run on solid metal so as to perfect the laser welding processes. Pipes were then butt-welded with straight edges. Two appropriately shaped plugs at the ends of the two test specimens and a threaded tie rod were used to attach the pipes to the spindle.

The seam was protected with argon gas dispensed from a nozzle coaxial with the laser beam and another nozzle located laterally. Since full penetration welding of the joints was required, the process parameter values giving complete penetration of the thickness were chosen, namely the three pairs of values in Table 2 with the same focus position and the same protective gas flow-rate. The welded joints were subjected to a series of tests and checks to qualify the laser process with reference to this type of steel. Non-destructive testing (visual inspection and radiographic inspection for both seam shape and internal defects) was followed by cutting of test specimens from the joints for macrographic and micrographic examination and mechanical tests.

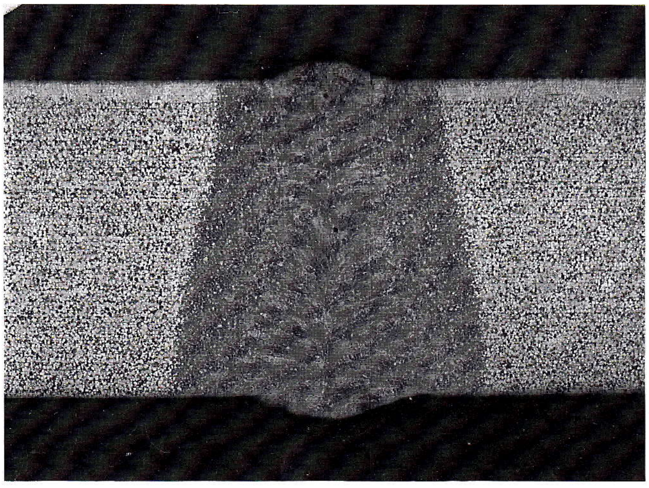
Qualification of laser-welded joints

Radiographic, macrographic and micrographic examinations were performed, as well as mechanical traction and bending tests. The joints were examined by eye prior to radiography to check the continuity of their seams on both sides. All the joints satisfied this essential pre-requisite for acceptance.

No microcracks were noted on the radiograms. In addition, the posority values were always well below those set out in the standards for conventional weldments. It must be pointed out, however, that the ASME standards refer to two-dimensional porosity distributions, whereas in laser-welded joints there is usually a concentration of porority along the bottom of the seam, and its distribution is aligned even if the dimensions of individual porosities are smaller than in conventional weldments. The effects of such a distribution on joint strength need to be examined in depth with a view to extending current standards to laser welding.

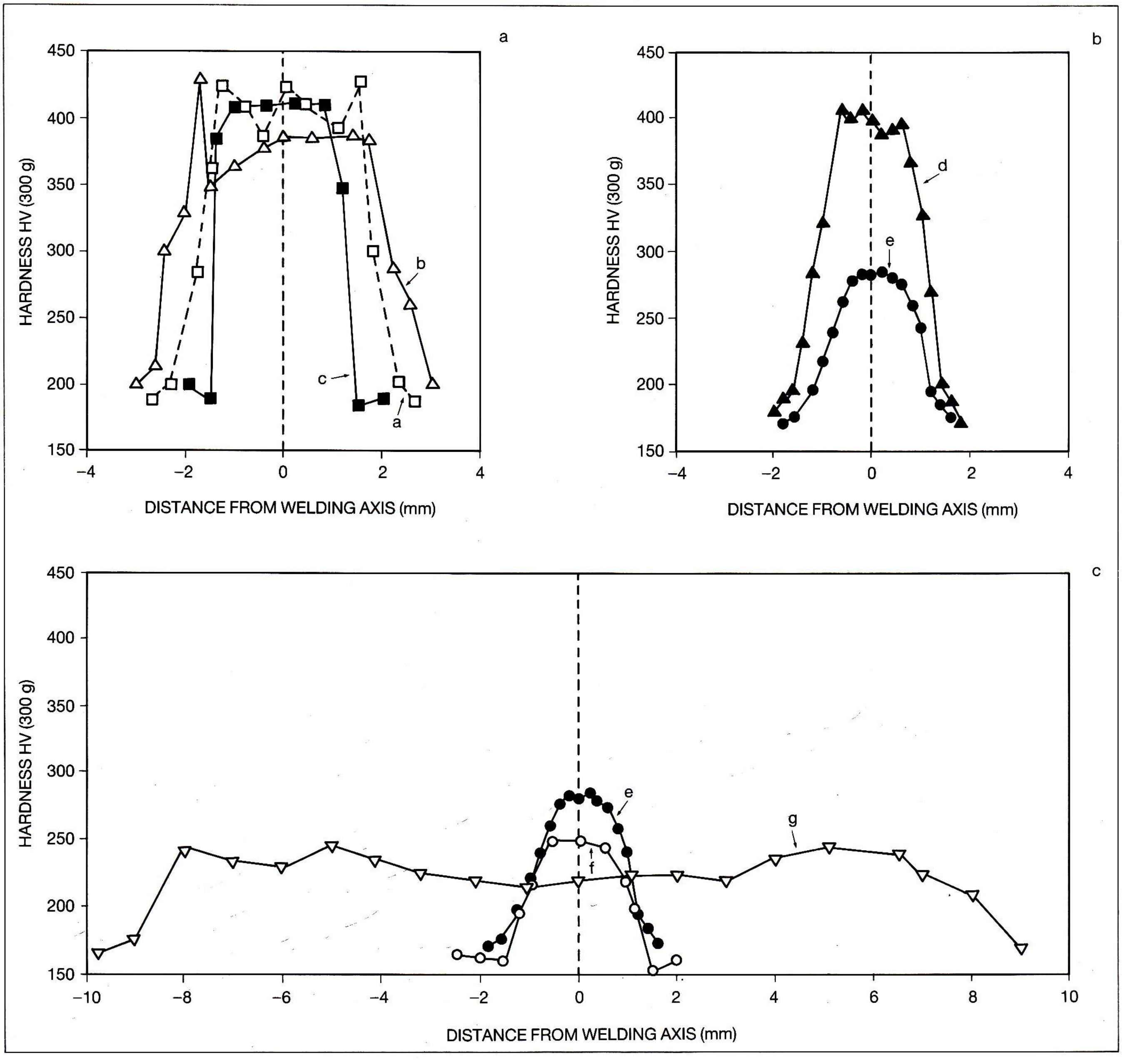
No cracks were noted on the macrophotographs, though some porosities were seen at the root of the seam.
The photo in fig. 2 illustrates the typical appearance of a laser-welded joint. It represents the pass made at 1.5 m/min at 2500 W.
The traction test followed the ASME criteria for the size of the test specimen and acceptability.
All the test results were satisfactory. Each specimen surpassed the ultimate tensile load value laid down (517 N/mm^2) and collapsed in areas at a distance from the weld seam. It was thus clear that laser welding can produce welds on P22 steel that are free from defects unacceptable in terms of tensile strength.
Transverse bending tests carried out on both sides in accordance with the ASME specifications and acceptability criteria were also entirely satisfactory.

Fig. 2 - Macrophotograph of laser weldment at 2500 W and a pass speed of 1.5 m/min.



There was no evidence of any kind of crack that was visible and hence well below that specified by the standards.
It must be pointed out, however, that the dimensional specifications laid down for bending test specimens are such that the test results are poorly significant. This is because the test stresses virtually nothing more than the base material on account of the small extent of the melted and the heat altered zones in laser-welded joints. For this reason, templates other than those

Fig. 3 - a. Mid-thickness microhardness profiles of laser weldments at parameter values a, b and c in Table 2.
b - Comparison between laser welded (curve d) and laser welded-and-annealed (curve e) states following welding according to parameter values c in Table 2. The profiles are the means of three passes: near the surface, mid-thickness, near the reverse side.
c - Comparison between laser welded-and-annealed (curve e), laser welded + furnace annealed (curve f), and TIG welded + furnace annealed (curve g).



indicated in the current standards should be envisaged. A test on a joint that is practically speaking stressed on the portion of metal near the seam is thus of little significance.

Microhardness imprinting with a 300 g load was also carried out on the specimens.
No provision is made for this test in the standards it was performed to assess the degree of hardness in the melted and heat altered zones of a laser weldment.
A series of imprints were made parallel to the surface of the pipe and at its mid-thickness.
The results for the three weldments obtained with the parameter values set out in Table 2 are illustrated in fig. 3.

The hardness pattern for laser-welded joints is characterised by certain features that distinguish it from that for steel P22 welded with conventional methods. Fig. 3 also includes the hardness diagram for a TIG butt-welded P22 pipe.
It can be seen that the use of weld material and a different heating cycle results in maximum hardness in the heat affected zone, whereas in the laser-welded joint the highest values were observed in the melted zone.

Laser subcritical annealing process

In addition to optimisation of the process for the laser welding of low-alloy steels for high-temperature applications, the feasibility study included an examination of the joint post-heating stage.
For materials of this kind, conventional welding manuals prescribe local subcritical annealing by induction or resistance of the welded joint to relieve excess hardening.

In this work, an original post-heating process using the laser source was devised and perfected. The advantages of this innovation lie in the fact that the treatment is quick and can be carried out straight after the welding pass.

Post-welding subcritical annealing processes using high-energy-density sources have already been described in the literature (3). These processes use the beam as a source of energy that is no longer concentrated, but distributed over a region wide enough to include both the seam and the heat altered zone. Their effectiveness is limited, however, since heating of the joint is not uniform throughout its thickness.
To overcome these difficulties, the technique now perfected provides for a time variation in the density of the incidence power. This expedient makes it possible to keep the surface temperature under the critical Ac1 point while continuing to supply heat to the welded area.

Description of the equipment employed

The on-line temperature control system used for laser post-weld subcritical annealing consisted of:
- a two-colour optical pyrometer focussed on the weldment
- a data acquisition card interfaced with a PC and the laser source power control.

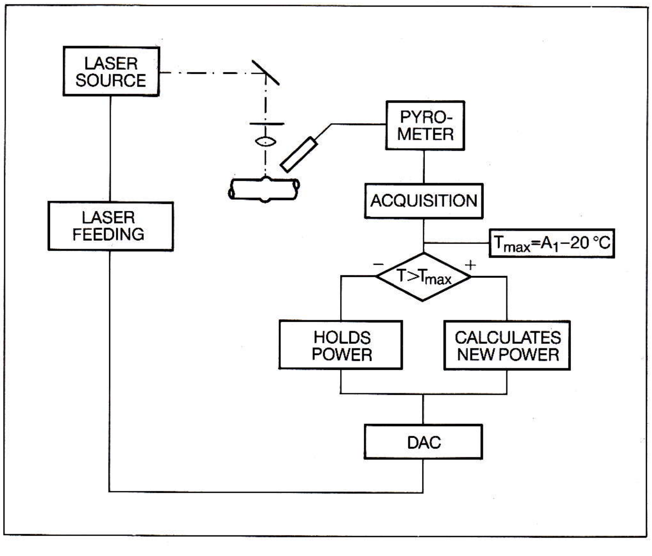
The system flow-chart is shown in fig. 4.

Vertical focussing of the beam on the test specimen was automated. At the end of the welding pass, the focussing head rose over the pipe surface and projected onto it a spot large enough to abundantly cover the melted and thermically altered zones. The spindle used in the welding experiment was again employed to handle the specimen.

Experiments on pipes

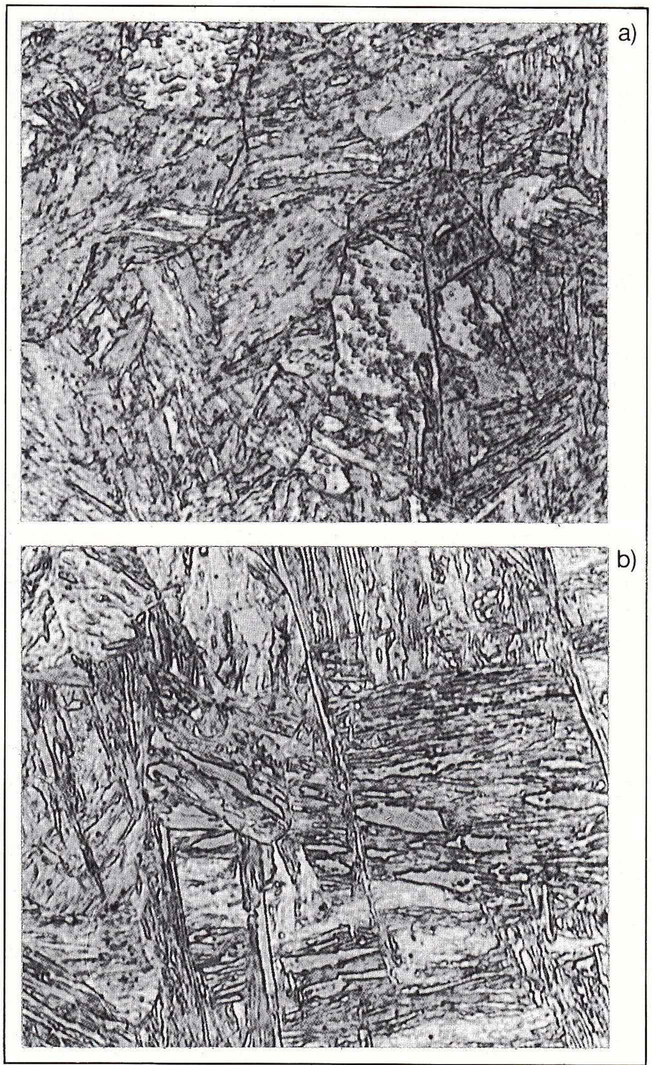
Weldments carried out according to the parameter values described were subjected to laser subcritical annealing at 650° C.

Fig. 4 - Flow-chart of laser annealing system.



The temperature was kept below the levels specified for post-welding heat treatments to prevent the risk of hardening. In view of the measurement error of the instrumentation employed, in fact, it was felt advisable to stay about 50° C below such levels. The main features of the treatment are: rapid heating (about 700° C/min), and holding at the annealing temperature for a very short time (about 3′) compared with conventional post-heating (4). The specimen was cooled at the end of the process by insulating the pipe with quartz wool for not more than 10′. Annealed pipe specimens were then examined by light and electron microscopy (TEM & SEM) and their hardness was determined.

Fig. 5 - Structure of melted zone in the solid state: as such (a) and after subcritical annealing (b) (1000 x).



The annealed joints were also put through the qualification tests (bending and traction) run on the laser-welded joints.

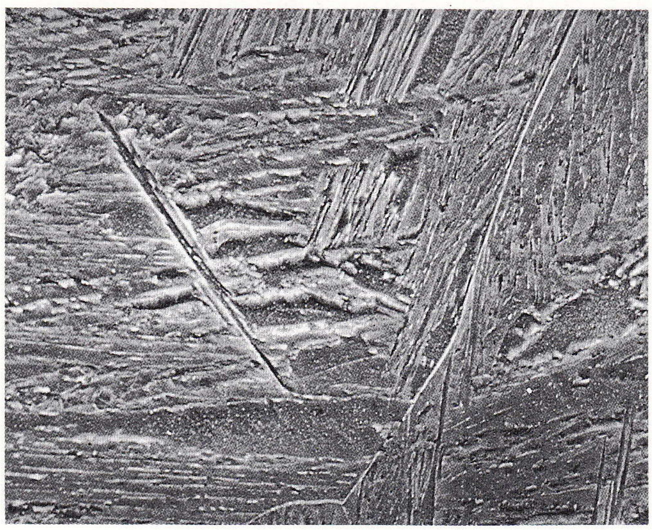
Results

The laser welded-and-annealed joints passed the tests and were qualified according to the ASME standards. The most critical part of the structure of a laser weldment is the melted zone. The elaboration of an annealing process for the central part of the seam is thus enough to dispel the persistence of hard phases in the heat altered zone.

The metallographic examination revealed marked variations between the annealed and the non-annealed states in both the melted and the heat affected zone. In the melted zone in particular, the martensite of the non-annealed specimen displayed a well-defined acicular structure, whereas in the annealed specimen there was a tempered martensite structure with less marked definition of the acicular structure. Within the irregular plate-like grains of the ferrite matrix and on the prior austenite grain boundaries there was a presence of finely dispersed precipitates (fig. 5).

This dispersion of carbides is a well-known peculiarity of low-alloy Cr-Mo steels and is responsible for their outstanding strength at high temperatures.
The results obtained in this first stage of the investigation were corroborated by the Vickers microhardness curves for the annealed specimens

Fig. 6 - SEM of structure of melted zone as welded (2500 x).



(fig. 3 b, c). The hardness of the melted zone dropped from about 400 HV to less than 300 HV. The mean hardness value for the melted area of the test specimen was 280 HV, showing that the martensite had been transformed.
SEM and TEM of the melted area offered a more detailed picture of the as-welded and annealed structures.

Fig. 7 - TEM of structure of melted zone as welded (33,000 x).

Martensite in low-alloy Cr-Mo steels is primarily found in the form of laths. This typical morphology is visible if figs. 6 & 7. Analysis of the annealed structures (fig. 8 & 9) showed large carbide precipitates and finer precipitates within the ferrite matrix.

Notes on the laser subcritical annealing process

Comparison between conventionally annealed and laser-annealed joints welded by means of a CO_2 laser brought out the inherent advantages of laser subcritical annealing:

— above all, its rapidity, in that it can be performed immediately after the welding pass by simply raising the focussing head enough to make the spot cover the seam;
— its duration: when applied to a laser-welded joint with its very small seam, the treatment does not demand the speed limits in the heating stage required to relieve the stress states typical of a conventional weldment with its heavy heat load.

The hardness analysis (fig. 3) disclosed lower values in conventionally annealed weldments: 250 HV as opposed to 280 HV for laser-annealed joints. The greater dispersion of precipitates in fig. 10, in fact, shows that furnace annealing is more thorough. The relevant standard for this class of steels (4) lays down that the hardness of joints for which post-welding heat treatment is envisaged must be less than 270 HV,

Fig. 8 - SEM of structure of laser-annealed melted zone (2500 x).

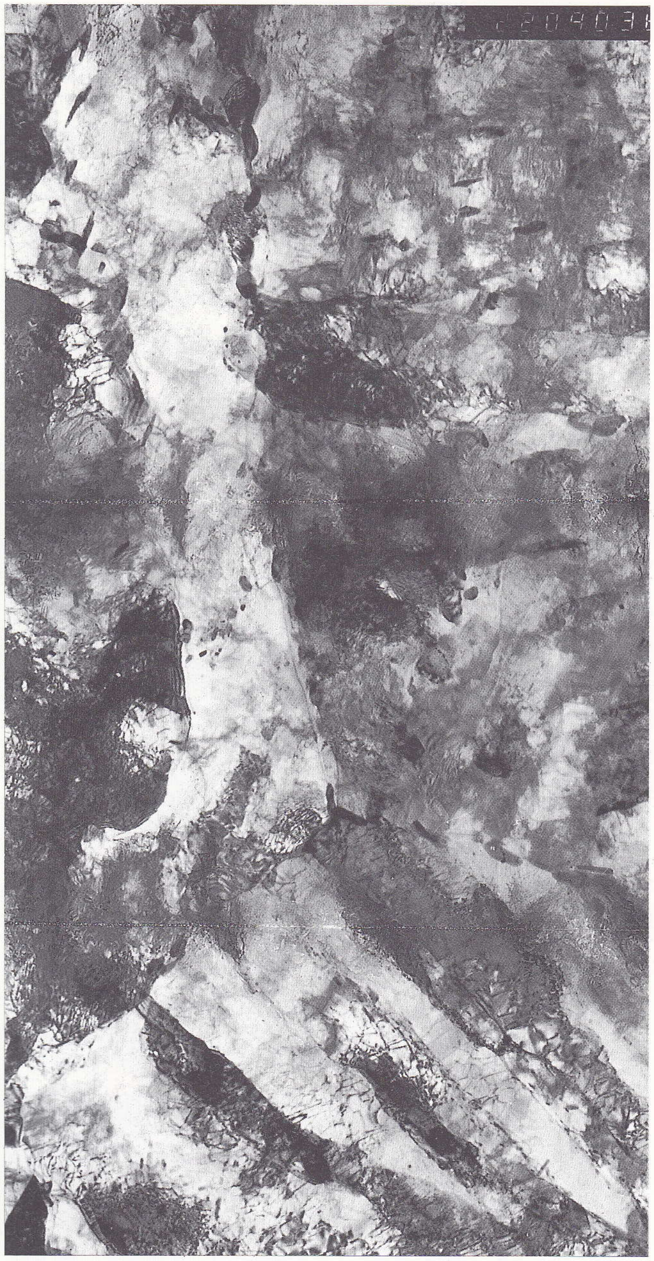


Fig. 9 - TEM of structure of laser-annealed melted zone (33,000 x).

whereas for those employed as welded the limit is 300 HV.
Furnace-annealed, laser-welded joints meet this specification, whereas unannealed and laser-annealed, laser-welded joints exceed the hardness limit imposed.

Investigation of laser-annealed joints must thus be extended to cover at least their creep and fatigue patterns, since the limits laid down by the standards

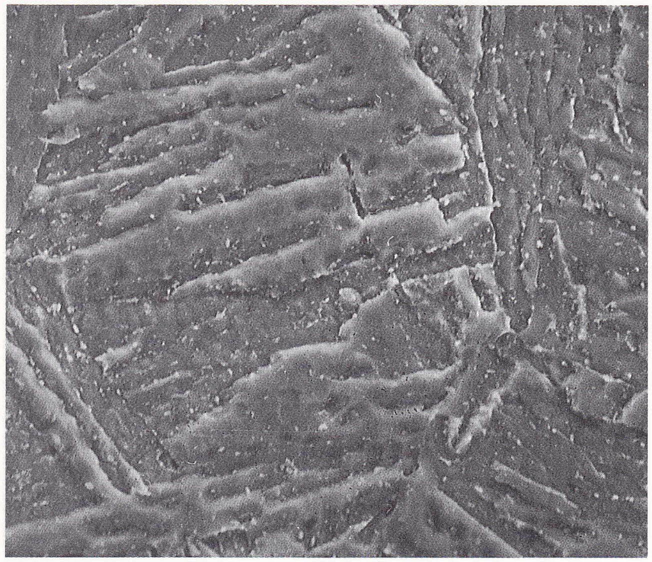


Fig. 10 - SEM of structure of furnace-annealed melted zone (2500 x).

stem from technological tests of this type performed on joints that are both morphologically and structurally different from laser-welded joints. The conclusion to be drawn from what has been achieved so far, therefore, is that the feasibility of an original laser subcritical annealing process has been established at the experimental level. Its application to real manufactured articles, however, must await further technological characterisation of their behaviour under operating conditions.

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