FUNDAMENTALS OF WELDING-RELATED METAL SCIENCE AND WELDABILITY OF MATERIALS

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Contents

Summary

The particularities of the welding process and welding thermal cycle are discussed. Different zones in welded joint are presented: ageing zone in low-carbon steels, sub-hardening zone in C-Mn steels, zone of tempered martensite in Q & T steels and carbide precipitation zone in austenitic steels. The special case of heterogeneous welded joints is presented. Fundamentals of weldability of materials are given: types of weldability, theoretical and practical methods of weldability assessment as well as weldability tests are given.

1. Welding Process

The process of welding is characterized by local melting and solidification which proceed successively along the edges of welded elements.

The welded metal known as parent metal and additional material referred to as filler metal are brought to the liquid state. The liquid metal solidifies in the "mould" created by partially molten edges of welded elements and forms the weld (Figure 1).

The molten metal is the area where various metallurgical processes i.e. physical and chemical reactions take place. The aforesaid reactions result from mixing of various materials i.e. parent and filler metals or are triggered by the contact of the weld pool with the gas shield, flux or slag.

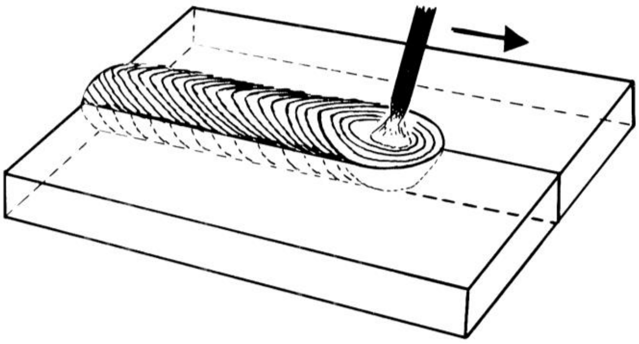

Figure 1. Weld-laying process (welded joint production)

While the weld is being laid, the solid parent metal adjacent to the molten area is subject to diversified heating followed by cooling. In other words, the parent metal is exposed to heat treatment. The welding-triggered phenomena proceeding in the parent metal in the vicinity of the weld are the subject of welding-related metal science investigation.

The ultimate objective related to the welding process is to ensure the continuity between welded materials and homogeneity of all properties within the welded joint area. Failure-free material continuity i.e. the continuity void of welding imperfections can be obtained by proper weld production. However, the condition of ensuring chemical and structural homogeneity as well as other joint-related properties is practically unfeasible. The divergence between the properties of the welded joint and those of the parent metal unaffected by welding reveal the level of welding process excellence and is related to the notion of parent metal weldability; the lower the divergence, the better (easier) weldability.

Apart from relatively easily detected material heterogeneities present in welded joints, it is also possible to observe specific stresses generated in the latter as a result of non-uniform heating and cooling of the elements of these joints during welding. Depending on their intensity, stresses may modify the shape of welded joints causing e.g. bends or be responsible for cracks occurring during welding, directly afterwards or even during further weld operation.

2. Welding Thermal Cycle

Each welding process is characterized by a welding thermal cycle (Figure 2), or more exactly, a number of welding thermal cycles, (Figure 3a) which together determine temperature distribution in the weld and weld-adjacent zones in each moment of heating and self-cooling times (Figure 3b).

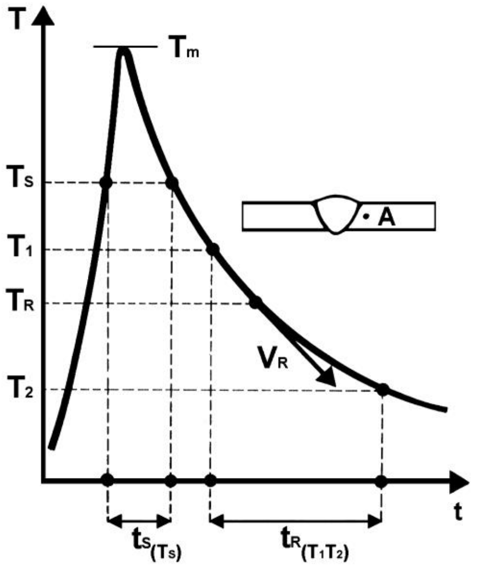

Figure 2. Single welding thermal cycle in point A of welded joint

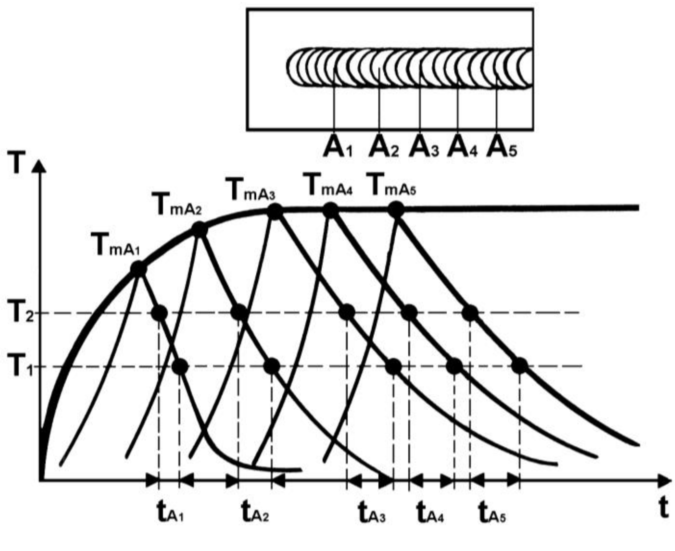

Figure 3a. Set of thermal cycles in successive points A_1, A_2, A_3 etc. along weld line

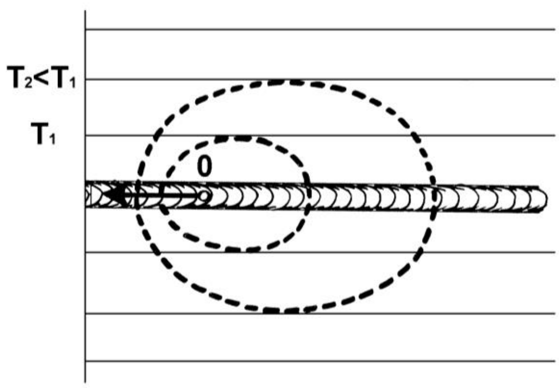

Figure 3b. Thermal fields on surface of welded element, corresponding to thermal cycles presented in Figure 3a

Unlike the thermal cycles of traditional heat processing, welding thermal cycles are characterized by a very high heating speed, high maximum temperature, short hold-time at maximum temperature and high cooling speed. Cycles determined at various distances from the weld line (Figure 4) differ from one another in maximum temperature, hold-time at maximum temperature and cooling speed. In case of multi-layer welding, welding thermal cycles repeatedly overlap one another.

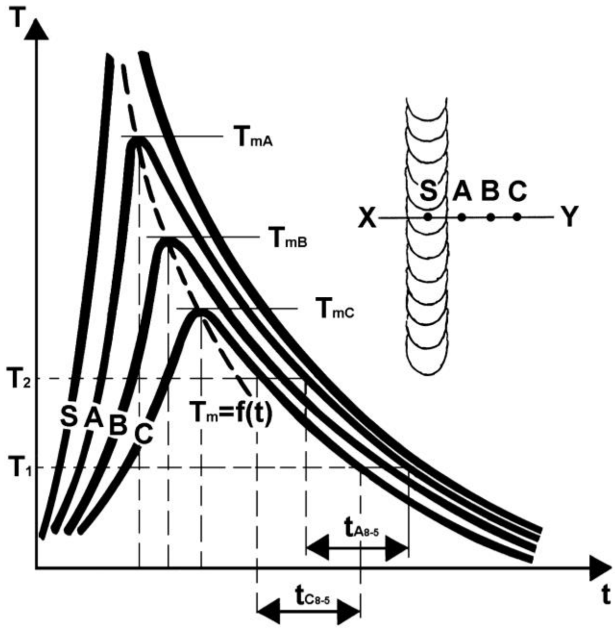

Figure 4. Thermal cycles in successive points S, A, B and C, along line perpendicular to weld line.

The actual temperature distribution in each point of the welded joint is revealed by “momentary temperature distributions” (Figure 5). The said “distributions” are obtained by marking momentary temperature values of each point specified by x and y coordinates on the *x-y-z* coordinate system. While doing so, it is assumed that the heat source moving towards 0*y* (along the weld and time axes) is situated in point 0 (0, 0, 0). The area of “momentary temperature distribution” determined by points x, y and z and intersected by a number of planes passing through points 0, A, B and C and parallel to plane *y*0*z* defines single thermal cycles. The projections of these thermal cycles on plane *y*0z form graphs exemplified by the graph presented in Figure 2. The curve connecting maximum temperatures T_{m} (Figure 5.), whose projection on plane *x*0*y* is a curve deviated from axis 0*x*, represents the distribution of the highest temperatures obtained in individual points of the welded joint.

The shape of “momentary temperature distributions” and welding thermal cycles is determined by the impact of the following factors:

- welding method (individual methods significantly vary in energy concentration degree - Figure 6 - considerable differences in thermal cycles are present - in case of arc-utilizing welding methods: manual welding with covered electrode, gas-shielded automated welding, automatic submerged arc welding or electroslag welding, and in case of methods characterized by high energy concentration: plasma welding, electron beam welding or laser welding),

- welding parameters,
- initial temperature of welded elements (preheating prior to welding),
- heat capacity and heat conductivity of welded material,
- mass and thickness of welded elements,
- location of elements relative to one another.

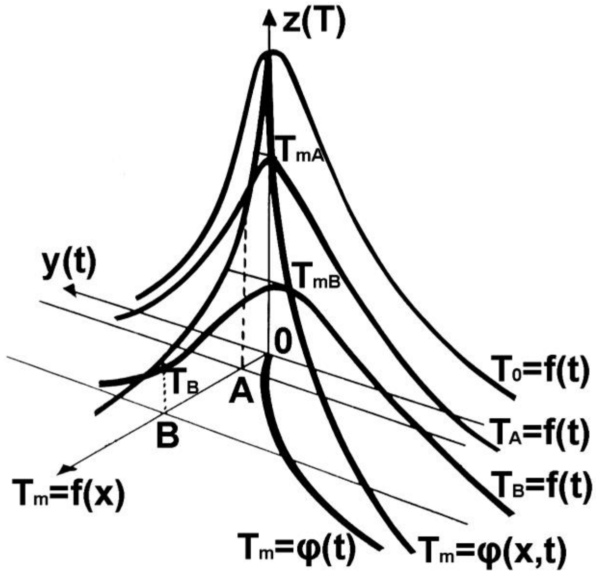

Figure 5. “Momentary temperature distribution” in welded joint

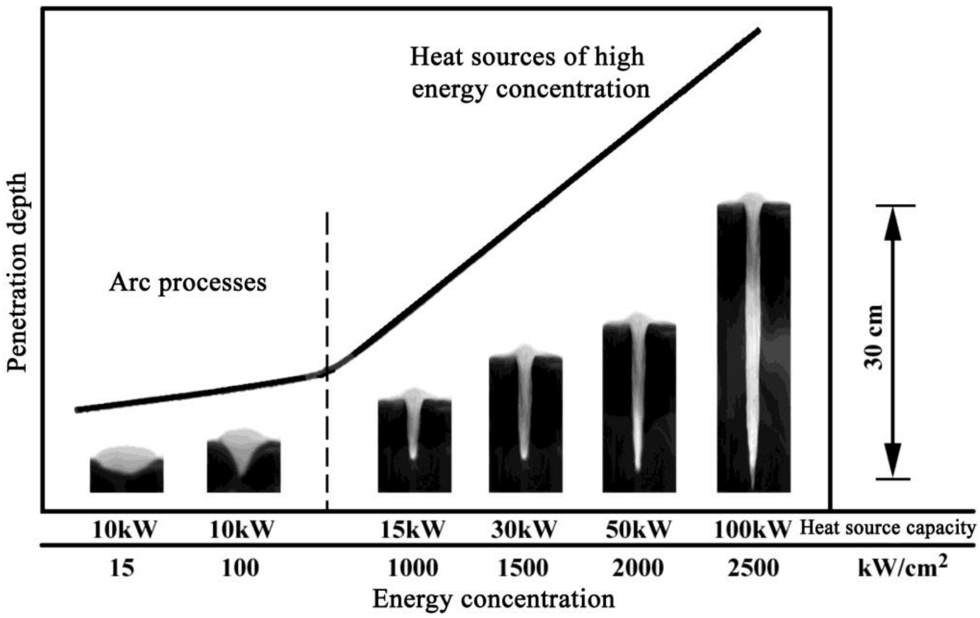

Figure 6. Differences in concentration of energy of welding heat sources, decisive for penetration depth (and welding thermal cycles)

The interrelation of some thermal cycle factors is expressed by Rykalin's equation:

$$V = \frac{2\pi\lambda \cdot (T - T_0)^2}{E \cdot \eta} \left[{}^{\mathrm{o}}\mathrm{C/s} \right]$$

where:

$$Q = U \cdot i; \quad E = \frac{Q}{v}; \quad v = \frac{l}{t}$$

and where:

V : cooling speed at temperature T,
T_0 : initial temperature of welded elements,
E : arc linear energy in welding process,
U : arc voltage in V,
i : welding current in A,
v : welding speed in cm/s,
λ : parent metal heat conductivity,
l : length of laid weld in cm,
t : welding time in s,
η : welding process efficiency factor.

Thermal cycles are determined in two basic ways i.e. by means of an analytical method based on Rykalin's theory as well as on the basis of an experimental method requiring the application of thermocouples fastened in specific points of the welded joint and temperature recorders drawing courses of temperature in a function of time.

In welding thermal cycles there is one special parameter i.e. cooling time within the temperature range 800 – 500 $^{\mathrm{O}}$C ($t_{8/5}$) (Figure 7) or less frequently – within the temperature range 700 – 300 $^{\mathrm{O}}$C ($t_{7/3}$). Being practically constant for all thermal cycles at the whole width of the heat affected zone, the parameter explicitly characterises the welding process.

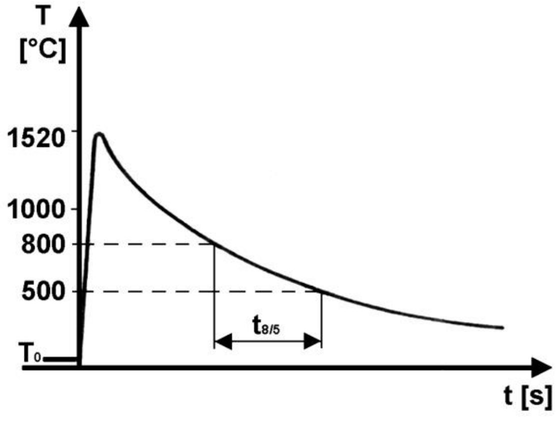

Figure 7. Special parameter of welding thermal cycle – $t_{8/5}$

3. General Zones of Welded Joints

The welded joint can be basically described as consisting of three distinguished areas (Figure 8 a and b) i.e. the weld itself (1), heat affected zone (2) and welded material (3). Figure 9 (a and b) contains a diagrammatic representation of the structural change observed in the welded joint made of low-carbon steel caused by the welding thermal cycle.

Within the temperature range up to A_1, no structural changes proceed in the welded material. The changes which may be possible to observe are those related to transition of unstable (metastable) structural components into stable ones such as, for instance, ageing (particularly that of ageing steels subject to pre-welding strain), tempering (while welding steels of hardening structure) and high-temperature tempering (in case of Q & T steels).

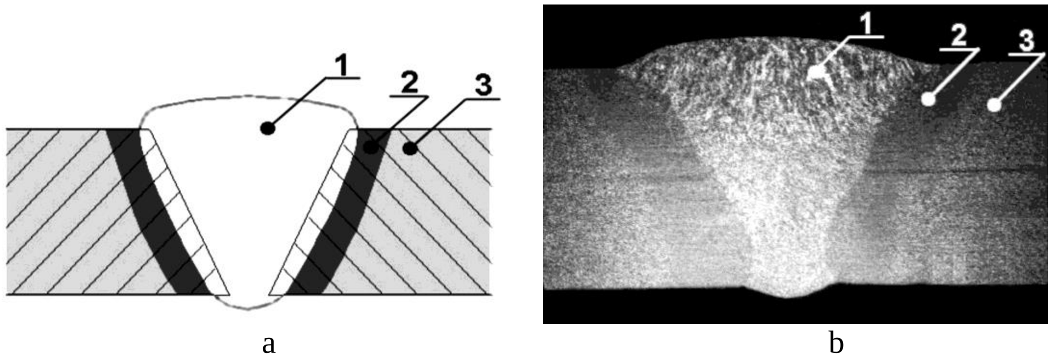

Figure 8. Welded joint: weld, heat affected zone and (welded) parent metal: a – diagram, b – photograph

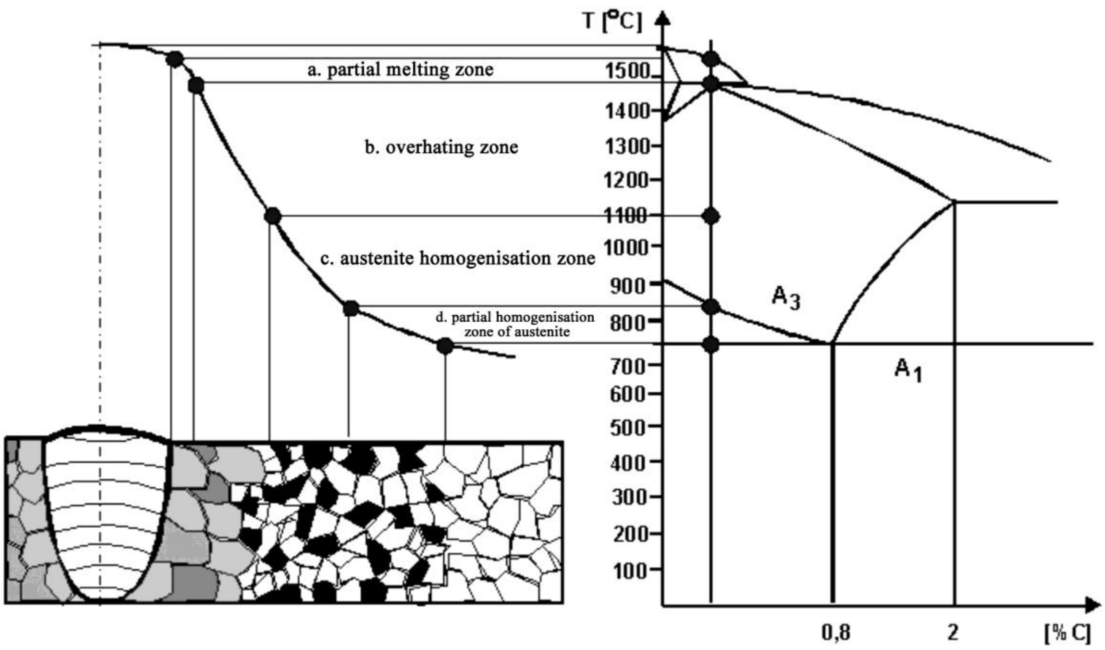

Figure 9a. Structural changes in welded joint in relation to system iron - carbon

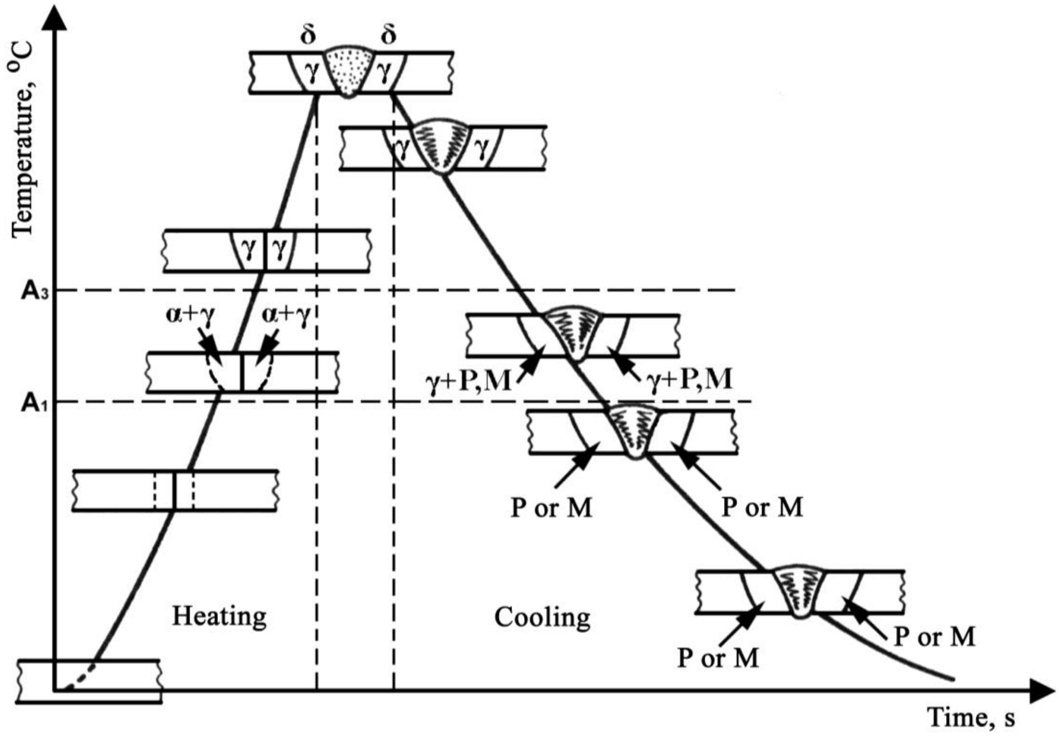

Figure 9b. Structural changes in welded joint in relation to temperatures determined by welding thermal cycle

Once temperature A_1 has been exceeded, austenitic transformation in the welded material begins to proceed (Figure 10). Going beyond temperature A_3 is accompanied by austenite homogenization. Austenite grains tend to grow at temperatures significantly higher than that of A_3. The high temperature of welding process favors austenitization and growth of austenite grains, whereas high heating speed together with short hold-time at high temperature limit the growth of austenite grains.

Immediately before the melting point and liquid state are obtained, in the very narrow area of welded material adjoining the weld being formed, it is possible to observe peritectic transformation (reaction) resulting in the formation of high-temperature ferrite δ.

Obtaining the liquid state is equivalent to the formation of a weld pool, in which chemical composition changes proceed being triggered by the three groups of phenomena:

- intermixing of parent and filler metals, in as much as filler metal is applied,
- metallurgical reactions on the border: liquid metal – slag or gas shield,
- metallurgical reactions in the fusion zone.

The relocation of the weld pool in welding direction results in the formation of a weld characterized by solidification structure composed of dendrites arranged in the direction overlapping with that of heat off-take.

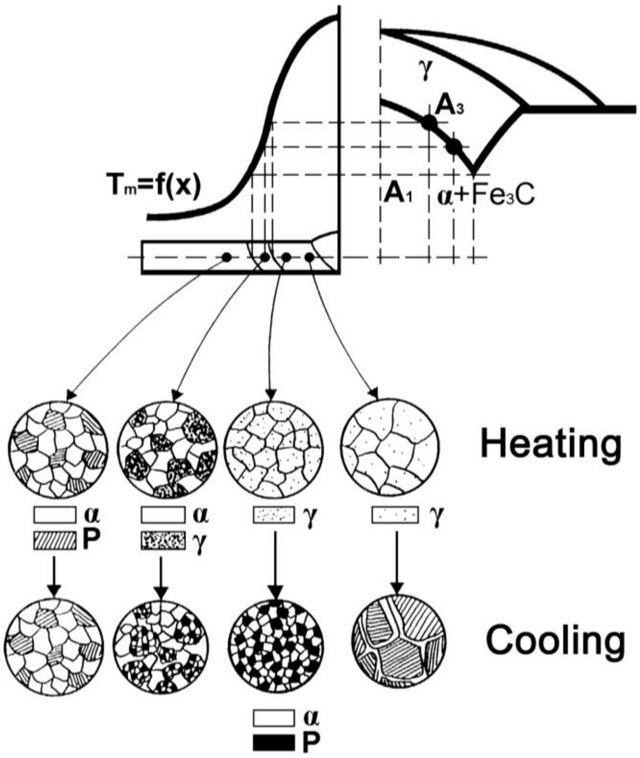

Figure 10. Structures in heat affected zone of welded joint made of low-carbon steel

The welded material enclosing the solidifying weld remains in the austenite state; it is only in the narrow area of the aforesaid material adjoining the weld, that one may observe the transformation of high-temperature ferrite δ into austenite. The austenitic transformation usually takes place at a temperature significantly lower than that of A_1: this being the result of considerable cooling speed in the welded joint. Depending on the hardenability-affecting chemical composition of steel, austenite transformation may be similar to that of pearlite or martensite. The structure formed as a result of austenite transformation is characterized by diversified grain sizes depending on characteristic quantities of the welding cycle.

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Biographical Sketch

Jan Pilarczyk has received his diploma of Master of Science in Mechanical Engineering from the Silesian Technical University in Gliwice, Poland in 1963. After completing further studies at ESSA Paris, France he obtained an Post-Graduate Welding Engineer Diploma in 1967. In 1972-1973 he served an apprenticeship in Cranfield Institute of Technology, UK. He joined the Instytut Spawalnictwa (The Welding Institute) in Gliwice, Poland in 1963 as a junior research worker in investigations into weldability of steel and mechanical testing of welded structures. He was continuing as a senior research worker and the head of Weldability Department. In 1980-1990 he was the Director for Research, Management and co-ordination of research activities of the Instytut Spawalnictwa, management of State research programs on the area of welding. Since 1991 to date he is being the Director of the Instytut Spawalnictwa. During his association with the Instytut Spawalnictwa he earned a PhD-degree and DSc-degree from the Technical University Gliwice, Poland in 1972 and 1977 respectively. In 1991 he was awarded the Professor title by the President of Poland. In 1992 he obtained the European Welding Engineer degree from the ESSA Paris France. His scientific contributions and technical papers (more than 100) have been published in different Technical Journals and Magazines in the field of weldability of steels, case studies, welding development etc. On the other side he is the author of 4 technical books in welding. He is the member or fellow of many scientific, technical and social organizations. In some of them he is a chairman or president.