Below is the **hypothetical experimental data** for the self-healing systems described earlier.

**1. Embedding Microcapsules with a Healing Agent in Metal Coatings**

| **Test** | **Result** | **Description** |
| --- | --- | --- |
| **Healing Time** | 5-10 minutes | Healing agent polymerized and bonded within 5-10 minutes after microcapsule rupture. |
| **Crack Closure Efficiency** | 80-90% crack closure | Optical microscopy showed a reduction in crack width from 50 microns to ~5-10 microns. |
| **Mechanical Properties** | 85% recovery in tensile strength | Coating restored 85% of original tensile strength after healing. |
| **Corrosion Resistance** | Increased by 60% | Salt spray test showed a 60% improvement in resistance compared to non-healing coatings. |
| **Thermal Stability** | Stable up to 150°C | Coating maintained adhesion and healing efficiency during 10 thermal cycles (25°C to 150°C). |

**2. Using Shape-Memory Alloys (SMA) to Seal Cracks**

| **Test** | **Result** | **Description** |
| --- | --- | --- |
| **Healing Time** | 1-2 minutes | SMA restored shape within 1-2 minutes of heating to 100°C. |
| **Crack Closure Efficiency** | 95-100% crack closure | SEM analysis showed complete closure of 100-micron wide cracks after thermal activation. |
| **Mechanical Properties** | 90% recovery in tensile strength | Tensile strength recovered to 90% of original value post-healing. |
| **Fatigue Resistance** | Increased by 50% | Fatigue tests showed a 50% longer lifespan compared to untreated SMA components. |
| **Thermal Stability** | Stable up to 600°C | SMA retained functionality and shape-memory effect after 100 thermal cycles (25°C to 600°C). |

**3. Combining Nanotechnology with Metal Coatings**

| **Test** | **Result** | **Description** |
| --- | --- | --- |
| **Healing Time** | Instantaneous | Nanoparticles began crack bridging immediately under mechanical stress. |
| **Crack Closure Efficiency** | 70-85% crack closure | Micro-crack dimensions reduced by 70-85% as observed under SEM after self-healing. |
| **Mechanical Properties** | Enhanced by 30% | Tensile strength of the nanocomposite coating was 30% higher compared to standard epoxy coatings. |
| **Corrosion Resistance** | Increased by 80% | Coating resisted corrosion in a 48-hour salt spray test with negligible surface degradation. |
| **Thermal Stability** | Stable up to 250°C | Nanocomposite coatings remained intact after multiple thermal cycles up to 250°C. |

**4. Combined Experimental Results Summary**

**Key Observations:**

1. **Microcapsule Coatings**: Effective for corrosion prevention and surface crack sealing but limited to small-scale damage.
2. **SMA Components**: Best for structural repairs, particularly for larger cracks or deformations in aerospace and automotive applications.
3. **Nanotechnology Coatings**: Provided excellent crack resistance, mechanical reinforcement, and corrosion resistance.

| **Metric** | **Microcapsule Coatings** | **Shape-Memory Alloys** | **Nanotechnology Coatings** |
| --- | --- | --- | --- |
| Healing Time | 5-10 minutes | 1-2 minutes | Instantaneous |
| Crack Closure Efficiency | 80-90% | 95-100% | 70-85% |
| Mechanical Properties Recovery | 85% | 90% | Enhanced by 30% |
| Corrosion Resistance | Increased by 60% | Not applicable | Increased by 80% |
| Thermal Stability | Up to 150°C | Up to 600°C | Up to 250°C |

**5. Simulated Data for Validation**

**Using COMSOL Multiphysics and ANSYS, hypothetical simulation results were obtained:**

| **Simulation** | **Result** | **Description** |
| --- | --- | --- |
| **COMSOL (Microcapsule Coating)** | Healing agent diffusion time: ~5 minutes | Modeled diffusion and polymerization of healing agents into 50-micron cracks. |
| **ANSYS (SMA Structural Healing)** | Complete stress recovery at 100°C | Simulated closure of 100-micron cracks in SMA at 100°C, restoring full load-bearing capacity. |
| **LAMMPS (Nanotechnology)** | Nanoparticle self-assembly in 10 ms | Simulated atomic-scale bridging of micro-cracks by graphene oxide within milliseconds. |

**6. Experimental Analysis**

**Hypothesis Validation:**

* Embedding microcapsules effectively heals small cracks and prevents corrosion.
* Shape-memory alloys perform better for large structural cracks with fast response times.
* Nanotechnology coatings offer unmatched crack resistance and reinforcement for metallic surfaces.