Welding Materials and Technologies Expanding the Application of Steels*

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Synopsis:

The recent welding materials and welding technologies corresponding to the requirements of the welding engineering industries are outlined. In the field of welding materials for securing high efficiency and high quality welding, there have been developed welding materials having excellent fatigue characteristics, solid wire for the low spattering CO_2 arc welding, high efficiency one pass submerged arc welding process and flux with super-high heat input for heavy section plates. From the viewpoint of the weldability of steel materials, new welding technologies were established for the surface coated steel sheets and high tensile strength steel plates.

1 Introduction

Iron and steel materials have evolved in response to the changing needs of the social environment and market. As part of this trend, welding materials and welding technologies have played the important role in the applications of steel materials.

In particular in the development of steels for welded structures, welding materials with excellent toughness have been developed to apply high efficiency welding process with high heat input. On the other hand, in the development of steel materials, steel makers have a history of developing steel plates for high efficiency welding process with high heat input, which show excellent mechanical properties even in the weld heat affected zone (HAZ). Thus, the development of welding materials and technologies and the development of steel materials are in fact two sides of the same coin, mutually supporting each other, and their synergistic effect has contributed to the development new steel materials and welding materials and welding technologies. Moreover, this development relationship will remain essentially unchanged in the future.

As Kawasaki Steel commemorates its 50th anniversary, in terms of welding we would like to summarize the main requirements of the various industrial fields in recent years and introduce the welding materials and technologies corresponding to these needs.

2 Welding Materials and Technologies for Welding Engineering Requirements

2.1 Responding to Low Spatter Requirements in Gas Metal Arc Welding

In automation and robotization of gas metal arc welding, if a large amount of welding spatter is generated, spatter sticking onto the gas shielding nozzle may obstruct gas shielding and deteriorate weld quality. To respond to such problems in automation, the development of a low spatter welding technology, including stable feedability of the welding wire, was energetically promoted. **Photo 1** shows the arc behavior in MAG welding (Ar + CO_2) and CO_2 arc welding using conventional wire. In MAG welding, because the arc is generated from the top of the molten part of the wire end, a downward electro-magnetic force acts on the molten part, which includes the molten droplet. The tip of the wire keeps a sharp angle as is melts, and small diameter droplets are transferred to the molten pool virtually continuously (spray transfer). However, in CO_2 arc welding, the CO_2 gas undergoes thermal ionization and absorbs heat, causing cooling contraction of the arc. The voltage gradient of the arc is increased by the contraction of the arc and the arc is concentrated locally on the bottom of the droplet hanging from the wire. As result, the droplet

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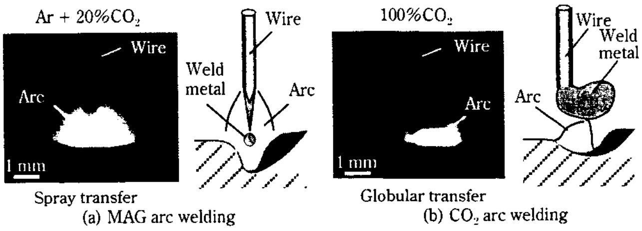


Photo 1 Comparison between MAG ($Ar + CO_2$) and CO_2 arc weldings in metal droplet transfer phenomena

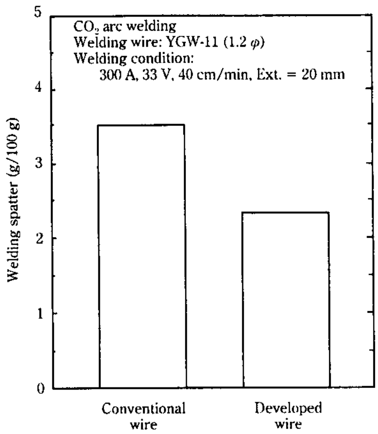


Fig. 1 Comparison between amount of welding spatter in CO_2 arc welding with newly develop wire and that with conventional one

is pulled upward by electro-magnetic force, creating a large droplet, and is transferred to the molten pool (globular transfer). In this process, the large droplet, in that form, scatters as spatter due to the electro-magnetic force. Further, because the arc length is shortened, the droplet can easily short circuit with the molten pool, and the droplet is then scattered by the explosion caused by the sudden rise in temperature when arcing is restored. For this reason, the amount of spatter that occurs during CO_2 arc welding is extremely large in comparison with MAG welding.

Accordingly, when attempting to reduce the amount of spatter in CO_2 arc welding, suppressing the increase in the voltage gradient caused by contraction of the arc becomes a key point for development. It is possible to ease the increase in the voltage gradient due to thermal ionization of CO_2 by adding elements with low ionization energy to the wire, thus alleviating local concentration of the arc. Based on this concept, a solid wire for CO_2 arc welding (KC-50-DH) that realizes low spatter welding was developed. **Figure 1** shows a comparison of the amount of welding spatter with the newly developed wire and a conventional wire.

Further, even in MAG welding, which is characterized by a relatively small amount of spatter, a low spatter wire for pulsed MAG welding was developed to meet the need for low spattering in order to achieve an even higher level of quality. Specifically, the newly developed welding wire (KM-50S) realizes stable detachment of the droplet from the wire when the pulse is applied by adjusting the viscosity of the droplet.

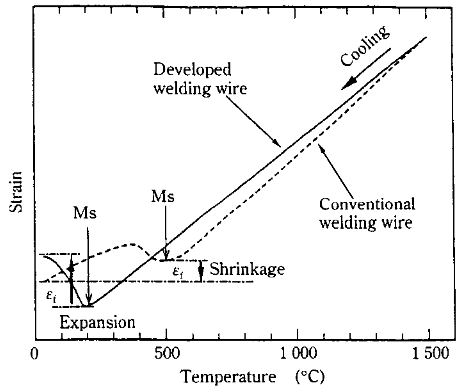


Fig. 2 Change in residual strain of the welding materials after cooling due to the transformation temperature

2.2 Responding to High Fatigues Strength Requirements

Generally, as-welded joints have a residual tensile stress which is of the same order as the yield strength of the base metal as a result of thermal contraction of the weld metal in the weld cooling process. This residual tensile stress markedly reduces the fatigue strength of the welded joint. For this reason, the fatigue strength of welded joints does not increase even if high strength steel is used in the base metal, with the unsatisfactory result that the piece as a whole does not demonstrate the advantages of high strength steel. Therefore, welding materials were developed to alleviate tensile weld residual stress or impart residual compressive stress. **Figure 2**[1] shows the thermal contraction that occurs in the process of cooling from the austenite phase. With conventional welding materials, transformation begins at approximately 500°C, as shown by the broken line in Fig. 2, and transformation expansion occurs. However, after transformation is complete, the material again undergoes thermal contraction. In highly restrained welded joints, this causes tensile residual stress at room temperature. In contrast to this, applying a weld metal which has a low transformation starting temperature and completes transformation at near room temperature, as shown by the solid line in the figure, makes it possible to introduce compressive residual stress, because cooling of the weld metal is completed in a condition of transformation expansion. Based on this mechanism the low transformation temperature welding wire, which is effective in improving the fatigue properties of welded joints, were developed by collaboration with the

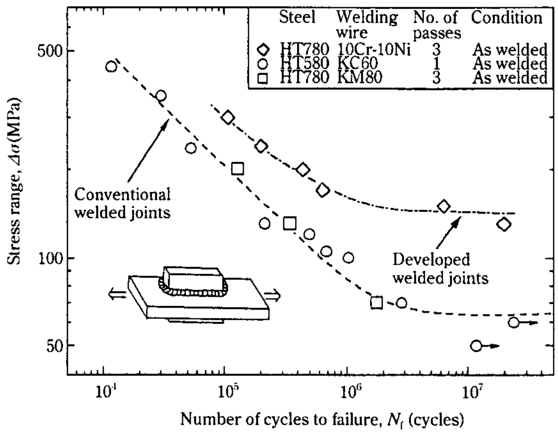


Fig. 3 Fatigue characteristics of the welded joint with the shielded metal arc welding material showing low transforming temperature

National Research Institute for Metals. **Figure 3**[1] shows the fatigue characteristics of box welded joints using conventional welding material and the low transformation temperature welding wire (10Cr-10Ni). By applying the newly developed material, fatigue strength in the as-welded condition can be increased to approximately twice the fatigue strength of conventional welded joints.

2.3 Responding to Anti-Hot Cracking (Anti-Solidification Cracking) Requirements

Conventional welding materials are designed for anti-hot cracking based on the assumption that welding is performed in a fixed groove. Accordingly, when welding is performed in a vibrating or shaking groove it is not possible to apply the welding material as-is. A typical example is repair welding and welding reinforcement of existing bridges and viaducts, which must be performed under use conditions without restrictions on traffic in order to alleviate congestion. **Figure 4**[2] shows an example of measurements of the relative displacement and its velocity between bed plates while an overhead bridge is in use. During welding, the similar variable strain due to passing vehicles also acts on the weld molten pool, causing hot cracking. In order to suppress hot cracking, Kawasaki Steel developed a shielded metal arc welding rod (KS-1000) with excellent anti-hot cracking characteristics, in which C, Si, and P, S, and other impurity elements in the weld metal are reduced. This welding material can also be applied to welding of mega-float structures on the sea, which shake due to ocean wave movements.[3] A high efficiency welding wire for gas shield arc welding was also developed.[4] **Figure 5** shows the solidification cracking ratio relative to the cyclical displacement of the root gap in MAG welding with a conventional wire and the newly developed wire. No cracking occured with the newly developed wire even when displacement was more than twice as large as critical displacement with the conventional material.

2.4 Responding to Anti-Low Temperature Cracking (Anti-Hydrogen Cracking) Requirements

Low temperature cracking in welded joints is induced by diffusible hydrogen. The diffusible hydrogen that penetrats into the weld metal during welding diffuses to and accumulates in high strain areas at room temperature after welding, causing hydrogen embrittlement, and cracks then occur as a result of tensile residual stress due to welding. Moreover, cracking susceptibility becomes extremely high in propotion to hardness of welds. Thus, as shown in **Fig. 6**, low temperature cracking is caused by three main factors, (1) the amount of diffusible hydrogen (H_D) in the weld, (2) the tensile stress (σ) applied on the weld, and (3) the hardness (H_V) of the weld. This means that low temperature cracking becomes a serious problem in welds of high strength materials, in which high tensile residual stress occurs and the weld shows marked hardening. In welds of high tensile strength steel, it is of course essential to use low hydrogen welding materials that have been adequately dried in order to reduce hydrogen penetration into the weld, and to avoid penetration by water vapor in the atmosphere. In addition, preheating, post-heating, and other measures have also been used to diffuse out hydrogen from the weld. However, high temperature preheat-

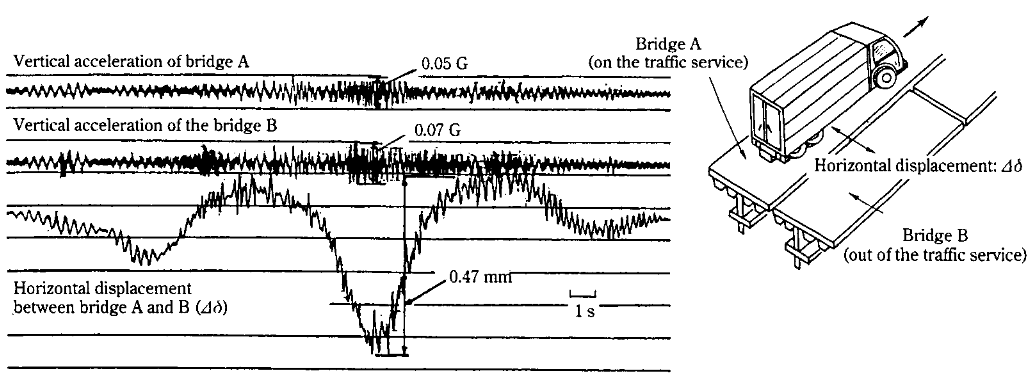


Fig. 4 Example of displacement between bridges on traffic service

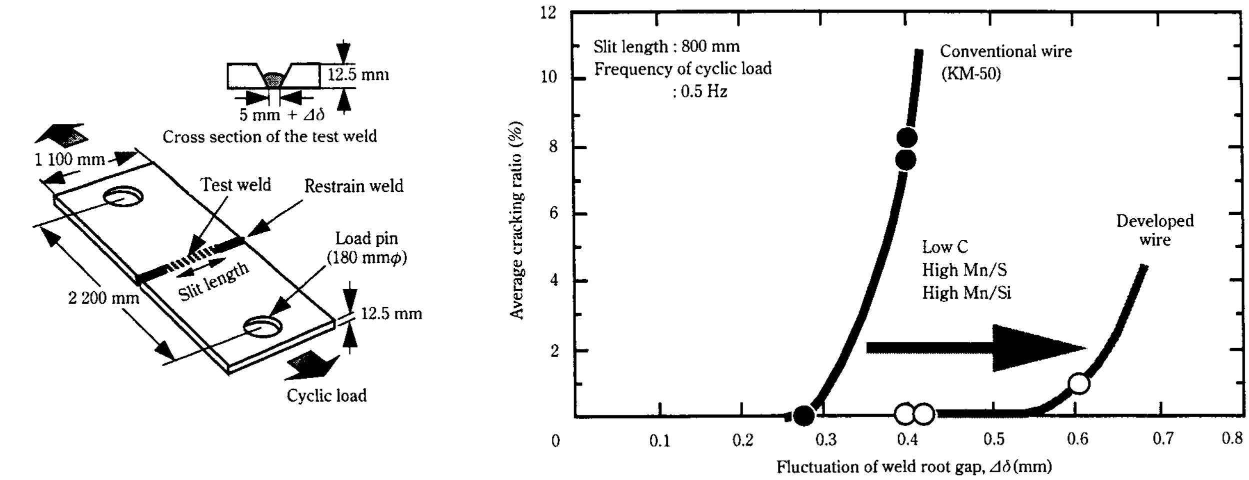


Fig. 5 Relation between fluctuation of root gap and solidification cracking ratio of the weld metal under the cyclic load

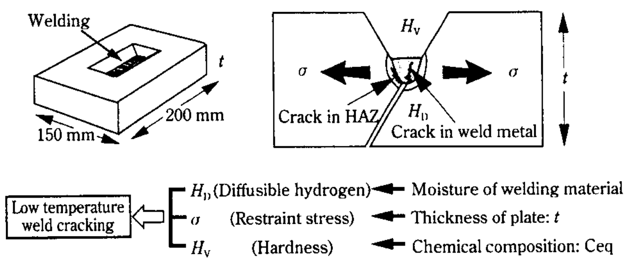


Fig. 6 Factors of low temperature weld cracking

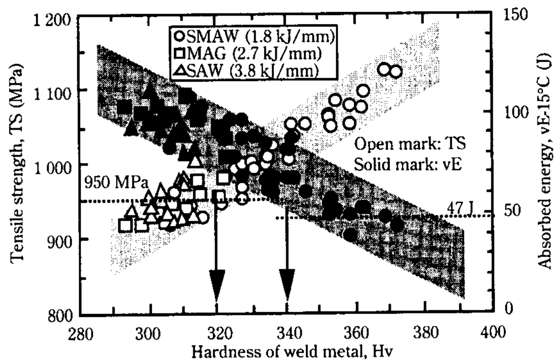


Fig. 7 Relation among hardness, tensile strength and Charpy absorbed energy of the weld metals in the multipass welded joints

ing and post-heating not only increase the number of processes, but also remarkably deteriorate the welding working environment. Thus, a technology which is capable of preventing low temperature cracking by using the lowest possible temperature for preheating is required.

With welds of HT980 steel, development focused on a welding technology and material that would not be susceptible to hydrogen cracking even with low temperature preheating, but would nevertheless maintain high strength and good toughness in the weld metal. However, there was particular concern of cracking in shielded metal arc welding, as this type of welding has the largest amount of diffusible hydrogen. In response to this, as shown in **Fig. 7**, the strength and toughness of the weld metal in welded joints was secured by adjusting the carbon equivalent (Ceq) resulting in the hardness of the weld metal. Where low temperature cracking is concerned, the abovementioned difficulty was solved by developing a welding material that suppresses the increase in hardness by adopting a low carbon material design. Specifically, in the root pass weld metal, which has an increased susceptibility to low temperature cracking due to the high cooling rate, attention was focused on the fact that the microstructure comprises martensite structure mainly in which hardness is dependent on the C content, and a low carbon composition was adopted without changing the carbon equivalent, as shown in **Fig. 8**. Applying this newly developed shielded metal arc welding rod to welding of HT980 made it possible to prevent low temperature cracking with preheating at 75°C, even in strict welding conditions such as a plate thickness of 75 mm, temperature of 30°C, and relative humidity of 80%.[5]

2.5 Responding to High Efficiency Welding Requirements

Beginning with the high rise building boom from the second half of the 1980s through the first half of the 1990s, there was increasing demand for high efficiency in welding of structural materials, as represented by box columns and weld built H-shape steel with heavy plates. In response, the submerged arc welding (SAW) procedure for deep penetration with high heat input and bonded flux with added iron powder were positively developed. As a result of direct X-ray fluoroscopy obser-

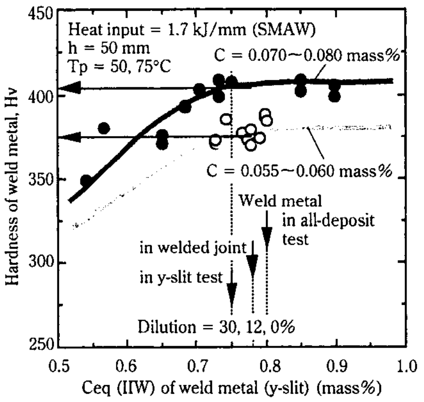


Fig. 8 Effects of the carbon equivalent and carbon content on hardness of the weld metal employed in the y-groove weld cracking test

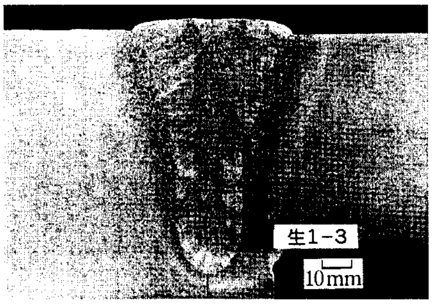


Photo 2 Cross sectional macrostructure of the 3-electrodes, 1 pass submerged arc welding for heavy section plate of 80 mm in thickness

vation of the behavior of the molten pool in high heat input SAW, it became clear that, in order to achieve deep penetration, it is important to control the amount of molten metal that flows in directly under the arc of the leading electrode, preferably by holding the welding current of the trailing electode to a low level. Based on this knowledge, a high efficiency 1-pass welding method was established for the corner joints of box columns with a plate thickness of 60 mm using a 2-electrode submerged arc welding method.[6] A welding method that enables high efficiency 1-pass welding of the above-mentioned 60 mm thickness, even with a low output welding power source of less than 2 000 A, was also developed by employing deep penetration with a high current density, which was made possible by applying a small diameter wire of 5.1 mm to the leading electrode (conventionally, 6.4 mm in diameter).[7] A 1-pass welding method for 80 mm plates by 3-electrode submerged arc welding, as shown in **Photo 2**,[8] was also developed by optimizing the groove configuration, distance between the electrodes, and other factors. Similar concept was applied to filet welding of weld built H-shape steel, and a bonded flux (KB-U, without iron powder addition) that enables

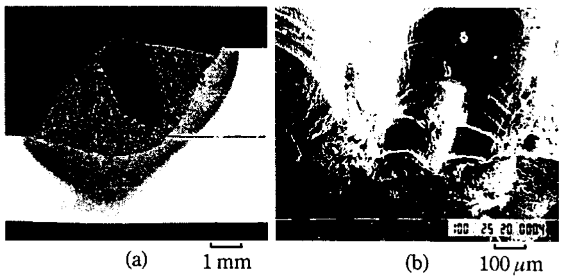


Photo 3 Cross sectional view (a) and inner surface (b) of typical blowhole generated in the lapped MAG welding of zinc coated sheets (45/45 g/m^2)

full penetration welding of plate thicknesses of up to 25 mm in grooveless T-shaped weld joints and a bonded flux (KB-US, with iron powder addition) that enables full penetration welding of extra heavy plates as thick as 80 mm in grooved T-shaped weld joints, were developed, greatly improving welding efficiency.[9] At the same time, considerable energy has been devoted to research on improvement of material properties in the weld metal and heat affected zone to cope with the application of SAW technique, elector-slag welding, and other ultra high heat input, high efficiency welding methods.[10-12]

2.6 Improvement of Weld Workability of Coated Steel Sheets

Beginning in the second half of the 1980s, coatings for automotive steel sheets to prevent auto body corrosion were rapidly adopted, and accompanying this trend, new tasks arose in the field of welding as well. Specifically, defects such as blow holes and pits in the arc weld metal of zinc coated steel sheets and unstable formation of nuggets in the resistance spot welding are important tasks for weld quality.

In arc welding of lapped zinc coated steel sheets, as shown in **Photo 3**, blow holes are formed when Zn in the lapped gap is vaporized by the welding heat and blows out into the weld metal, and is then trapped in the solidifying weld metal. Suppressing gas generation is effective for preventing this phenomenon. Accordingly, a method of preventing Zn vaporization was developed by coating FeP_2 in the area around the weld in the lapped gap in advance of welding. The FeP_2 reacts with Zn in the presence of welding heat, thus preventing vaporization.[13]

Two phenomena may be mentioned as causes of poor weldability in resistance spot welding of Zn coated steel sheets, as follows.

First, the Zn coating layer on the sheet surface melts during welding, which expands the welding current path, particularly at the interface between sheets. This reduces the current density and makes it difficult to form weld nuggets. If welding is performed with a high current suitable for Zn coated steel sheets, weld nuggets can be

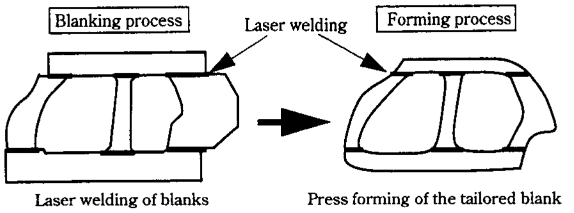


Fig. 9 Example of press forming process with tailored blanking technology

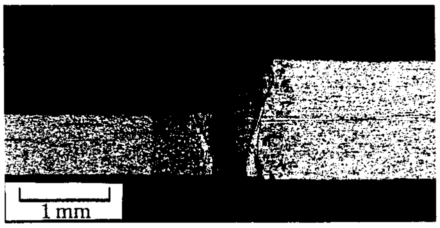


Photo 4 Example of laser welded joint of the sheets of different thickness, i.e., 0.7 and 1.4 mm in thickness, welding condition; 4.6 kW, 4 m/min

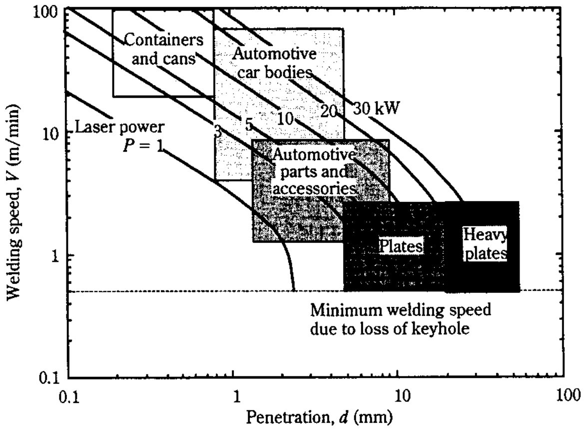


Fig. 10 Relation between laser power and penetration depth of laser welded beads

formed, but it is necessary to use a large capacity welding transformer to meet this requirement. This gave rise to a new task, because conventional welding robots could not withstand the increase in the weight of the welding transformer when large capacity transformers are adopted. To meet this need, the manufacturers of welding power sources developed inverter DC power sources that are capable of meeting the requirements of light weight and large capacity, and such devices have been applied practically in some cases.

As a second phenomenon which deteriorates weldability with Zn coated steel sheets, when continuously repeated resistance spot welding is performed, the zinc on the surface of the steel sheet forms a hard, brittle Cu-Zn alloy layer on the welding electrode by diffusion and penetration, causing extremely fast electrode wear. This also reduces the welding current density, and ultimately, it becomes impossible to form welding nuggets. Kawasaki Steel responded to the deterioration of electrode life from the viewpoint of the base material. A detailed analysis of electrode wear phenomena in continuous spot welding was carried out,[14] clarifying the relationship between the configuration of the electrode face and nugget formability.[15] As a result, a new galvannealed zinc coated steel sheet was developed, which is capable forming a stable tip on the electrode face and has excellent spot weldability.[16]

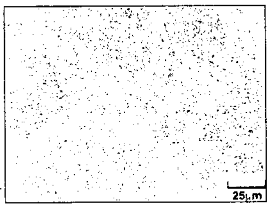
2.7 New Application of Laser Welding

From the 1980s through the 1990s, automobile makers developed and applied tailored blanking techniques with the aim of reducing auto body weight or enabling appropriate selection and application of materials. In tailored blanking, as shown in **Fig. 9**, multiple materials with different functions and thicknesses are joined into one piece by laser welding or other methods before blanking is actually performed. Accompanying this trend, research was carried out on laser welding procedures for steel sheets with different strengths, thicknesses, coatings, and other features (**Photo 4**), and on the press formability of such laser welded joints.[17,18] As a result, the range of applicable materials and locations was expanded.

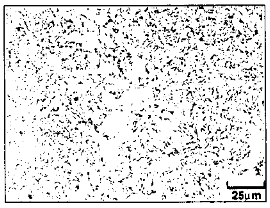
The power of CO_2 laser welding machines has increased dramatically in the last ten years. Functionally speaking, as shown in **Fig. 10**, practical devices of the 45 kW class have appeared, and can be applied even to heavy plates with satisfactory results. With the aim of applying welded joints produced by high power laser beams of this type to structures, basic research was conducted on the metallurgical performance of the weld metal, including cooling characteristics, chemical composition, microstructure, and toughness.[19,20] Even in laser welding, it is possible to obtain acicular ferrite structure by inclusions, with Ti as the main type, and it has been found that laser weld metal has a finer microstructure, high strength and toughness than arc weld metal (**Photo 5**).

3 Conclusion

This report has introduced the main welding materials and welding technologies developed by Kawasaki Steel in recent years to support fabrication of steel in various fields. The evolution of welding technologies is always closely related to the social environment and market needs. Moreover, welding technology plays the role of a key technology that determines whether new steel materials can be applied practically. It appears that this trend will remain unchanged in the new century. In the future, a wide range of welding and joining technologies will



(a) Laser weld metal (0.3 kJ/mm)



(b)Submerged arc weld metal (6.5 kJ/mm)

Photo 5 Microstructures of the laser and submerged arc weld metals

become even more important to meet the requirements of increasingly diversified and advanced materials.

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