Solid-State Welding of a 0.27 Carbon, Chromium/Molybdenum Steel

The solid-state dynamic diffusion welding process produced high-strength welds in a short time

BY P. LEFRANCOIS, B. CRIQUI AND M. HOURCADE

ABSTRACT. Solid state welding is often carried out in a vacuum chamber under rather low pressure (2 to 50 MPa) and temperatures. It offers considerable advantages, especially metallurgical ones. Indeed, with good process conditions, it generates no important microstructural degradation such as those occurring with classical techniques of fusion or friction welding. It is a soft joining process that generates only a small deformation of the samples.

However, classical diffusion welding requires welding durations ranging from some dozens of minutes to several hours. Because of the cost incurred, the process can be employed only in industries such as the electronic, nuclear, aerospace and military industries.

A new process, dynamic diffusion welding (DDW), was improved in our laboratory (Ref. 4). It offers the advantages of both classical diffusion welding and rapidity.

With DDW, new perspectives are opened for using this welding process in mass production, since it is consistent with the constraints of productivity. For this reason, dynamic diffusion welding of 27CD4 steel has been studied. The application targeted has been the welding of transmission shafts, which are presently made by friction welding.

It was proven possible to carry out high-strength joints in a very short time: 30 s for heating to the welding temperature and a few seconds at the isothermal anneal.

With the optimal conditions defined in this study, namely a welding time of several seconds, in a nitrogen with 5% hydrogen gas, with a proper surface preparation (Rmax = 0.4 μm) and under a modulated pressure during the whole welding process:

1) The tensile behavior of the joints is reproducible.

2) Failure occurs out of the interface with a tensile strength of 950 MPa and with an elongation of 22% (bainitic and martensitic structure).

3) Deformation of the welded specimens is limited to about 2% of the heated length.

4) The failure energy of joints measured with impact tests is lower than that of the base metal.

This process is also efficient for making other ferrous alloy welds.

An additional mechanical characterization is now going on in our laboratory, our purpose being, among others, to assess the fatigue endurance.

KEY WORDS

Solid-State Welding
Dynamic Diff. Welding
Steel Diffusion Welding vs. Friction Welding
27CD4 Steel
Rapid Welding Time
Mechanical Testing
Metallographic Analysis
Fractographic Analysis
Industrial Production

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Introduction

Solid state welding is often carried out in a vacuum chamber under rather low pressure (2 to 50 MPa) and temperatures. It offers considerable advantages, especially metallurgical ones. Indeed, with good process conditions, it generates no important microstructural degradation such as those occuring with classical techniques of fusion or friction welding. It is a soft joining process that generates only a small deformation of the samples.

A wide range of materials can be used to produce similar or dissimilar metal

joints by diffusion welding. The use of suitable interlayers also makes possible the welding of metallurgically incompatible materials, and to obtain strong and ductile joints.

However, classical diffusion welding requires welding durations ranging from some dozens of minutes to several hours. Because of the cost incurred, the process can be employed only in industries such as electronic, nuclear, aerospace and military industries.

A new process, dynamic diffusion welding (DDW), was improved in our laboratory (Ref. 4). It offers the advantages of both classical diffusion welding and rapidity. In this way, Ti/Ta and Zy/Ta specimens have been welded in 30 s (Ref. 15), and have been shown to possess the same properties of those obtained with durations from 1 to 4 h with the classical process.

With DDW, new perspectives are opened for using this welding process in mass production, since it is consistent with the constraints of productivity. For this reason, dynamic diffusion welding of 27CD4 steel has been studied. The application targeted has been the welding of transmission shafts, which are presently made by friction welding.

Experimental Details

DDW Procedure

The goal of dynamic diffusion welding is to obtain a significant reduction of the welding time, which requires the development of new manufacturing routes, requiring the following:

1) To choose a welding environment according to the material.

2) To quickly heat the specimens by high-frequency induction, in order to reduce thermal inertia.

3) To give an isothermal treatment of several seconds at a temperature according to the metals to be welded.

4) To apply a high pressure on the pieces, so that a clean and complete contact (first stage of diffusion welding) between the surfaces to be welded can be quickly achieved. This is achieved by the crushing of the surface asperities as much as possible, so that no contact defects remain. This is very important because during such a short diffusion time (a few seconds), the defects can't be resorbed. However, during the entire heating cycle, the pressure must be modulated so that it stays below the flow stress of the material as far as is possible, in order to avoid too great deformation of the specimens. Because of the lack of defect in the interface, with a proper surface preparation, efficient diffusion of atoms occurs throughout the length of the weld interface (second stage of diffusion welding), so that a strong metallurgical weld is achieved in a very short time.

Material and Specimens

Small cylindrical specimens (height H = 12 mm, diameter Ø = 8 mm) were used. Before welding, the surfaces were given a final fine grinding to Rmax equal to 0.4 µm (1200 grit paper), degreased in acetone and then alcohol.

Table 1 shows the chemical composition of the 27CD4 steel (u type) used in this study. It must be noted that the sulfur content reached the upper limit value of the specifications. The structure of the as-received material was a banded structure of ferrite and pearlite with a lot of long manganese sulfides normal to the weld plane.

The curve of the yield compression strength of this steel as a function of temperature was experimentally determined — Fig. 1.

DDW Equipment

The welding environment of the chamber (Fig. 2) was nitrogen with 5% hydrogen gas or a vacuum. The specimens were quickly heated by high-frequency induction, over their whole length, with a generator whose power was adjusted by a processing program. A thermocouple directly welded to the interface of the specimens measured the sample temperature. An Instron tensile-compression machine ensured the dynamic application of the pressure during heating.

Testing Procedure

The joint quality was assessed by metallographic examinations (optical and scanning electron microscopy), mechanical testing (tensile, torsion and impact tests (Fig. 3) with nonstandard specimens (because of our samples' dimensions), and fractographic examinations.

Optimized Welding Parameters

- Pressure: The preload at 20°C was 300 MPa. The pressure on the specimens followed the curve shown in Fig. 4 during the heating (this option is explained below). The pressure was cycled between 6 and 18 MPa at the welding temperature (this procedure enabled the average pressure to be controlled).
- Roughness: Rmax = 0.4 µm.
- Welding temperature: 1050°C.
- Heating time: 30 s.
- Duration of the isothermal anneal: several seconds.
- Welding environment: nitrogen with 5% hydrogen gas.
- Thermal inertia cooling in the chamber, which provides a bainitic with martensite structure (Hv ≈ 330).

Table 1 — Specification and Chemical Composition of the Tested 27CD4 Steel

Element wt-%	C	Mn	Si max	Cr	Mo	Al	Ni max	Cu max	P max	S
Specification										
27CD4	0.24	0.60	0.40	0.95	0.20	0.05	0.30	0.30	0.025	0.020
u	0.31	0.85	—	1.25	0.30	—	—	—	—	0.040
Welded specimens	0.28	0.81	0.31	1.00	0.24	0.023	0.20	0.05	0.008	0.039

O_2: 36 ppm, N_2: 64 ppm

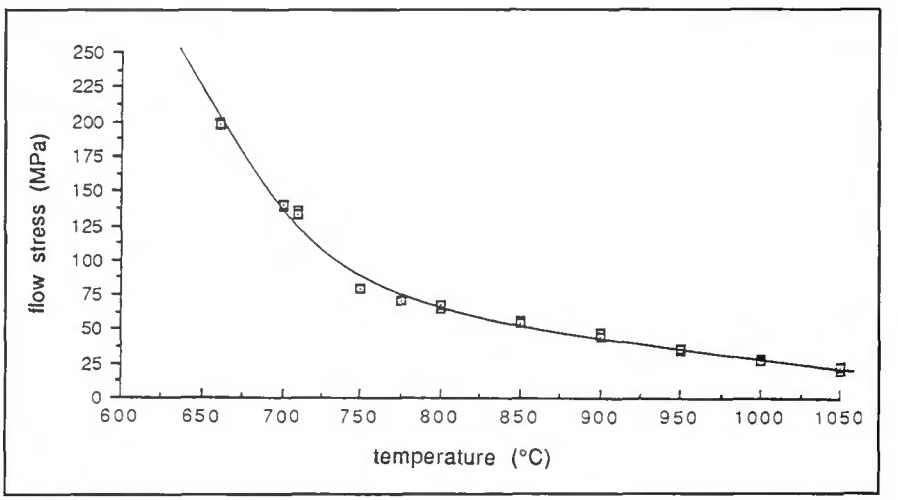

Fig. 1 Effect of temperature on flow stress of 27CD4 steel.

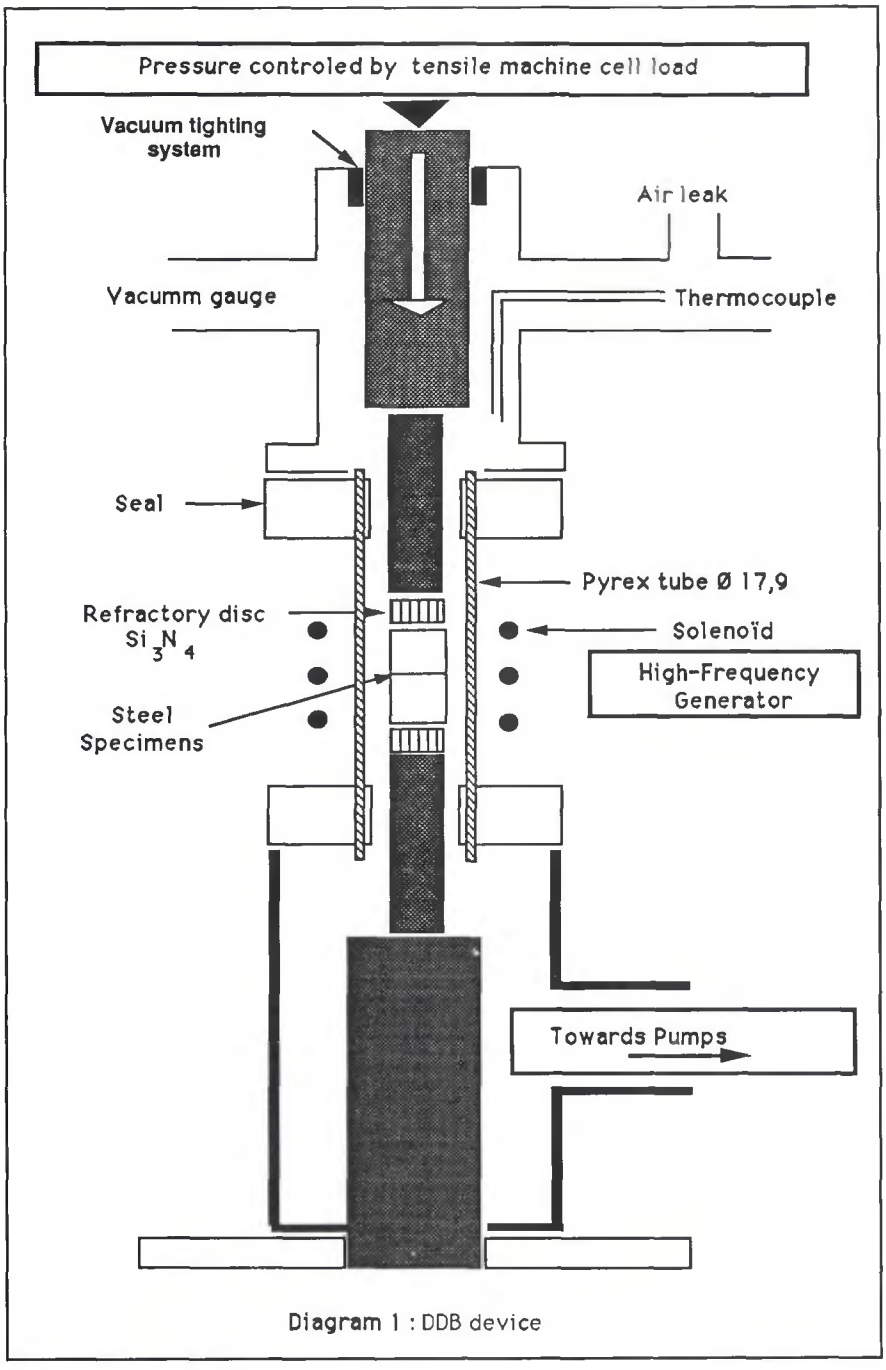

Fig. 2 — A dynamic diffusion welding device.

Specific Problems with Diffusion Welding of Steel

The number of papers on diffusion welding of steel is rather limited, because of there being little interest in this technique, which, until now, was rather costly for these materials.

Among the most important papers, the works of the Welding Institute (Ref. 11) should be cited, as well as those of M. Kergoat (Ref. 12), which have revealed the difficulties met for diffusion welding of steel.

Problems of Mechanical Characterization of Welded Specimens

Whatever the technique (DW or DDW), both of the above-mentioned publications show that:

1) It is possible, by vacuum diffusion welding or dynamic diffusion welding, to obtain steel joints having a tensile strength equal to that of the base metal heat treated under the same conditions. The welding temperatures were between 900 and 1100°C, with isothermal level durations varying from some seconds (Ref. 12) to several minutes and even one hour or more (Ref. 11).

2) For identical bonding conditions, failure occurs either through the interface without necking (or even with some material deformation away from the weld) or in the base metal. The authors do not give the reasons for this heterogeneity of the behavior of their specimens. Thornton and Wallach (Ref. 14) have advanced the hypothesis of the presence of microvoids of 20 nm as explaining this behavior. These microvoids have been observed using a transmission electron microscope. Their presence is supported to be stabilized by the presence of sulfur and phosphorus, which could have diffused to them.

3) The welding time extension increases the probability of failure away from the interface, without nevertheless securing failure in the base material.

4) Across the weld interface some defects remain that are very small in size, less than 1 μm diameter, and this occurs whatever the welding conditions. These defects were not identified by the Welding Institute (Ref. 11), but Kergoat (Ref. 12) observed very small particles (0.1 to 0.5 μm) on cross-sections of joints, some of which were pulled out during metallographic polishing and etching — Fig. 5.

5) The tensile fracture surface of specimens failed through the weld plane showed remaining grinding marks. This indicates that the welding cycle (pressure, time and temperature) was underestimated. The numerous small particles observed along the weld interface generated numerous dimples in the flat areas of failures.

Kergoat (Ref. 12) concluded that microstructural configuration promotes intergranular failures through the weld plane: the interface is weakened by the particles layer and the interfacial grain boundary is planar because of the short welding time, which prevents the grains from crossing the weld interface. The author's assumption is that these particles are carbides or oxides.

Other authors (Refs. 11, 14, 15) note the low impact strength of the as-welded specimens. Neither a postweld heat treatment, nor a suitable modification of welding parameters enable them to get a significant increase in fracture energy.

Oxidation Problems

Several authors emphasize the importance of the welding environment and of the surface preparation on joint quality.

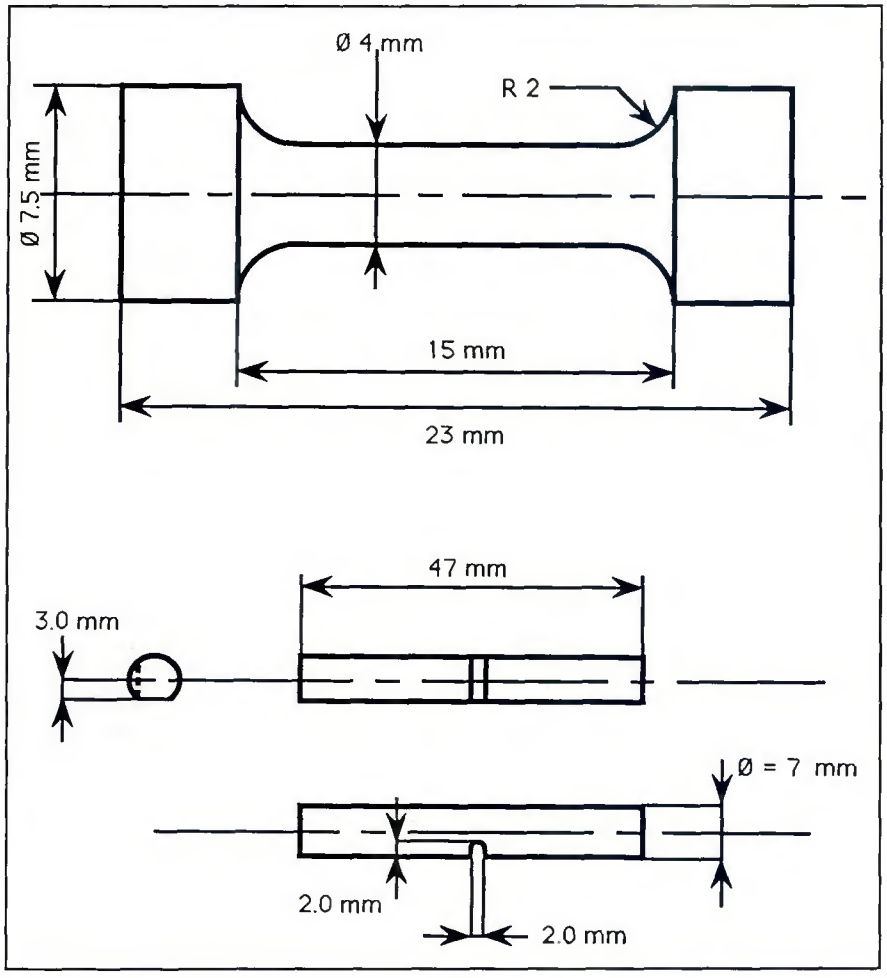

Fig. 3 — Drawing of tensile and impact test specimens.

The hypothesis and interpretations given in the literature show that the problems due to oxidation at the interfaces are not fully understood. According to Ohashi and Hashimoto (Ref. 6), the oxide layer spheroidizes during welding. This explanation is apparently compatible with the fact that the dissolution of the iron oxide layer into the material requires, at 1000°C, a heating time longer than one week (Ref. 13), and that the observed particles are spherical.

The oxidizing phenomena which occur in the weld can explain som e of the difficulties previously put into evidence.

At this stage, the mechanisms that could possibly generate the above problems were to be studied.

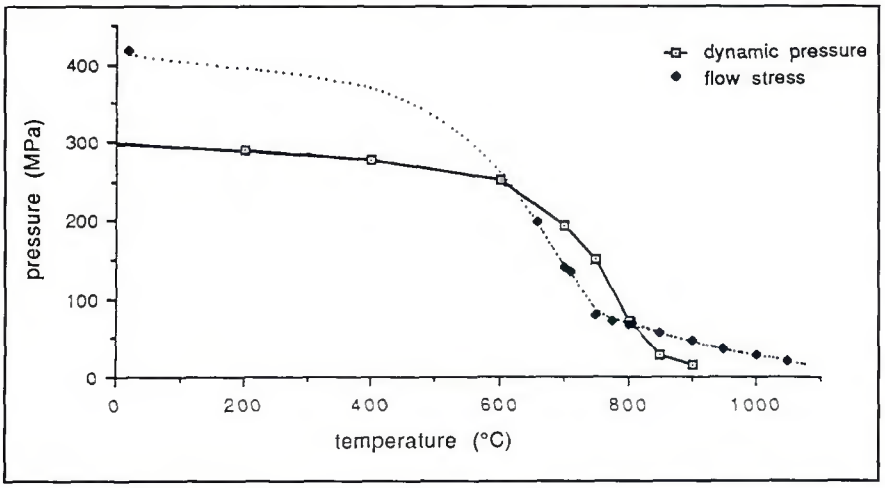

Fig. 4 — Evolution of the pressure during the heating cycle.

Study of Negative Factors and their Solutions

Several factors may explain the mechanical behavior of joints. In particular, the causes of the particles layer forming must be understoood.

Identification of Particles Observed by M. Kergoat

The EDS analysis of the biggest particles have shown that these were characterized by a high manganese and silicon content compared to the base metal — Fig. 6. A few particles contain calcium and aluminum resulting from steel elaboration. These metals are the most oxidizable element in the composition of the alloy — Table 2. So, it is probable that these particles are Mn, Si/Ca or Al oxides.

In order to prove this hypothesis, a heat treatment at 1200°C was carried out on diffusion welded samples. If the particles observed were carbides, they should dissolve at this temperature. As they do not dissolve at this temperature, it is proven that they are oxides.

Their formation may come from several sources :

1) The physical and chemical surface preparation.

2) The oxide layer spontaneously formed after polishing.

3) The oxygen-adsorbed molecules.

4) The oxygen dissolved in the alloy.

5) The oxygen of the chamber environment.

In order to reduce the oxidation process at the interface, we implemented a precise surface preparation and chose a reducing environment gas, namely nitrogen with 5% hydrogen. We also shortened, as far as possible, the time between surface preparation and introduction of the specimens in the DDW equipment.

Bigger particles could also be observed around the inclusions occuring at the interface. They were manganese sulfides.

Other Assumptions

- The flatness of the interfacial grain boundary, resulting from the shortness of the isothermal anneal which prevented grain growth through the interface. This weld structure is suboptimal for the mechanical behavior of the joints, especially with respect to the impact strength.
- The residual contact defects:

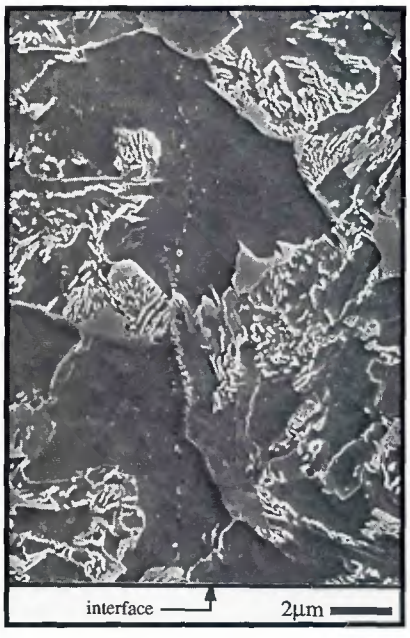

Fig. 5 — Polished section showing fine oxide particles along the bond line of a joint produced at 1050°C under vacuum.

Table 2 — Standard Free Enthalpies of Oxide Formation at 1000°C, kcal

Al_2O_3	SiO_2	MnO	Cr_2O_3	FeO
205	162	140	127	85

grinding marks on fracture surfaces show that a perfect physical contact of the surfaces was not completed under the welding conditions defined by Kergoat (Ref. 12).

Pressure was then increased so as to overstep, during a few seconds, the flow stress of the 27CD4 steel between 600 and 800°C. This resulted in a macroscopic welding deformation that did not exceed 2% of the heated length of the specimens.

➧ Possible segregations of S, P, N and Sb were cited in the literature (Ref. 14). We did not verify this hypothesis.

The adopted welding conditions are given in the section entitled "Optimized welding parameters"; they take into consideration the above analysis.

Results and Discussion

Using the above welding procedure, which resulted in a macroscopic welding deformation that did not exceed 2% of the heated length of the specimens, we carried out mechanical tests and metallographic observations of butt joints. Then, the possible variation ranges of welding temperature and specimen roughness were improved with a short parametric study.

Results from Mechanical Tests

After welding, some specimens are machined for tensile, torsion and impact tests — Fig. 3. The results were compared to those obtained with unwelded samples submitted to the same heat treatment.

The tensile test results shown in Table 3 confirm the validity of our assumption and of the proposed solutions: all the test specimens failed away from the weld interface at the point of maximum necking, in a ductile manner with an elongation equal to those of the base metal, and this for an isothermal anneal (1050°C) of a few seconds. The cooling rates were not perfectly reproducible, which explains the scatter of the experimental tensile strength measurements.

The purpose of this study was to use this process for manufacturing transmission shafts. We tried to characterize the behavior of the joints under torsion with a torsion Amsler machine of the Renault Co. The machine was not well adapted to the dimension of the test specimens produced with the dynamic diffusion welding equipment, and, as a result, it was impossible to use the results of many tests, the tested samples having slipped in the clamping tools. Nevertheless, the single available result is promising although not yet confirmed: we measured a torsion torque of 60 mN for the welded specimens compared with 66 mN for the unwelded pieces having the same microstructure as the weld.

Some authors showed that impact tests characterized the quality of the butt joints more accurately than tensile tests.

Because of the inherent limits of the equipment, we had to carry out these tests with unstandardized impact test specimens. The failure energy was compared to that of the unwelded specimens (Table 4), and this for two different microstructures.

For both structures, the failure energy of joints had similar values, but it was lower than those of unwelded samples. Neither the postweld treatment, nor the ductility of the structure seemed to noticeably change the failure energy of the joints as it was observed in the literature.

Table 3 — Tensile Properties of Specimens Welded in N_2 (H_2 5%) (a few seconds at 1050°C)

Tensile strength, MPa	Elongation%	Failure location[a]
995	26	MB
955	24	MB
940	21	MB
970	19	MB
1000	17	MB
970	23	MB
995	23	MB
1080	17	MB

(a) MB: failure through base material

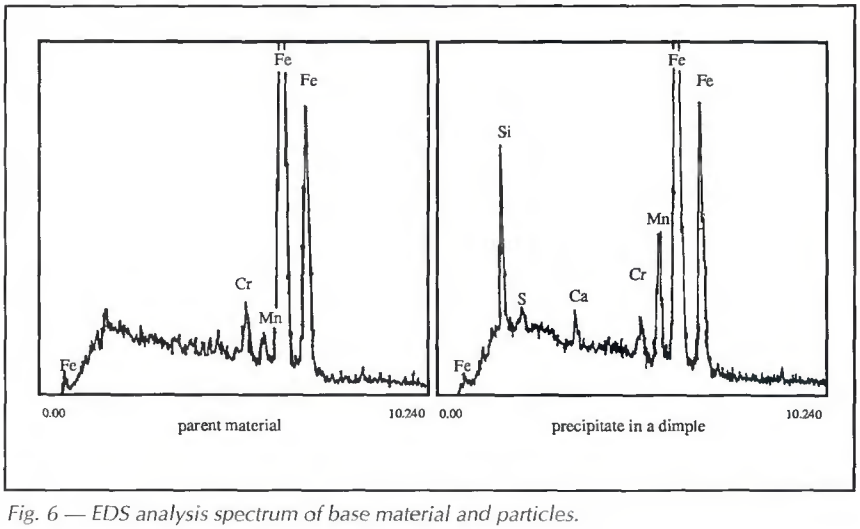

Fig. 6 — EDS analysis spectrum of base material and particles.

Table 4 — Impact Energy of U-Notch Specimens, J

	As-welded	Postweld heat treatment[a]
Structure	Bainite	Ferrite and pearlite
Control Specimen	28.2 27.6 28.8 28.0	>50
Welded Specimen	12.8 1.4 9.0 9.4	12.8 8.0 15.2 12.8

(a) 850°C, 15 min, cool to 600°C and hold for 15 min, air cool

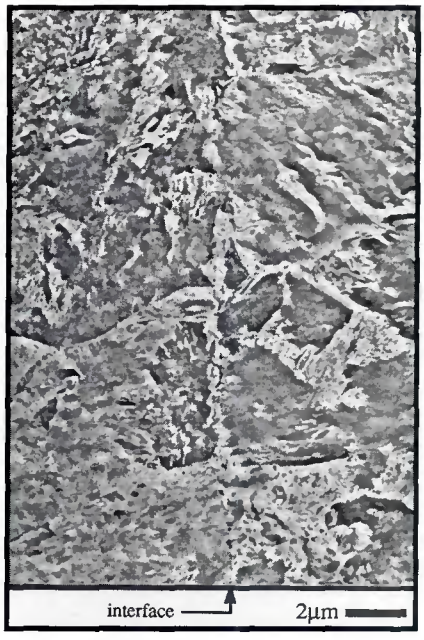

Fig. 7 — Backscattered electron image of the weld interface of joints produced at 1050°C in N_2 (H_2 5%).

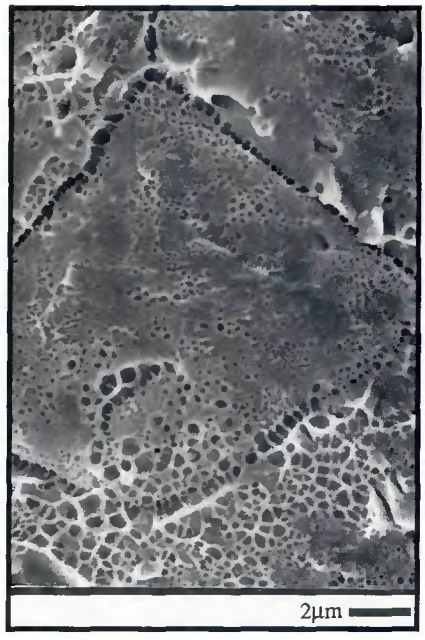

Fig. 8 — Fracture face of impact specimen bonded at 1050°C.

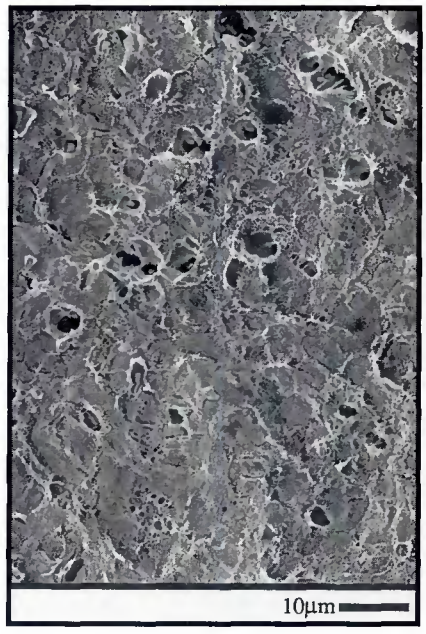

Fig. 9 — Flat failure showing many sulfides.

Metallographic and Fractographic Examinations of Butt Joints

Examination of polished cross-sections of the joints were carried out with a scanning electron microscope equipped with a backscattered electron detector. Very few particles (Fig. 7) remained in the weld interface (compared with the interface shown in Fig. 5) when the welding process was optimized, which explained the improved tensile properties compared with the results of Kergoat (Ref. 12). These very small particles were not observed by the Welding Institute (Ref. 11) and other authors (Refs. 14, 15).

We also observed some sulfide inclusions occuring at the interface. They were ductile at 1050°C and bent against the opposite surface during welding and were divided into particles located around the initial sulfide.

The fractographic examinations of the impact test specimens with a bainitic structure showed that the failure of the unwelded specimens was totally driven by cleavages. In the butt joints, the fracture initiated in the interface and ran by cleavage processes through the base metal. Rather thin dimples (some of which pin the grain boundaries) could be observed in the interfacial plane — Fig. 8. However, these were clearly less numerous than those of the fracture surfaces of joints welded in vacuum (Ref. 12), which confirmed the micrographic examinations.

Several sulfides emerged also on the flat fracture surfaces — Fig. 9. They were circled with particles bigger than the oxides and resulted from the fragmentation of the initial inclusion.

Parametric Study

Effect of Welding Temperature

Welding tests were carried out at 950 and 875°C, the other parameters remaining constant.

At these temperatures, the tensile test results (Table 5) showed a sharp deterioration of mechanical properties: all the failures occured through the interface. Moreover, if at 950°C the tensile strength of the test specimens was similar to that of the base metal, at 875°C it was considerably lower. The elongations were only a few percents in both cases.

Tensile fracture interfaces are mainly of an intergranular type with areas looking like simple decohesion.

Effect of Roughness

As in the previous section, all the joining parameters were constant, roughness excepted. Two microgeometric states at Rmax of 0.55 µm and 1.50 µm were compared to the reference state (Rmax = 0.4 µm).

The tensile tests results (Table 6) showed that at a roughness higher than the optimal conditions, failure occurred through the weld interface, and the tensile strength of the joints and of the base metal were equal. The elongations were

Table 5 — Effect of Welding Temperature on Tensile Properties

Temperature	Tensile strength, MPa	Elongation, %	Failure location[a]
1050°C	995	26	MB
	955	24	MB
	940	21	MB
	970	19	MB
	1000	17	MB
	970	23	MB
	995	23	MB
	1080	17	MB
950°C	844	04	Int
	900	08	Int
875°C	740	03	Int

(a) MB base material failure
Int failure through the weld plane

not negligible since they reached around 14%.

Discussion

With the optimal welding conditions, the interfacial grain boundary remained flat and pinned with sulfide and oxide particles. However, these were clearly less numerous than those of joints welded in vacuum (Ref. 12).

This configuration explains the results:

1) The tensile properties were improved compared with the results of Kergoat (Ref. 12).

2) The failure energy of joints was lower than those of unwelded samples.

Because of the presence of this particles layer in the weld, and because of the flatness of the interface, impact behavior of specimens could not be improved despite the smaller quantity of particles resulting from the optimization of the DDW process. Impact strength is not a problem with the diffusion welding process when no brittle or weakening components (intermetallic or particle layers) are present in the interface.

The other authors did not observe these hardly visible particles, which explains the heterogeneity of the behavior of their tensile test specimens and the low-impact strength of the welded pieces (Refs. 11, 14, 15).

At 950 and 875°C welding temperature, defect-free weld interfaces were observed, which indicated that the pressure cycle applied between 20° to 875°C or 950°C was optimal:

1) At low temperatures, the high applied stress crushed the asperities and quickly improved the surface contact.

2) This stress decreased as the temperature increased, and the flow stress decreased sharply, as shown by Fig. 4, so that the applied stress became higher than the flow stress for a short time. According to metallographic examinations, this was very efficient for resorbing the remaining defects.

Consequently, the first stage of diffusion welding (intimate contact of surfaces) was already completed at 875°C. But, at this welding temperature, the diffusion became too slow to form a good metallic weld, and test specimens failed at the interface under a tensile strength of 740 MPa only. An increase in the welding time should improve the weld quality, but this solution does not fit the industrial constraints to be respected here.

Thus, keeping the same requirement about the whole welding duration, the temperature variation range is very limited around 1050°C.

Table 6 — Effect of the Grinding Preparation on Tensile Properties (a few seconds at 1050°C)

Emery paper	Roughness, μm Ra	Rmax	Tensile strength, MPa	Elongation %	Failure location[a]
P1200	0.04	0.40	940	21	MB
			970	19	MB
			1000	17	MB
			970	23	MB
P600	0.055	0.55	980	14	Int
			960	12.5	Int°
P320[b]	0.100	1.00	930	14	Int
P320[c]	0.150	1.45	930	14	Int°

(a) MB = base material failure
Int = flat failure through the weld plane
Int° = necking away from interface followed by brittle failure through the weld
(b) worn paper, (c) new paper

Since the elongations reached around 14% for the two microgeometric states at Rmax of 0.55 μm and 1.50 μm, a slight increase of the welding time should reduce defect sharpness caused by the increased roughness and, by this way, get the expected mechanical characteristics. The welding parameters adopted in this study are therefore very close to the ones necessary to get optimal properties with a higher roughness.

The latter parameter appears to be a less-sensitive parameter than temperature. This result confirmed that the pressure cycle was well fitted in the case of this steel.

Comparison of Results from Diffusion and Friction Welding

The two processes have the same operating duration. Table 7 shows the superiority of diffusion welding (under optimal conditions) compared to friction welding, at least in a laboratory test, as regards to the tensile performances of welded specimens (with identical structures), especially for elongation. The friction welded samples failed through the weld region because of heavy sulfide grain flow generated by this technique (this structure does not exist in diffusion welded specimens).

It is interesting to note that the friction joints were produced with steel having a lower sulfur content (p type) than the one of this study (u type). Despite its higher sulfur content, diffusion welding gave better tensile results. It is a soft process with lower microstructural deterioration. With low sulfur content or globular sulfide steels, the mechanical properties, especially impact strength of the diffusion welded pieces, should be improved.

Moreover, it must be underlined that under diffusion welding the deformation of the samples remains below 2% of the induction heated zone.

Of course, friction welding is more tolerant to changes in conditions and in pre-weld preparation than diffusion welding is, but further studies pointed out that this last process permits good welds to be obtained with high-carbon-content steels or with different steels (results not published).

Table 7 — Comparative Table between Diffusion Welding and Friction Welding for Welding 27CD4 Bainitic Structure Steel with Low (p-Type) or High (u-Type) Sulfur Content

Diffusion Welding 27CD4, u-type (bainite, 340 Hv)			Friction Welding Junction p/p[a] (bainite, 300 Hv)			Junction u/p[b]		
Tensile strength, MPa	A%	Failure location	Tensile strength, MPa	A%	Failure location	Tensile strength, MPa	A%	Failure location
995	26	MB	860	19	Weld	B80	12	Weld
955	24	MB	850	11	Weld	B80	11	Weld
940	21	MB	860	14	Weld			
970	19	MB	890	11	Weld			
1000	17	MB						
970	23	MB						
995	23	MB						
1080	17	MB						

(a) p/p: The two pieces to be welded are of p-type
(b) u/p: One piece is of u-type and the other of p-type

Conclusion

This study revealed the feasibility of solid state dynamic diffusion welding of steels. It was proven possible to carry out high-strength welds in a very short time: 30 s for heating to the welding temperature and a few seconds at the isothermal anneal. A patent has been obtained for this process.

With the optimal conditions defined in this study, namely a welding time of several seconds, in a nitrogen with 5% hydrogen gas, with a proper surface preparation (Rmax= 0.4 μm) and under a modulated pressure during the whole welding process:

1) This process does not generate important microstructural perturbations.

2) The tensile behavior of the joints is reproducible.

3) Failure occurs out of the interface with a tensile strength of 950 MPa and with an elongation of 22% (bainitic and martensitic structure). These results are better than those obtained with friction welded 27CD4 p-type steel specimens as regards to the tensile performances, especially for elongation. Indeed, in this latter case, the failure occurs through the weld region (because of the heavy sulfide grain flow) with smaller elongation (the samples had the same structure).

4) Deformation of the welded specimens is limited to about 2% of the heated length.

5) The failure energy of joints measured with impact tests is lower than that of the base metal. That can be explained by the flatness of the interfacial grain boundary pinned by oxide and sulfide particles. With a low-sulfur-content steel, mechanical characteristics of the joint may be improved.

The techniques to be implemented were proven consistent with the industrial features of mass production: induction heating, modulated pressure with temperature, nitrogen with 5% hydrogen gas, and short welding time. Only pre-weld preparation can be unfavorable (cost barrier) for this process expansion. However, it is not excluded that some technical solutions could be found to overcome this difficulty. Moreover, a slight increase in welding time could result in improved joints with higher roughness: feasibility tests of diffusion welding with higher roughness specimens (Rmax = 1.5 μm) have proven that high-quality welds (tensile test specimens failed away from the weld interface) are achieved at the same temperature (1050°C) with a duration of 60 s only (unpublished results).

Ongoing Works

An additional mechanical characterization is now going on in our laboratory, our purpose being, among others, to assess the fatigue endurance. For this study, we have to weld specimens of 16 mm diameter. Using a more powerful generator (12 kW, middle frequencies) with an optimal heating program, we succeeded in achieving welds of the same quality than those described above. So, it is proven feasible to carry out high-strenth joints of larger diameter components like transmission shafts, with a sufficiently powerful generator.

This process is also efficient for making welds on other ferrous alloys . Some tests have already proved the efficiency of this technique on 0.12 and 0.38 wt-% carbon content steels, and we are now studying 100C6 steel. The results are promising.

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